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Normalograptus kufraensis, a new species of graptolite from the western margin of the Kufra Basin, Libya

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Abstract – *Normalograptus kufraensis* sp. nov. occurs as monospecific assemblages in the Tanezzuft Formation at the western margin of the Kufra Basin (Jabal Eghei), southern Libya. These graptolites have parallel-sided rhabdosomes with long, straight virgellae, climacograptid thecae and a full straight median septum. *N. kufraensis* is intermediate between Ordovician graptolites from the *N. angustus* (Perner) lineage and the younger sister species *N. ajjeri* (Legrand) and *N. arrikini* Legrand. *N. kufraensis* differs from these taxa as follows: it is broader than *N. angustus*; it has greater thecal spacing than *N. ajjeri* or *N. arrikini*. A table comparing measurements of *N. kufraensis* with 44 other *Normalograptus* taxa differentiates it from other members of this morphologically conservative group. Even though *N. angustus* and *N. ajjeri* are very long-ranging graptolites, a stratophenetic approach suggests that the specimens from Jabal Eghei may be of late Hirnantian or younger age. The faunal composition and preservation suggests these graptolites occupied the 'cratonic invader' biotope. The stratigraphic succession records deglacial flooding and fluctuating of redox in the Tanezzuft Formation, with the graptolites indicating a short-lived interval of anoxia.

Keywords: biostratigraphy, Silurian, Gondwana, Africa, evolution, glaciation, Palaeozoic.

1. Introduction

The late Ordovician and early Silurian graptolite faunas from the northern margin of Gondwana are crucial to determining the age and event stratigraphy of the region's petroleum rich rocks (P. Legrand, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999; Legrand, 2003; Armstrong *et al*. 2005; Loydell, 2007). This is particularly the case as limestone-hosted shelly faunas are generally absent (Walker, Wilkinson & Ivany, 2002; cf. Fortey & Cocks, 2005; Cherns & Wheeley, 2007), and most localities yield low-diversity graptoloid faunas comprising long-lived cosmopolitan forms and short-lived endemic taxa (Underwood, Deynoux & Ghienne, 1998; P. Legrand, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999; Zalasiewicz, 2001; Legrand, 2003). However, recent detailed studies of more complete successions from the Hirnantian and Llandovery of northern Gondwana (e.g. Underwood, Deynoux & Ghienne, 1998; Štorch & Massa, 2003; Loydell, 2007, 2012*b*; Zalasiewicz *et al*. 2007) have shown the total regional graptolite fauna to be comparable to those of peri-Gondwanan Europe, affording relatively detailed biostratigraphic correlation for the very latest Ordovician and early Silurian of northern Gondwana (Loydell, 2007, 2012*a*).

Nonetheless, in the late Ordovician of North Africa the picture is more complicated: though the occurrence of an endemic graptoloid fauna has been documented and a regional stratigraphy erected (see P. Legrand, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999; Legrand, 2003), the precise age of the local zonation remains uncertain. This may be in part owing to a glaciotectonic unconformity that persists through much of Africa and Arabia of Caradoc (viz. Sandbian – mid Katian) to Hirnantian age (Destombes, Holland & Willefert, 1985; P. Legrand, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999; Legrand, 2000, 2003; Sutcliffe *et al*. 2001; Ghienne *et al*. 2007; A. A. Page, unpub. Ph.D. thesis, Univ. Leicester, 2007; Le Heron & Craig, 2008). This unconformity has recently been recognized in the northern and eastern flanks of the Kufra Basin (Le Heron & Howard, 2010; Le Heron *et al*. 2010). Legrand (2003, p. 19) noted that understanding the regional stratigraphy of the 'Algerian Sahara and adjacent regions . . . [is hindered by lack of constraint concerning] (a) epeirogenic movements and erosion; (b) the nature of the glacial, periglacial, deltaic and fluvial sediments; (c) one glaciation, multiple

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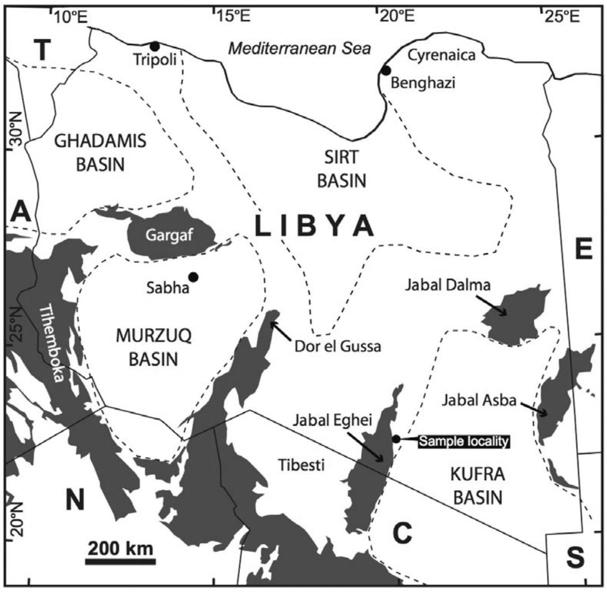

Figure 1. Map of Libya showing surface outcrops with Palaeozoic rocks (dark grey colour). The sampling locality of graptolite-bearing specimens is indicated.

glaciations or only a polyphase glaciation; (d) the varying importance of unconformities; (e) the age of the uppermost Ordovician formations, i.e. whether they are uppermost Ashgillian or upper Caradocian–upper Ashgillian and the precise age of the last Hirnantia fauna'. Nevertheless, if Ordovician or early Silurian graptolites can be precisely identified, regional if not global correlation is possible.

In this study, we describe *Normalograptus kufraensis*, a new species of normalograptid graptolite from a thin marker horizon in the Lower Palaeozoic Jabal Eghei succession of the western Kufra Basin in southern Libya. Though graptolites from the Murzuq Basin in NW Libya have been recently documented (Loydell, 2012*b*), the graptolites of the Kufra Basin are poorly known. These specimens, uncovered in CASP fieldwork in November–December 2008, are the first graptolites from Kufra Basin outcrops, and comprise well-preserved specimens that may be of key importance for understanding regional stratigraphy, particularly the timings of glaciation and of the onset of anoxia.

2. Geological setting

Marine and continental Palaeozoic and Mesozoic sandstones and shales of up to 2600 m in thickness fill the Kufra Basin in SE Libya (e.g. Bellini *et al.* 1991). This paper describes material recovered from Jabal Eghei, an outcrop belt located at the western margin of the Kufra Basin (Fig. 1). Sections were studied about 100 km north of the Libya–Chad border. The graptolite-bearing bed belongs to the Tanezzuft Formation, which is described below as well as in Le Heron *et al.* (in press).

In Jabal Eghei, the Tanezzuft Formation displays distinct sedimentological characteristics not encountered elsewhere in the Kufra Basin (Fig. 2). These include, from the base up, (1) a calcareous, bryozoa-bearing sandstone immediately at the basal contact of the formation to the underlying Mamuniyat Formation, (2) *Planolites*-bearing sandstones, (3) a soft-sediment striated surface of putative glacial origin (Le Heron *et al.* 2005), (4) an interval with calcareous, pebble-sized clasts (?dropstones) below and above this surface, (5) a second bioturbated horizon, and further up a shale succession with (6) an impressive (20 cm thick) marker bed containing well-preserved graptolites. The Tanezzuft Formation has a maximum thickness of about 50 m owing to post-depositional erosion.

Note that macrofossils are generally rare in the Lower Palaeozoic succession of southern Libya, and palynomorphs have mostly been destroyed at outcrop by intensive surface weathering. This hampers precise dating and correlation with successions elsewhere in Libya and North Africa. More common are trace fossils (e.g. Lüning *et al.* 1999; Seilacher *et al.* 2002), but their use for stratigraphy is limited and controversial. Though drilling boreholes may recover material for palynological analysis from below the weathering zone (e.g. Grignani, Lanzoni & Elatrash, 1991), it is expensive and time consuming. Where drilling is not possible, the intensive search for macrofossils is the only alternative. In the Kufra Basin, graptolites have only previously been found in boreholes through the Tanezzuft Formation in Jabal Dalma (Grignani, Lanzoni & Elatrash, 1991). The uppermost shales of the formation have a latest Rhuddanian or earliest Aeronian age (*cyphus* or *triangulatus* biozones) based on microfossil data (Lüning *et al.* 1999). Exposures of the basal part of the Tanezzuft Formation were hitherto unknown in the Kufra Basin. Hence, the presence of normalograptids below the microfossil-bearing shales provides new age constraints for the basal part of the Tanezzuft Formation. As the graptolite-bearing marker bed overlies putative glacially-influenced deposits, this delimits both the temporal extent of ice cover and the onset of anoxic shale deposition in the Kufra Basin.

