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Early Silurian (Llandovery) graptolite assemblages of Saudi Arabia: biozonation, palaeoenvironmental significance and biogeography

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Analysis of Silurian graptolite assemblages from 1017 sample horizons in 132 cores (from 65 boreholes) through the Qusaiba Member, Qalibah Formation of Saudi Arabia, provides a refined graptolite biostratigraphy for the Arabian Peninsula comparable in its resolution to that from the British Isles and the Czech Republic. Over 150 graptolite species characterize 11 biozones from the lowermost Rhuddanian *lubricus* Biozone to the lower Telychian *guerichi* Biozone, with sub-zonal resolution for several intervals. Graptolite biozonal boundaries and the Rhuddanian–Aeronian and Aeronian–Telychian stage boundaries can be placed with high precision. Detailed analysis of graptolite spatial distribution suggests persistent depth-stratified marine assemblages across the Silurian palaeo-Arabian Plate. Near-surface-dwelling assemblages probably occupied the mixed-layer of Silurian oceans, enabling colonization of shallow shelf environments. They are low-diversity (1–2 species) assemblages characterized by *Neodiplograptus, Coronograptus, Neolagarograptus* and *Stimulograptus* species and often are preserved in strata with extensive shelly faunas. Deeper marine assemblages are of higher diversity (up to 15 species per horizon), and are characterized by dorsally curved or helically coiled species of *Spirograptus*, *Demirastrites*, *Lituigraptus*, *Rastrites* and *Torquigraptus*. Recognition of depth-stratified graptolite assemblages provides an important tool for establishing palaeo-basin topography and water depth at the time of sedimentary deposition. At the species level, the graptolite assemblages of Saudi Arabia are remarkably similar to contemporaneous faunas from peri-Gondwanan Europe and, from the middle Rhuddanian onwards, also to the Avalonian and Laurentian Llandovery graptolites of the UK.

Key words: Saudi Arabia, Silurian, graptolites, biozonation.

INTRODUCTION

Graptolites provide one of the most enduring and highly resolved macrofossil biostratigraphies for rocks of Ordovician and Silurian age (e.g., Elles and Wood 1901–1918; Zalasiewicz et al., 2009 and references therein). Their rapid evolution, manifested in a multitude of distinctive morphologies, enables their ready application to the establishment of biozonal schemes both at outcrop and in boreholes. In Saudi Arabia, graptolites have been reported from the Qusaiba Member of the Qalibah Formation, from rocks of Early Silurian (Llandovery) age (Rickards and Koren', 1974; El-Khayal, 1985, 1986, 1987a, b, c; McClure, 1988; Legrand in Mahmoud et al., 1992; Legrand in Vaslet et al., 1987; Legrand in Vaslet, 1989; Zalasiewicz et al., 2007). These works document "snapshots" of the graptolite fauna from strata of Rhuddanian, Aeronian and Telychian age. In this paper we establish the first integrated graptolite biostratigraphy for the Lower Silurian (Llandovery) of Saudi Arabia, identifying 11 biozones and a number of intervals of sub-zonal correlative importance, especially in the lower Telychian. We also establish the biogeographical and palaeoenvironmental importance of the fauna, commenting on the regional importance of the Saudi Arabian graptolites for interpreting the recovery of high-latitude Gondwanan graptolite assemblages after the Late Ordovician Hirnantian mass extinction.

GEOLOGICAL SETTING

During the Late Ordovician a continental-sized ice sheet was centred on sub-Saharan Africa, covering a large area of high southern latitude palaeocontinental Gondwana. The glacial advance resulted in the incision of deep valley systems by glacial and fluvial processes; these valleys have been traced into the subsurface of northern Saudi Arabia with seismic data (Konert et al., 2001). During earliest Silurian times, the Arabian Platform lay between 30° and about 50° latitude south. During the glacial maximum, the depositional setting of the latest Ordovician and Early Silurian northern Gondwana coast may have been analogous to the present-day Antarctic (Jones and Stump, 1999). As a major phase of global warming developed during the Llandovery, the glaciers began to retreat. The Ara-