3. Material and method

This paper presents the study of over 30 graptolites preserved on 15 weathered slabs collected from exposures. Specimens CAM SM X.50191.1 to X.50191.15 were recovered from a ~ 20 cm thick marker bed exposed in Jabal Eghei (N 22.662307, E 19.962156) at the western margin of the Kufra Basin, southern Libya (Figs 1, 2). This bed is characterized by its more brownish colour compared to the surrounding greyish–reddish shales. In addition to the graptolite fauna, the same horizon or a horizon a few centimetres above yielded specimens X.50191.16 (N 22.71759, E 19.970541), a brachiopod similar to ?*Eocoelia* (D. A. T. Harper, Copenhagen, pers. comm. to G. Meinhold),

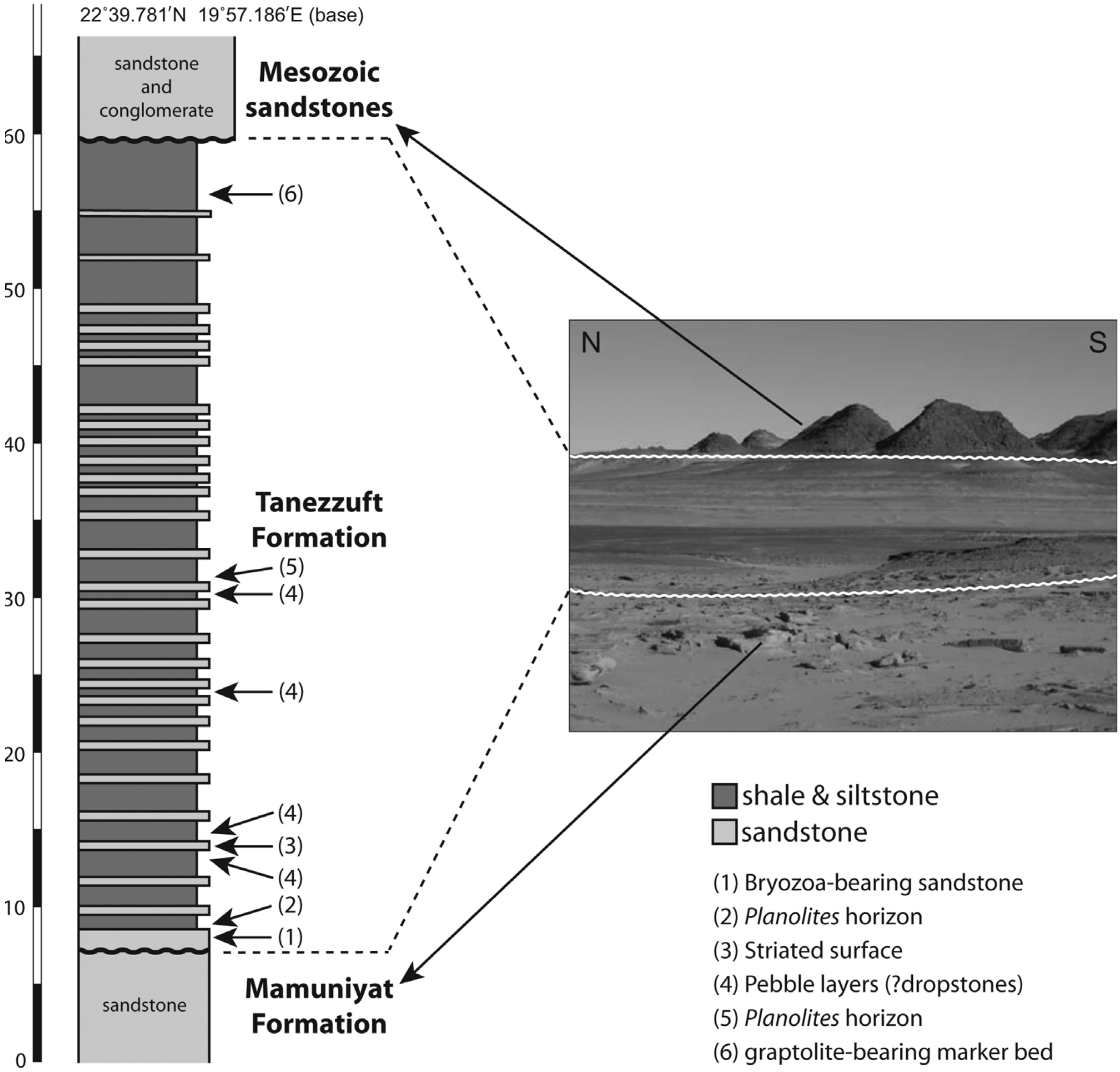

Figure 2. Schematic stratigraphic column (left) and field photograph (right) to illustrate the location of the graptolite-bearing bed within the Lower Palaeozoic succession of the western margin of the Kufra Basin.

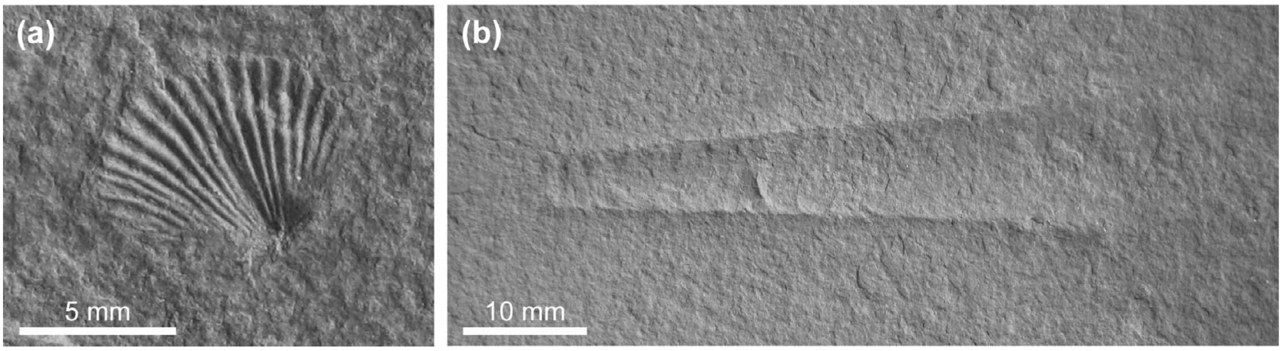

Figure 3. Shelly fossils from the Tanezzuft Formation in Jabal Eghei, western Kufra Basin. (a) Brachiopod similar to ?*Eocoelia* X.50191.16. (b) Orthocone, X.50191.17.

and X.50191.18 (N 22.662307, E 19.962156), an orthoconic nautiloid cephalopod (Fig. 3). The latter preserves no morphological features, precluding identification at a higher taxonomic level. Though the brachiopod cannot be confidently ascribed to *Eocoelia*, this genus is well known from the early Silurian

Table 1. Mean thecal measurements and standard deviations (σ) in millimetres for the population of *Normalograptus kufraensis* from the graptolite-bearing bed of the Tanezzuft Formation in Jabal Eghei, Kufra Basin, Libya

	th1^{1}	**th2^{1}**	**th3^{1}**	**th5^{1}**	**th10^{1}**	**th15^{1}**	**th20^{1}**
2TRD$_{\mathrm{mean}}$	–	1.77	1.83	1.97	2.05	2.07	2.09
σ_{2TRD}	–	0.12	0.24	0.15	0.18	0.09	0.03
n =	–	24	23	22	13	9	2
DVW$_{\mathrm{mean}}$	0.83	0.97	1.04	1.13	1.20	1.19	1.29
σ_{DVW}	0.11	0.13	0.12	0.12	0.14	0.15	–
n =	24	23	24	22	16	8	1

(e.g. Jin, 2003). There may be other *Eocoelia*-like brachiopods in older strata, however.

The graptolites were studied using reflected light microscopy, with selected specimens measured, drawn and/or photographed. Measurements and characters recorded in these graptolites (Table 1) follow those described by Loydell (2007) as useful for identifying biserial graptolites with particular attention paid to dorso-ventral widths (DVWs) and two theca repeat distances (2TRDs) *sensu* Howe (1983). These measurements are critical in speciating normalograptids, which tend otherwise to be very morphologically similar (cf. Melchin, 2008; Blackett *et al*. 2009). One major problem in the identification of biserial graptolites in high latitude sequences is that they may show considerable intraspecific variation, especially in the genus *Normalograptus* (e.g. Legrand, 1977, 2000, 2009; P. Legrand, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999; Loydell, 2007) with identification requiring measurements taken at several different levels along the rhabdosome in tens of specimens.

As well as comparing the measurements of *N. kufraensis* with the type material and recent descriptions of *N. ajjeri*, *N. angustus* and *N. arrikini*, species which bear a close resemblance to it (Table 2), Table 3 compares it with width and thecal packing measurements in 44 other graptolites assigned to *Normalograptus*. Measurements have been extracted from descriptions in recent publications, giving as representative a view of current species concepts as possible. References to type material are also included. The list of taxa is far from exhaustive. For example, Legrand (unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999) included many taxa that have never been formally described, and the fusiform Mauritanian specimens of Underwood, Deynoux & Ghienne (1998) have been omitted as no measurements were given in that work. Taxa such as *N. bicaudatus* (Chen & Lin, 1978), *N. bifurcatus* Loydell (2007), *N. lubricus* (Chen & Lin, 1978), *N. minor* (Huang, 1982), *N. rhizinus* (Li & Yang, 1983) and *N. trifilis* (Manck, 1923) have been excluded as they are readily identified by their proximal ornamentation. Taxa with elaborate nemata are included in the list, however, as this feature may not be so readily preserved. Taxa only known from pre-Hirnantian strata have been omitted as many problems have arisen from Katian or older climacograptids being misidentified as *Normalograptus* (Štorch *et al*. 2011) and recent monographic studies of these strata are comparatively rare. This low-diversity older fauna is listed in Goldman *et al*. (2011), which shows that *N. normalis* and *N. angustus* were the only species to survive the mid Katian extirpation and range into the Hirnantian when *Normalograptus* diversified markedly. Though the measurements given in Table 3 are the basis of much of the classification of *Normalograptus*, further information such as the nature of the supragenicular wall and median septum or degree of geniculation should be assessed before a confident diagnosis can be made. In addition to giving minimum and maximum values for thecal measurements (e.g. Tables 2, 3), future authors may wish to quote average measurements of mean plus or minus standard deviation (e.g. Table 1) and illustrate graphs of measurements in similar taxa (e.g. Loydell, 2007, text-fig. 9; Blackett *et al*. 2009, fig. 6). These techniques allow comparison and distinction more readily. Nonetheless, the data in Table 3 may be of some use for distinguishing taxa within what is often a morphologically anonymous group.

4. Preservation and palaeoecology

The graptolites are preserved in heavily weathered shales. They are generally cast as bas-relief impressions, though some specimens preserve periderm or the residue thereof (e.g. Fig. 4a–c). A few specimens are preserved in part-relief as steinkerns of iron oxides pseudomorphing pyrite (e.g. Fig. 4a). Regardless of the degree of weathering or flattening, the morphological fidelity displayed by these fossils can be very high with fusellae apparent in both 2D and 3D specimens. However, fossils occurring in coarser-grained rocks within the collection are more poorly preserved. Most graptolite assemblages display current alignment and many are in scalariform view (see Fig. 5). There is no evidence of tectonic deformation in either the rocks or fossils and the black colour of the periderm suggests little thermal alteration (cf. Goodarzi & Norford, 1989).

The graptoloid fauna were probably cratonic invaders (*sensu* Finney & Berry, 1997) that lived above the shelf rather than in the open ocean. This interpretation is consistent with the geological setting and seems sensible given the similarity in preservation and faunal composition with on-shelf assemblages from the Silurian of Saudi Arabia reported by Zalasiewicz *et al*. (2007). *Eocoelia* occurs in shallow waters (Ziegler, Cocks & Bambach, 1968), and other eocoeliomorphs such as the one in our section could plausibly share this habitat. Pyritization or partial-pyritization of graptolites most likely reflects deposition under dysoxic conditions in which the graptolites became a locally reducing micro-environment, whilst the abundant occurrence of flattened graptolites probably

Table 2. Comparative thecal measurements in millimetres for graptolites similar to *Normalograptus kufraensis* sp. nov including populations from type localities as highlighted

Taxon	Data source	Locality	Age	DVW th2^1	DVW th5^1	DVW th10^1	2TRD th2^1	2TRD th5^1	2TRD th10^1
N. kufraensis	This study	Kufra Basin, Libya	?Hirnantian	0.70–1.20	0.85–1.45	1.00–1.40	1.55–1.90	1.60–2.10	1.80–2.35
N. angustus (type loc.)	Štorch, 1989	Prague Dist, Czech Repub.	Katian	0.80–1.00*	0.90–1.20	0.90–1.20‡	1.50–1.80†	1.80–2.00	2.00–2.20‡
N. angustus	Štorch *et al.* 2011	Nevada, USA	Hirnantian	0.75–0.95*	1.00–1.15	–	1.35–1.50	1.60–2.00	–
N. angustus	Loydell, 2007	southeast Jordan	Hirn.–Rhudd.	0.65–0.90	0.95–1.10	–	1.80–2.20	2.15	–
N. angustus	Štorch & Feist, 2008	Montagne Noire, France	Rhuddanian	0.80–0.85	1.00–1.10	1.05–1.10	1.80–2.05	1.90–2.00	–
N. angustus	Štorch & Speragli, 1993	Sardinia	Rhuddanian	0.60–0.80*	0.80–1.10	0.80–1.10‡	1.50–1.80	1.80–2.00	2.00‡
N. ajjeri (type loc.)	Legrand, 1977	l'Oued in Djerane, Algeria	Hirnantian	1.10–1.15	1.10–1.40	1.20–1.40	1.00–1.60	1.50–1.70	1.80
N. ajjeri	Štorch *et al.* 2011	Nevada, USA	Hirnantian	0.70–1.10*	1.00–1.30	1.25–1.60	1.50–1.85	1.65–2.00	1.65–2.10
N. ajjeri	Legrand, unpub. Ph.D. thesis, 1999	l'Oued in Djerane, Algeria	Hirn.–Rhudd.	0.80–1.10	1.10–1.35	1.40–1.60‡	1.20–1.60	1.40–1.65	1.50–2.15
N. ajjeri	Štorch & Feist, 2008	Montagne Noire, France	Rhuddanian	1.10–1.20	1.40–1.60	1.80	1.45–1.60	1.80–1.85	2.00
N. ajjeri	Loydell, 2007	southeast Jordan	Rhuddanian	0.85–1.20	1.00–1.40	1.10–1.65	1.20–2.15	1.35–1.95	1.50–1.95
N. ajjeri	Loydell, 2012*b*	Murzuq Basin, Libya	Rhuddanian	1.05–1.25	1.00–1.60	1.40–1.55	1.30–1.65	1.40–1.80	1.55–1.70
N. aff. *ajjeri* 'A'	Legrand, unpub. Ph.D. thesis, 1999	l'Oued in Djerane, Algeria	Hirnantian	1.30	1.60	1.60	1.60	1.70	1.75
N. aff. *ajjeri* 'B'	Legrand, unpub. Ph.D. thesis, 1999	In Azaoua, Algeria	?Hirn.–Rhudd.	1.20–1.40	1.15–1.80	1.60–1.90	1.20–1.80	1.40–1.80	1.60–1.80
N. aff. *ajjeri* 'C'	Legrand, unpub. Ph.D. thesis, 1999	l'Oued in Djerane, Algeria	?Rhuddanian	0.75–0.95	1.15–1.30	1.55–1.80	1.30–1.40	1.20–1.40	1.40–1.70
N. aff. *ajjeri* 'D'	Legrand, unpub. Ph.D. thesis, 1999	l'Oued in Djerane, Algeria	?Rhuddanian	0.85–0.90	0.95–1.10	–	1.30–1.70	1.60–1.85	–
N. aff. *ajjeri* 'E'	Legrand, unpub. Ph.D. thesis, 1999	l'Oued in Djerane, Algeria	?Rhuddanian	1.00–1.10	1.40–1.55	1.55–1.60	1.35–1.40	1.40–1.70	1.65–1.70
N. aff. *ajjeri* 'F'	Legrand, unpub. Ph.D. thesis, 1999	l'Oued in Djerane, Algeria	?Rhuddanian	0.70	1.05	1.35	1.50	1.60	1.55
N. aff. *ajjeri* 'H'	Legrand, unpub. Ph.D. thesis, 1999	In Azaoua, Algeria	?Rhuddanian	0.80–1.00	1.05–1.10	1.00	1.75–1.80	1.80	1.80
N. aff. *ajjeri*'I'	Legrand, unpub. Ph.D. thesis, 1999	In Azaoua, Algeria	?Rhuddanian	0.90–1.00	1.15–1.35	1.40–1.45	1.35–1.80	1.40–1.95	1.60–2.00
N. aff. *ajjeri* 'J'	Legrand, unpub. Ph.D. thesis, 1999	In Azaoua, Algeria	?Rhuddanian	1.00–1.20	1.25–1.60	1.15–1.40	1.30–1.70	1.20–1.65	1.60–1.80
N. arrikini (type)	Legrand, unpub. Ph.D. thesis, 1999, 2009	l'Oued in Djerane, Algeria	mid Hirn.	0.85–0.90	1.00–1.05	1.10–1.30‡	1.80	1.80–1.90	1.85–1.95
N. aff. arrikini 'A'	Legrand, unpub. Ph.D. thesis, 1999, 2009	l'Oued in Djerane, Algeria	mid Hirn.	1.00	1.35	1.35‡	1.70	1.80	–
N. aff. arrikini 'B'	Legrand, unpub. Ph.D. thesis, 1999, 2009	l'Oued in Djerane, Algeria	mid Hirn.	1.00	1.20	1.30–1.60‡	1.60	1.75	1.80
N. aff. arrikini 'C'	Legrand, unpub. Ph.D. thesis, 1999, 2009	l'Oued in Djerane, Algeria	mid Hirn.	0.95	1.15	1.30	1.60	1.80	1.80
N. sp. 1	Štorch & Feist, 2008	Montagne Noire, France	Rhuddanian	0.95	1.25	1.25‡	2.00	1.85	2.00