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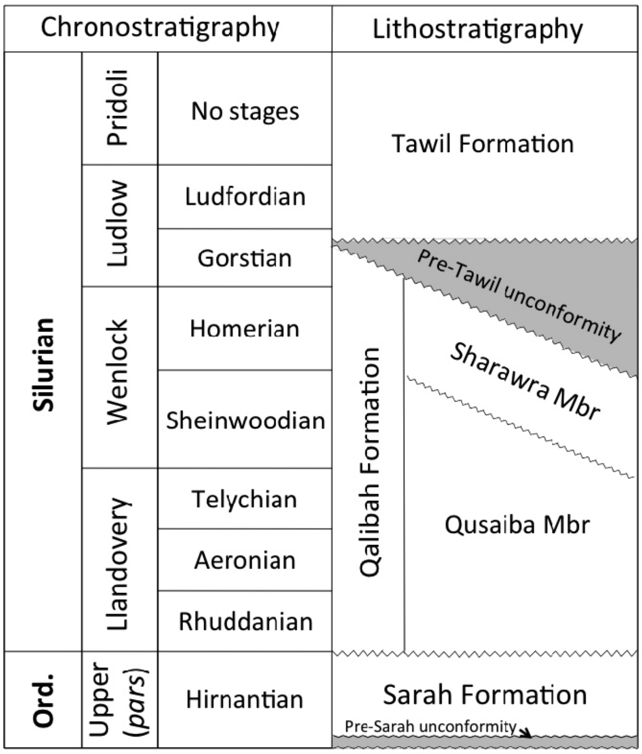

Fig. 1. Simplified Upper Ordovician and Silurian stratigraphy for Saudi Arabia (adapted from Senalp, 2006), showing the context of the graptolite-bearing Qusaiba Member of the Qalibah Formation

The major unconformities at the base of the Sarah and Tawil formations represent intervals of glacial lowstand

bian Platform flooded as sea level rose rapidly. In the marginal areas, shallow to open marine environments were established, while deeper marine environments covered the platform and extended southwards along a subsiding intra-shelf basin located in central Saudi Arabia. Anoxic bottom water conditions within the marine basins resulted in the preservation of organic-rich shales with graptolites. These form the shales of the Qusaiba Member in Saudi Arabia (Fig. 1), the Mudawwara Formation in Jordan, the Sahmah Formation in Oman, the Abba Formation in Syria, the Tanezzuft Formation in North Africa, the Dadas Formation in south-east Turkey, and the Ghakum Formation in Iran (Konert et al., 2001).

In Saudi Arabia, the shales of the Qusaiba Member are encountered in many subsurface boreholes: their thickness ranges from 420 to 914 m (1400 to 3000 ft). In some boreholes they can be completely eroded by younger unconformities. The Qusaiba Member has traditionally been considered as the lower member of the Early Silurian Qalibah Formation (see Fig. 1), which was first defined by Mahmoud et al. (1992) in the Al-Qalibah–Tayma area to replace the Tayyarat Formation of Vaslet et al. (1987) for the same lithostratigraphic succession. The Qalibah Formation, which includes a significant part of the Silurian System in Saudi Arabia, consists of the shale-dominated Qusaiba Member in its lower part and sand-dominated Sharawra Member in its upper part. The base of the Qalibah Formation is generally characterized by a disconformable, erosional or non-depositional contact with the underlying glaciogenic deposits of the Late Ordovician Sarah Formation. Further discussion of this stratigraphy can be found in Vaslet et al. (1994), Janjou et al. (1996), Senalp et al. (2002), and Miller and Al-Ruwaili (2007).

The Qusaiba Member represents the interval between the worldwide marine transgressive surface MFS S10 of Sharland et al. (2001) at its base, and a type-1 sequence boundary (erosional unconformity surface) at its top (Senalp, 2006). The "Qusaiba hot-shale facies," an interval of extremely organic-rich graptolite-bearing shales forming the main hydrocarbon source of the Paleozoic formations in Saudi Arabia, occurs in the basal part of the Qusaiba Member and is dated to the Rhuddanian Stage of the Llandovery Series. The "hot shale" interval is diachronous, and usually about 10–30 m thick, and is interbedded with variable amounts of well to moderately sorted, very fine grained sandstones and coarse siltstones (Jones and Stump, 1999). The Aeronian part of the Qusaiba Member contains a distinctive interval, usually between about 30 to 60 m thick, that is significantly more sandy than the deposits occurring immediately below and above it. This sandstone body has been termed the "mid-Qusaiba Sand" by Wender et al. (1998). Miller and Melvin (2005) interpreted the mid-Qusaiba Sand as being associated with a lowstand event.

MATERIAL STUDIED, REPOSITORY, AND NOTE ON THE CONFIDENTIALITY OF DATA FROM INDIVIDUAL BOREHOLES

The material studied here is sourced from 1017 sample horizons, from 65 boreholes and 132 cores that penetrated the Qusaiba Member (Fig. 2). Precise geographical and biostratigraphical details of individual boreholes in Saudi Arabia are unavailable due to operational confidentiality and therefore here we provide a summary of the graptolite biostratigraphy of these cores, following the style of the paper by Rickards (1976) for the UK graptolite succession. Some cores sampled in the 1970s have suffered extensive pyrite decay, but the more recent cores, which make up the bulk of material studied, provide well-preserved graptolites. The cores penetrate a range of lithologies including black pyritic mudstones, hemipelagic mudstones, turbiditic grey mudstones, siltstones and sandstones. Graptolites have been recovered from all of these lithologies but the best-preserved and most diverse material is yielded from black mudstones. For the latter, sampling of the core is possible to centimetric accuracy, enabling biozonal and stage boundaries to be identified with precision: in the continuous cores we have sampled, fracture zones or faulting have not disrupted the continuity of the graptolite ranges and biozones. Core material and the figured graptolites are stored in the collections of the Saudi Arabian Oil Company (Saudi Aramco) Dhahran, Saudi Arabia.