* – th 1^2; † – th 1^1; ‡ – distal max.

All measurements are as quoted in cited texts, except for 2TRDs from Legrand (1977, 2009, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999) and Štorch & Feist (2008) and DVWs – excluding distal maxima recorded in Legrand (1977, 2009, unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999) and Štorch & Feist (2008) – which were taken from figured specimens in those works.

Table 3. Comparative thecal measurements in millimetres for normalograptids

Taxon		DVW th1	DVW th5	DVW dist	2TRD th2^1	2TRD th5^1	2TRD dist
N. acceptus (Koren' & Mikhaylova, 1980)	[4]	0.40–0.60	0.60–0.85	0.75–0.95	1.05–1.55*		1.40–1.80
N. ajjeri (Legrand, 1977)	[11]	0.70–1.10	1.00–1.60	1.10–1.80	1.00–1.85	1.35–2.00	1.50–2.15
N. angustus (Perner, 1895)	[11]	0.60–1.00	0.80–1.20	1.05–1.15	1.35–2.20	1.80–2.15	2.00–2.20
N. arrikini (Legrand, 2009)	[11]	0.85–0.90*	1.00–1.05	1.10–1.30§	1.80	1.80–1.90	1.85–1.95
N. avitus (Davies, 1929)	[3]	0.70–0.90		1.50–1.80	1.60–2.00		2.00–2.20
N. cortoghiaensis (Štorch & Sperlagi, 1993)	[7]	0.90	1.20		1.65	1.75	
N. crassus Štorch & Feist (2008)	[10]	1.00–1.35	1.70–1.90	1.70–1.90	1.35–1.95	1.70–2.00	
N. daedalus (Mu & Ni, 1983)	[3]	0.70–0.90		1.80–2.30	1.30–1.50		1.80–2.00
N. elegantus (Mu & Ni, 1983)	[10]	0.90–1.15	1.40–1.65	1.50–1.85§	1.00–2.00	1.90–2.30	2.10–2.45
N. extraordinarius (Sobolevskaya, 1974)	[3]	1.10–1.50		2.90–3.50	1.50–1.70		1.90–2.20
N. extraordinarius (Sobolevskaya, 1974)	[10]	0.90–1.20	1.40–2.00	1.70–2.70§	1.35–1.85	1.50–2.10	1.60–2.20§
N. gelidus Legrand (2009)	[6]	0.80		1.60–2.00§	1.60–2.00*		1.80–2.40
N? guihouensis (Chen & Lin, 1978)	[3]	0.75–0.85		1.90–2.10	1.50–1.70		1.90–2.20
N. aff. *indivisis* (Davies, 1929)	[3]	0.75–0.80		1.15–1.90§	1.25–1.50		1.50–1.80
N. jidelensis (Koren' & Mikhaylova, 1980)	[4]	0.65–0.90	0.90–1.25	1.1–1.35	1.08–1.40*		1.2–1.55
N. kufraensis nov. sp.	[11]	0.70–1.20*	0.85–1.45	1.00–1.40	1.55–1.90	1.60–2.10	1.80–2.35
N. laciniosus (Churkin & Carter, 1970)	[3]	0.75–0.90		1.60–1.80	1.20–1.60		1.50–2.00
N. larini Koren' & Melchin (2000)	[4]	0.60–0.70	0.90–1.10	1.00–1.15	1.25–1.55*		1.25–1.55
N. larini Koren' & Melchin (2000)	[7]	0.65	1.00		1.60	1.75	
N. legrandi Koren' & Rickards (2004)	[5]	0.40–0.58	0.60		0.83–1.05*		
N? lungmaensis (Sun, 1933)	[3]	1.00–1.10		2.10–2.40	1.40–1.90		1.80–2.00
N? magnus (H. Lapworth, 1900)	[12]	0.60–1.00	1.40–1.80	1.70–4.10§	1.30–1.50	1.20–1.70	1.40–1.90§
N. medius (Törnquist, 1897)	[3]	1.10–1.30		2.10–2.40	1.30–1.60		1.60–2.00
N. medius (Törnquist, 1897)	[7]	0.90–1.10	1.30–1.75	1.60–1.85§	1.40–1.75	1.45–1.75	1.45–1.75§
N. melchini Koren' & Rickards (2004)	[5]	0.32–0.46		0.32–0.46	1.02–1.36*		
N. mirnyensis (Obut & Sobolevskaya, 1967)	[3]	0.60–0.85		1.05–1.20	1.30–1.60		1.50–1.80
N. mirnyensis (Obut & Sobolevskaya, 1967)	[4]	0.55–0.60	0.80–0.90	0.95–1.10	1.25–1.55*		1.35–1.75
N. mirnyensis (Obut & Sobolevskaya, 1967)	[7]	0.65–0.80	0.75–1.05	0.95–1.10§	1.45–1.70	1.45–1.90	1.60–1.65§
N. mirnyensis (Obut & Sobolevskaya, 1967)	[10]	0.70–1.10	1.05–1.15	1.20	1.20–1.60	1.45–1.55	
N. normalis (C. Lapworth, 1877)	[7]	0.80–1.05	1.20–1.75	1.60–1.85§	1.40–1.75	1.45–1.75	1.45–2.00§
N. cf. *normalis* (C. Lapworth, 1877)**	[7]	0.85–1.20	1.30–1.75	1.25–1.60§**	1.30–1.55	1.40–1.75	1.45–1.90§
N. nseirati Legrand (2009)**	[6]	1.20	2.00–2.40‡	2.60–3.20§**	1.60*		2.00
N. ojsuensis (Koren' & Mikhaylova, 1980)	[3]	1.00–1.40		2.10–2.40	1.60–1.90		2.10–2.30
N. ojsuensis (Koren' & Mikhaylova, 1980)	[10]	0.90–1.15	1.15–1.70	1.50–2.20§	1.40–1.85	1.60–2.00	1.70–2.30
N? parvulus (H. Lapworth, 1900)	[1]	0.90	1.25‡		1.50		
N? parvulus (H. Lapworth, 1900)	[2]	0.70–1.00	1.05–1.60	1.25–1.70§	1.05–1.65	1.20–1.80	1.15–1.75§
N? cf. *parvulus* (H. Lapworth, 1900)	[1]	0.70–1.00	0.90–1.50	0.90–1.20§	1.10–1.60	1.50–1.80‡	1.50–1.90‖
N? aff. *parvulus* (H. Lapworth, 1900)	[1]	0.60–1.00	0.90–1.50	0.90–1.20§	1.50–2.20	1.70–2.40‡	1.90‖
N? persculptus (Elles & Wood, 1907)	[1]	0.70–1.10	1.00–1.70	1.10–2.00§	1.30–2.00	1.50–2.30‡	1.70–2.60‖
N? persculptus (Elles & Wood, 1907)	[2]	0.85–1.15	1.05–1.60	1.40–2.25§	1.25–1.70	1.25–2.10	1.80–2.30§
N? cf. *persculptus* (Elles & Wood, 1907)	[1]	0.80–1.20	1.20–1.60	1.20–1.90§	1.20–1.50	1.50–1.90‡	1.70–2.10‖
N. premedius (Waern, 1948)	[8]	0.60	0.95	1.25§	1.95	2.40	2.50§
N. pretilokensis Legrand (2009)	[6]	1.10–1.20	1.60‡	1.80–2.30	1.80¶		1.80¶
N. rectangularis (M'Coy, 1850)	[7]	0.60–1.05	1.20–1.55	1.50–1.80§			
N. rectangularis (M'Coy, 1850)	[9]	0.75–0.95	1.20–1.90	1.50–2.20§	1.40–1.70	1.40–1.80	1.40–1.80
N. skeliphrus Koren' & Melchin (2000)	[4]	0.40–0.60	0.60–0.75	0.60–0.80	1.20–1.55*		1.20–1.55
N. sobolevkayae Koren' & Rickards (2004)	[5]	0.37–0.46			0.95–1.29*		
N. targuii Legrand (2001)	[7]	0.70–1.00	1.00–1.45	1.05–1.60§	1.30–1.80	1.40–1.85	1.40–2.10§
N. tilokensis (Legrand, 1986)	[9]	0.90–1.15	1.50–2.05	1.60–2.65§	1.45–1.90	1.55–2.00	1.70–2.05§
N. transgrediens (Waern, 1948)	[7]	0.65	1.15		1.45	1.50	
N. ugurensis (Koren' & Mikhaylova, 2000)	[3]	0.80–1.00		1.60–1.80	1.30–1.60		1.80–2.20
N. wangjiawanensis (Mu & Lin, 1984)	[3]	0.70–1.00		1.70–1.90§	1.50–2.00		1.80–2.20
N? wyensis Zalasiewicz & Tunnicliff (1994)	[12]	0.60–0.80	0.90–1.20	1.40§	1.10–1.50		1.60§
N. sp. of Štorch *et al*. (2011)	[10]	0.80–0.90*		1.00–1.20	1.70¶		1.70¶

* – proximal; † – th4; ‡ – th6; § – th10; ‖ – th 11; ¶ – throughout; ** – fusiform

[1] – Hirnantian–Rhuddanian of central Wales, UK (Blackett *et al*. 2009); [2] – localities listed in Loydell (2007, text-fig. 9) as given in Blackett *et al*. (2009); [3] – Hirnantian of the Yangtze Region, China (Chen *et al*. 2005); [4] – Rhuddanian of the Kurama Range, Uzbekistan (Koren' & Melchin, 2004); [5] – Llandovery of the southern Urals, Russia (Koren' & Rickards, 2004); [6] – Hirnantian of Algeria (Legrand, 2009); [7] – Hirnantian–Rhuddanian of Jordan (Loydell, 2007); [8] – Hirnantian or Llandovery of the Southern Uplands, Scotland (Loydell, 2007); [9] – Rhuddanian of the Murzuq Basin, Libya (Loydell, 2012*b*); [10] – Hirnantian of Nevada, USA (Štorch *et al*. 2011); [11] – Table 2 (this study); [12] – Rhuddanian of the Wye Valley, Wales, UK (Zalasiewicz & Tunnicliff, 1994). All measurements are as quoted in descriptions or tables. An Excel spreadsheet version of these data is available from the authors on request.

represents preservation in a fully anoxic environment (Underwood, 1992; Underwood & Bottrell, 1994; A. A. Page, unpub. Ph.D. thesis, Univ. Leicester, 2007; Zalasiewicz *et al*. 2007; Loydell *et al*. 2009). Though causes of anoxia are various, transgressive black shales are common in shelf successions of this age, arguably deposited in response to deglaciation (Armstrong *et al*. 2005; Page *et al*. 2007).

5. Systematic palaeontology

Family NORMALOGRAPTIDAE Štorch & Serpagli, 1993
emend. Melchin *et al*. (2011).

Genus *Normalograptus* Legrand (1987) emend. Melchin & Mitchell (1991) emend. Melchin *et al*. (2011).

Type species. [OD] *Climacograptus scalaris* var. *normalis* Lapworth (1877).

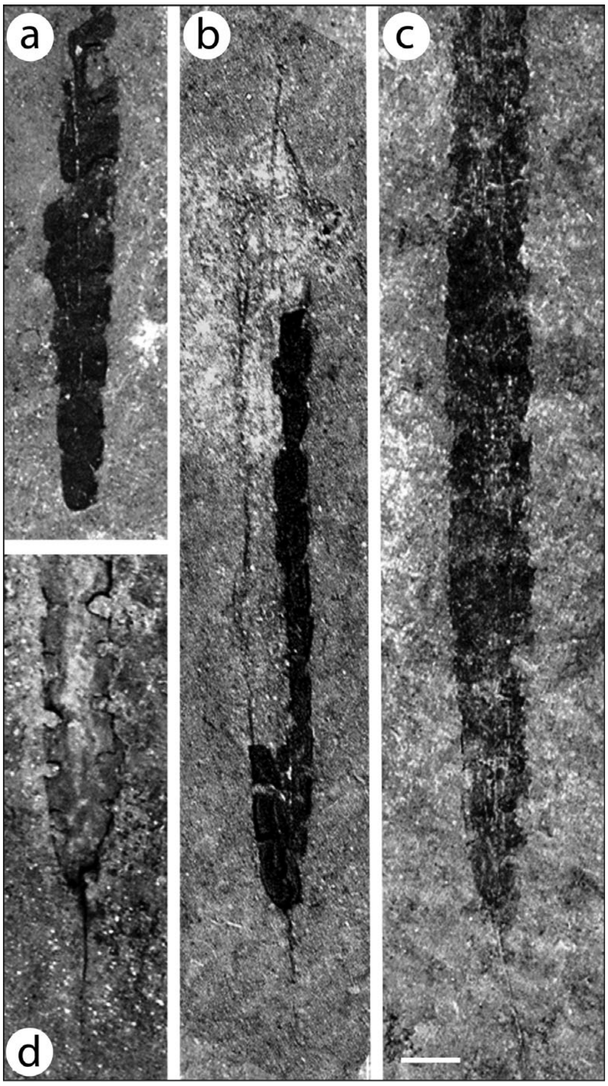

Figure 4. Photomicrographs of *Normalograptus kufraensis* sp. nov. from the graptolite-bearing bed of the Tanezzuft Formation in Jabal Eghei, western Kufra Basin. Specimen numbers: (a) X.50191.10, (b) X.50191.6b, (c) X.50191.6a, (d) X.50191.13. Scale bar = 1 mm.