GRAPTOLITE BIOSTRATIGRAPHY

The biostratigraphical distribution of over 150 graptolite species in the Lower Silurian rocks of Saudi Arabia relative to the graptolite biozones that we recognize are summarized in Figure 3. In all, 11 graptolite biozones are recognized, extending from the lowermost Silurian *Normalograptus lubricus* Biozone to the lower Telychian *guerichi* Biozone (Fig. 3). In some Aramco cores a near-continuous succession of biozones from the Rhuddanian to lower Telychian can be established, with the first and last occurrences of the graptolites placed with accuracy. In our analysis of cores we have prioritized the identification of biozone and subzone boundaries. Thus, we expect

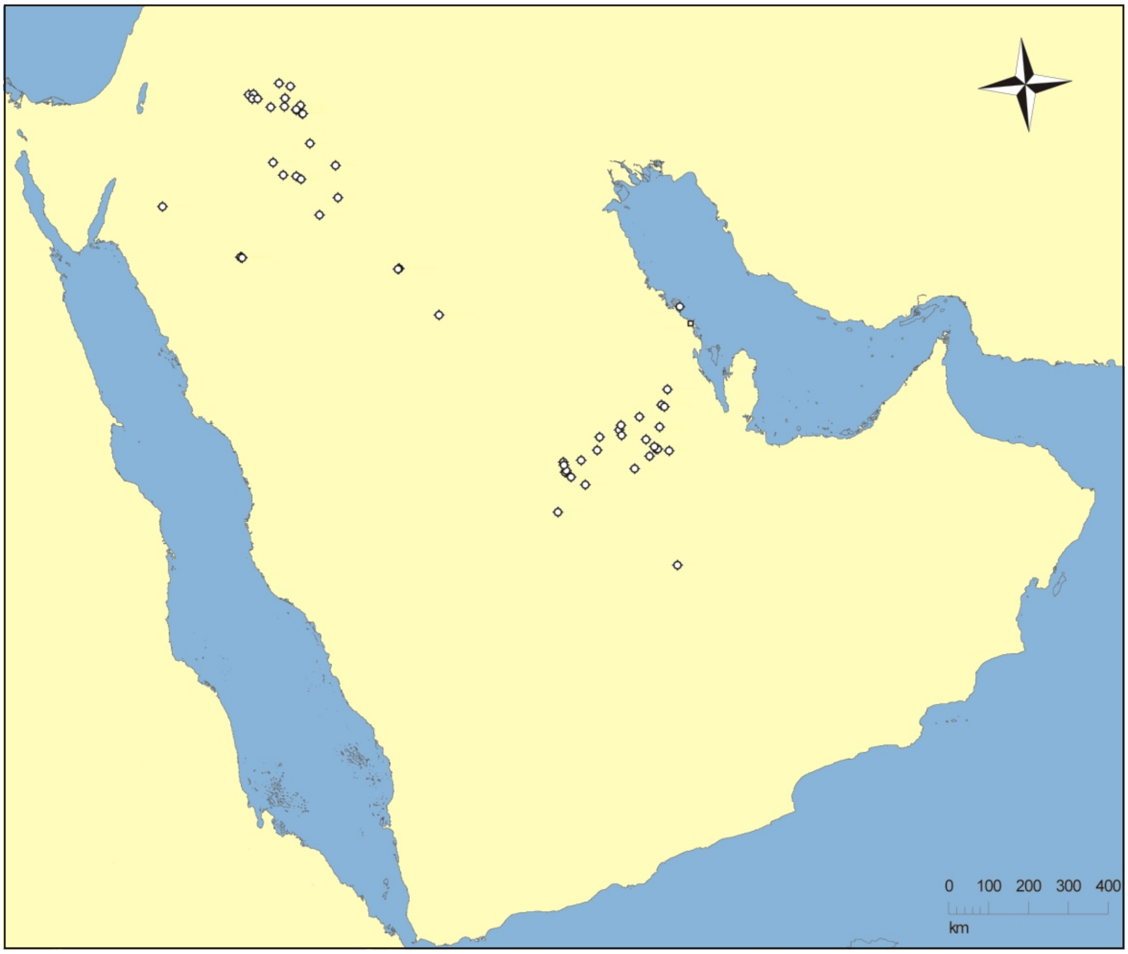

Fig. 2. Regional distribution of graptolite-bearing boreholes drilled by the Saudi Arabian Oil Company on the Arabian Peninsula