Diagnosis. Biserial graptolites of astogenic Pattern H with unornamented climacograptid thecae having straight or concave interthecal septa throughout the rhabdosome and a full median septum, which may be delayed.

Normalograptus kufraensis sp. nov.

Figures 4a–d, 5a–h

Holotype. Specimen CAM SM X.50191.3c (Fig. 5b) from the Tanezzuft Formation, Jabal Eghei, Libya (N 22.662307, E 19.962156).

Material. 30+ graptolites on samples CAM SM X.50191.1 to X.50191.15, of which 23 were sufficiently well-preserved for detailed morphological study, being CAM SM X.50191.1a–c, X.50191.3a–f; X.50191.4a, X.50191.6a–b, X.50191.7a–b, X.50191.8a, X.50191.9a; X.50191.10a, X.50191.12a, X.50191.13a, X.50191.14a–b and X.50191.15a–b. These specimens are stored in the Sedgwick Museum, University of Cambridge, UK.

Locality and horizons. All specimens come from a single marker bed at the western margin of the Kufra Basin, southern Libya (Figs 1, 2).

Preservation. As above.

Etymology. After the Kufra Basin where the graptolites were found.

Diagnosis. Normalograptid with a long virgella, long, straight nema, climacograptid thecae with long, parallel supragenicular walls and a full, straight median septum; 2TRDs and DVWs range, respectively, between 1.55–1.90 mm and 0.70–1.20 mm at theca 2^1, between 1.60–2.10 mm and 0.85–1.45 mm at theca 5^1, and 1.90–2.35 mm and 1.05–1.45 mm distally. Maximum width achieved at or around the sixth thecal pair.

Description. Mature rhabdosomes are up to 24 mm long consisting of 25 thecal pairs. The rhabdosome widens rapidly achieving constant maximum DVWs and 2TRDs by thecae 4–6. The nema and virgella protrude up to at least 5 and 7 mm from either end of the rhabdosome, respectively. The undivided virgella runs straight down following the line of the median septum in all but one example. The sicula ranges between 1.60 and 2.40 mm in length, and 0.30 and 0.45 mm in width; its apex typically lies between thecae 2^1–2^2, though rarely it may reach slightly more distally than the level of theca 2^2. Theca 1^1 grows down 0.20–0.30 mm below the sicula aperture and is 0.90–1.20 mm long, whilst the length of the exposed margin of the sicula below theca 1^2 is 0.25–0.45 mm. Thecae are of typical climacograptid form with sharp genicula and long, straight supragenicular walls that run parallel to the median septum. The thecal apertures are horizontal and a complete median septum is apparent in most specimens. A summary of 2TRDs and DVWs for these specimens is given in Table 1 and Figure 6.

Discussion. With no bimodality observed in its populations and little variation between slabs, *N. kufraensis* clearly represents a single taxon, dissimilar in measurements to comparable graptolites (Tables 2, 3). Though *N. kufraensis* exhibits a considerable range of DVW and 2TRD variation, this may in part reflect the style of preservation, with some specimens flattened and others in relief. But such a range of variation is typical in normalograptid specimens from high palaeolatitudes (Loydell, 2007) and comparable to the range of variation of three-dimensionally preserved material from lower palaeolatitudes (e.g. Blackett *et al.* 2009). The smaller range of variation seen in other taxa included in Table 2 may reflect the fact that many of these data are taken from measurements of figured specimens rather than large populations. Likewise, the range in virgella length apparent in *N. kufraensis* is typical of that in other normalograptids (see Chen *et al.* 2005; Loydell, 2007). This may reflect an ecophenotypic response to the local hydrodynamic regime as Rickards *et al.* (1998) showed that the virgella served to align the graptolite to the ambient current. Though some specimens appear slightly fusiform (e.g. Fig. 5a, h), this is not apparent in most, especially not in any in biprofile preservation, suggesting it may be an artefact of flattening. The preponderance of subscalariform preservation may indicate that *N. kufraensis* had similar dorsoventral and lateral widths.

N. kufraensis belongs to a small distinctive clade of slender, elongate normalograptids with climacograptid thecae and long nemata and virgellae that superficially resemble the unadorned climacograptid *Styracograptus* Štorch *et al.* (2011). *N. kufraensis* may be confidently assigned to *Normalograptus* based on its narrow triangulate proximal end, however. Other more subtle distinctions between it and *Styracograptus* include simple distal thecal ontogeny from theca 2^1, a typical unflexed graptoloid sicula and the absence of cross bars on *Normalograptus* nemata (Goldman *et al.*

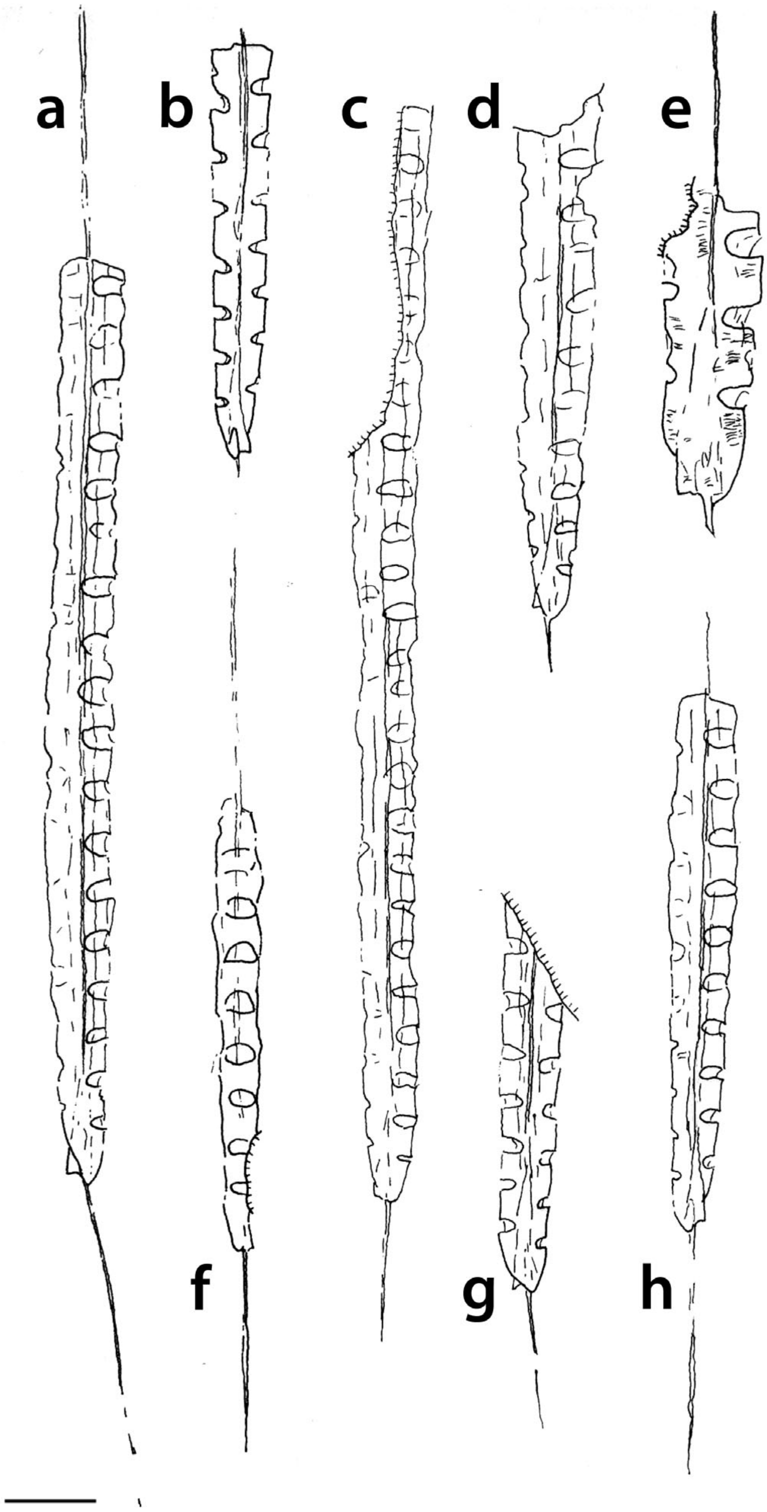

Figure 5. Camera lucida drawings of *Normalograptus kufraensis* sp. nov. from the graptolite-bearing bed of the Tanezzuft Formation in Jabal Eghei, western Kufra Basin. Specimen numbers: (a) X.50191.6a, (b) X.50191.3c, holotype, (c) X.50191.1, (d) X.50191.13, (e) X.50191.3e, (f) X.50191.3d, (g) X.50191.14b, (h) X.50191.3a. Scale bars = 2 mm (a–d, f–h); 1 mm (e).

2011). The distinction between the genera has simplified the synonymy of the *Styracograptus*-like normalograptids, with many Katian forms reassigned to *Styracograptus*. The specimens from Jabal Eghei cannot be accommodated in any established species: Table 2 compares its width and thecal packing with the *Styracograptus*-like normalograptids *N. ajjeri*, *N. angustus* and *N. arrikini*, and Table 3 compares it with other normalograptids. The elongate graptolite *N. rectangularis* is larger in all dimensions, and *Normalograptus normalis* like many other normalograptids is significantly more robust. Others differ markedly.

Though there is some overlap between the measurements of *N. kufraensis* and specimens of *N. ajjeri*, *N. angustus* and *N. arrikini*, the range of variation in *N. kufraensis*

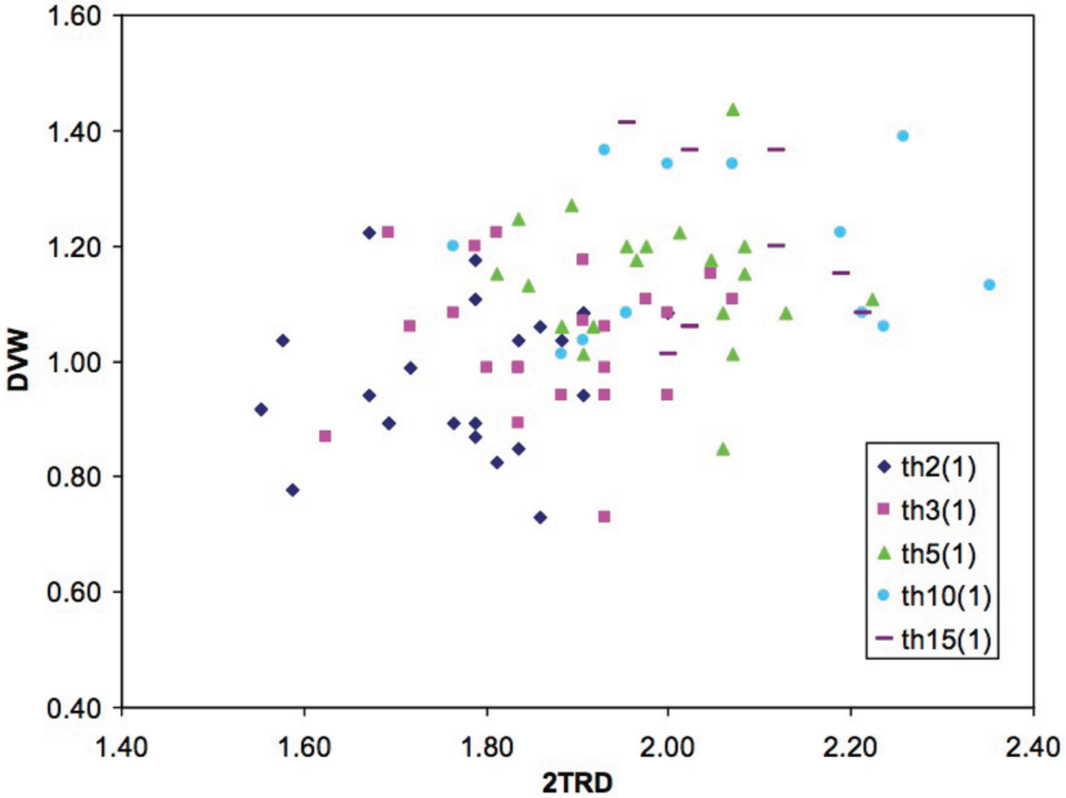

Figure 6. (Colour online) Scatter plot of dorso-ventral widths (DVW) and two theca repeat distances (2TRD) measured on *Normalograptus kufraensis* from the Lower Palaeozoic succession of Jabal Eghei, western Kufra Basin.

is centred almost exactly on the 'gap' in morphospace between the other taxa. *N. angustus* (Perner, 1895) is too gracile, whilst the sister species *N. ajjeri* (Legrand, 1977) and *N. arrikini* Legrand (2009) have their thecae too closely spaced (Table 2), as is true of many other slender normalograptids (cf. Loydell, 2007; Blackett *et al*. 2009). Working on material from the late Ordovician of Nevada, Štorch *et al*. (2011) observed that *N. angustus* is more strongly geniculate than *N. ajjeri*, and that it may have an undulating median septum. *N. kufraensis* is intermediate in geniculation and has a fully straight median septum. Though there is some overlap between their the 2TRDs of specimens of *N. ajjeri* from Nevada and *N. kufraensis*, the Libyan graptolites have their thecae significantly more widely spaced on average (Tables 1, 2). By having climacograptid thecae, *N. kufraensis* appears more similar to *N. ajjeri* than *N. arrikini*. But as distortion in flattening can result in climacograptid thecae taking on a glyptograptid appearance (Briggs & Williams, 1981; Loydell, 2007), this distinction could be artefactual: the Algerian taxa are very similar indeed. Whilst Legrand (unpub. Ph.D. thesis, Univ. Michel de Montaigne-Bordeaux III, 1999) reported many 'aff.' forms of either taxon (Table 2), none of these agree with the dimensions of *N. kufraensis*. Although the Libyan graptolites appear to conform to *N.* sp. 1 of Štorch & Feist (2008) in terms of their measurements (Table 2), the latter, which is only known from a single specimen, has a highly asymmetrical proximal end precluding synonymy. Thus *N. kufraensis* clearly represents a new species.

N. kufraensis may have plausibly evolved from *N. angustus* in the latest Ordovician. The *N. angustus* lineage undergoes a considerable reduction in rhabdosome width in the Silurian (cf. Rickards, 1970; Hutt, 1974; Štorch, 1989; Štorch & Speragli, 1993; Chen *et al*. 2005; Loydell, 2007; Table 2), with the dimensions of some broader Ordovician forms of *N. angustus* overlapping with *N. kufraensis* a little (Table 2). Until this lineage has been explored in more detail, it is impossible to conclude as to whether certain specimens assigned to *N. angustus* may be better ascribed to *N. kufraensis*. *N. angustus* is both temporally and geographically wide ranging. *N. ajjeri* is also relatively long-lived, with Loydell (2007) sensibly synonymizing almost all previous reports of *N. normalis* with it. He did not, however, discuss Katian reports of *N. normalis* (e.g. Williams, 1982*a*; Chen *et al*. 2000; Rickards, 2002), which might push its first appearance somewhat earlier. It seems at present, however, that *N. kufraensis* is best viewed as an intermediate between the broader Ordovician specimens of the *N. angustus* lineage and the sister species *N. ajjeri* and *N. arrikini*, which have a Hirnantian or younger age. This is certainly consistent with the pattern of *Normalograptus* biogeography and evolution: aside from *N. angustus*, normalograptids with climacograptid thecae are unknown between the mid Katian and Hirnantian, when they diversified considerably (Goldman *et al*. 2011).

6. Biostratigraphic age constraints and deglacial anoxia

Graptolites from Jabal Eghei can be confidently assigned to the genus *Normalograptus*, which provides lower and upper bounds for the age of the graptolite-bearing marker bed and hence for the Tanezzuft Formation in Jabal Eghei. In the UK, *Normalograptus* is known from the *murchisoni* Zone of the Darriwilian (late Middle Ordovician) through to at least the *magnus* Zone of the Aeronian (mid Llandovery, Silurian) (Zalasiewicz *et al*. 2009). However, graptolites referred to the genus *Glyptograptus* extend to the *griestoniensis*

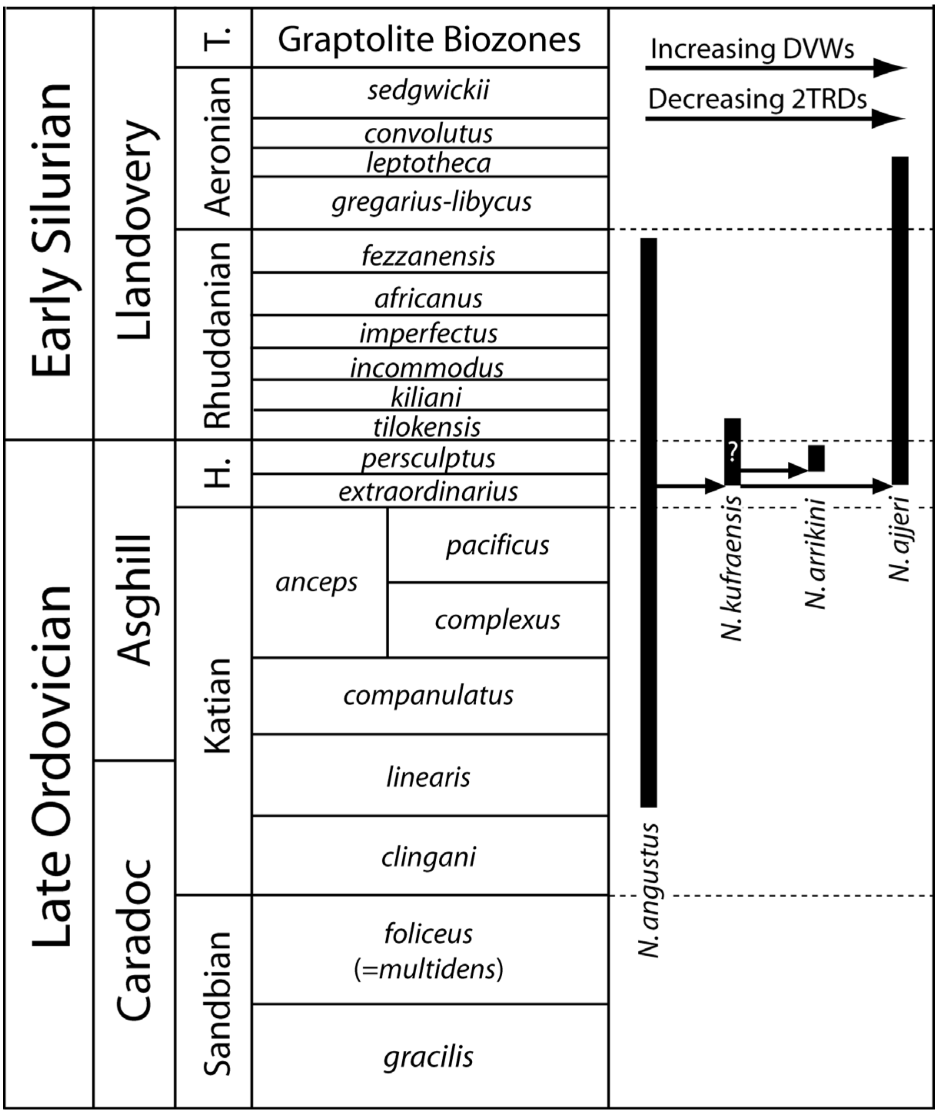

Figure 7. Stratigraphic range of the graptolites *Normalograptus angustus*, *N. ajerri* and *N. arrikini* with proposed relationship to *N. kufraensis* illustrated. The biozonation and correlation between regions follows Loydell (2012*a*). See text for other references.

Zone of the Telychian (late Llandovery, Silurian) (Zalasiewicz *et al*. 2009) and Melchin (1998) showed that Llandovery 'glyptograptids' with a full distal median septum should be assigned to *Normalograptus*. Some of the earlier occurrences of *Normalograptus* may in fact be *Styracograptus* (Goldman *et al*. 2011). At first sight though, *N. kufraensis* may potentially be of anything from Darriwilian to Llandovery in age.

The oldest age for *N. kufraensis* may be in principle inferred from stratophenetic considerations. As noted above, *N. kufraensis* is best viewed as an intermediate between the Ordovician branch of the *N. angustus* lineage and Legrand's sister species *N. ajjeri* and *N. arrikini*. Both *N. angustus* and *N. ajjeri* are long-ranging taxa, whereas *N. arrikini* is restricted to the latest Ordovician (Fig. 7). *N. angustus* is known from the earlier part of the *linearis* Zone (Katian, late Ordovician) to the *cyphus* Zone (Rhuddanian, early Silurian) (see Rickards, 1970; Hutt, 1974; Zalasiewicz *et al*. 2009; Goldman *et al*. 2011, who reassigned reports of *clingani* Zone occurrences such as in Williams, 1982*b* to *Styracograptus miserabilis*). Loydell (2007) states that *N. ajjeri* ranges from the Hirnantian to early Aeronian. If *N. kufraensis* was an evolutionary intermediate between broader Ordovician forms of *N. angustus* and *N. ajjeri* itself, then *N. kufraensis* must have originated in the Hirnantian suggesting the outcrop in Jabal Eghei could be of Hirnantian (*persculptus* Zone) or younger age. However, further data either on the stratigraphy of the Tanezzuft Formation or on the evolution of the *N. angustus* and *N. ajjeri*–*N. arrikini* lineages are needed for this to be confirmed.

The uppermost shales of the Tanezzuft Formation have a latest Rhuddanian or earliest Aeronian age (*cyphus* or *triangulatus* biozones) (Lüning *et al*. 1999). Grignani, Lanzoni & Elatrash (1991) mentioned *Climacograptus medius* Törnquist from core samples of well KW-2, drilled by AGIP in Jabal Asba in 1975. The occurrence of this graptolite suggests a late Ordovician (Hirnantian) or early Llandovery age (Rhuddanian to early Aeronian) for the studied core interval (Lüning *et al*. 1999). These data indicate that the graptolite marker bed must have been deposited before the early Aeronian. The graptolite-bearing bed occurs above a glaciogenic unconformity thought to be of Hirnantian age (Le Heron & Howard, 2010). Given the stratophenetic argument that *N. kufraensis* emerged from the *N. angustus* lineage in the latest Ordovician, the lowermost shales of the Tanezzuft Formation were deposited at sometime in or after the Hirnantian and before the earliest Aeronian.

The sedimentary succession at Jabal Eghei records deglaciation and a short-lived episode of transgressive anoxia (Le Heron *et al.* In press). This is seen elsewhere in northern Gondwana and at lower latitudes in which the onset of anoxia occurs in the *persculptus* Biozone (Armstrong *et al*. 2005; Page *et al*. 2007). However, the temporal extent of the unconformity in this section has yet to be determined and the Rhuddanian also contains notable intervals of anoxia. Though the biostratigraphic resolution is currently too coarse to definitively place these shales in the Hirnantian, and the conventional view is that marine flooding of the Kufra Basin occurred in the early Silurian (Lüning *et al*. 1999), there is increasing evidence pointing to a prolonged deglacial oceanic anoxic episode originating in the latest Ordovician (Page *et al*. 2007). In Jabal Eghei, however, the anoxia was short-lived.

7. Conclusions

An assemblage of *Normalograptus kufraensis* nov. sp. – an intermediate between *N. angustus* (Perner) and *N. ajjeri* (Legrand) – has been recovered from exposures in the western Kufra Basin of southern Libya. Although it is morphologically similar to the long-ranging graptolites *N. angustus* and *N. ajjeri*, stratophenetic considerations suggest *N. kufraensis* from Jabal Eghei may have been of Hirnantian age or younger. If so, this would show that the basal part of the Tanezzuft Formation is exposed at the western margin of the Kufra Basin. Thus, following late Ordovician glaciation, major marine flooding of the Kufra Basin may have begun in the Hirnantian or earliest Rhuddanian (see also Grignani, Lanzoni & Elatrash, 1991; CASP, unpub. data), plausibly earlier than thought. Establishing the relationship between anoxia, deglaciation and organic carbon burial at this time may further constrain our understanding of the Early Palaeozoic Icehouse climate (Page *et al*. 2007).

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