The graptolite dataset comprises 1017 sample horizons, from 65 boreholes and 132 cores that penetrate the Qusaiba Member. Some borehole sites that are situated in close proximity to each other are superimposed in the figure

that with further intra-zonal analysis the complement of graptolite species and resolution of the graptolite biostratigraphy can be further refined. A number of younger graptolites have also been recovered, including possible *Streptograptus johnsonae* Loydell (suggesting the lower *turriculatus* Biozone), and those indicative of higher levels in the Telychian (*Retiolites geinitzianus* (Barrande)*, Stimulograptus clintonensis* (Hall). At present this graptolite material is scant, and it cannot be placed in a continuous succession of biozones; therefore, it is not treated here.

The Arabian succession shows a marked degree of similarity in the first and last occurrences of key species that are used to define the graptolite biozonal scheme applied to the UK (Zalasiewicz et al., 2009 and references therein), and we therefore largely follow this biozonal scheme. Representative illustrations of the graptolites are shown in Figures 4–13.

NORMALOGRAPTUS LUBRICUS BIOZONE

The stratigraphically lowest graptolite assemblages recovered from core in the Qusaiba Member are dominated by *Normalograptus ajjeri* (Legrand), *Normal.*? *parvulus* (H. Lapworth), *Normal. normalis* (Lapworth), *Normal. angustus* (Perner), *Normal.*? cf. *lungmaensis* (Sun), *Normal. medius* (Törnquist), *Normal. bifurcatus* Loydell, *Normal. targuii* Legrand, and *Normal. mirnyensis* (Obut and Sobolevskaya *in* Obut et al.). Similar assemblages in Jordan have been assigned an age of either latest Ordovician or earliest Silurian (see Loydell, 2007), but unpublished palynological data in Saudi Arabia suggests this level is likely to be in the earliest Rhuddanian. Typically no more than two graptolite species are present at any one horizon in this interval. *Normal.*? cf. *persculptus* (Elles and Wood) is recorded, albeit rarely, whilst *Normal. lubricus* (Chen and Lin) is present sporadically from near the base of this interval: elsewhere, this latter species has been used as an indicator for the base of the Silurian (Koren' and Melchin, 2000), as it is, tentatively, here.

AKIDOGRAPTUS ASCENSUS–PARAKIDOGRAPTUS ACUMINATUS BIOZONE

The *ascensus-acuminatus* Biozone was originally distinguished (as the *acuminatus* Biozone) by Lapworth (1878) in the Birkhill Shales Formation of southern Scotland and in its original definition also embraced the graptolites of the underlying *persculptus* Biozone (see Zalasiewicz et al., 2009: 827). In Saudi Arabia this biozone is characterized by more than 20 graptolite species that enable its subdivision into two intervals

Graptolite biozones and graptolite species	*lubricus*	*ascensus–acuminatus*		*vesiculosus*	*cyphus*	*triangulatus*	*thuringiacus*	*leptotheca*	*convolutus*	*sedgwickii*	*halli*	*guerichi–gemmatus*	*guerichi–renaudi*
		L	U										
Neodiplograptus daedalus	aff.												
Normalograptus angustus	X												
Normalograptus lubricus	X												
Normalograptus bifurcatus	X	X											
Normalograptus? persculptus	cf.	cf.											
Normalograptus? parvulus	X	X											
Normalograptus? lungmaensis	cf.	cf.											
Normalograptus targuii	X	X											
Normalograptus normalis	X	X	X	X									
Normalograptus medius	X	X	X	X									
Normalograptus mirnyensis	X	X	X	X									
Normalograptus rectangularis	?	?	X	X	X								
Normalograptus ajjeri	X	X	X	X	X	X	?						
Nediplograptus shanchongensis		X											
Normalograptus jideliensis		cf.											
Akidograptus ascensus		X											
Nediplograptus apographon		cf.	cf.										
Neodiplograptus lanceolatus		X	X										
Normalograptus cortoghianensis		X	X										
Neodiplograptus sp. 3 *sensu Loydell*		X	X	X									
Normalograptus longifilis			X										
Neodiplograptus parajanus			X										
Parakidograptus acuminatus			X										
Normalograptus minor			X										
Normalograptus trifilis			X										
Neodiplograptus africanus			X	X									
Sudburigraptus sp.			X	X									
Huttagraptus incurvus				?									
Rhaphidograptus extenuatus				X									
Neodiplograptus elongatus				X									
Huttagraptus praestrachani				X									
Metaclimacograptus slalom				X	X								
Huttagraptus sp. 2 *of Koren' & Bjerreskov*				X	X								
Neodiplograptus fezzanensis				X	X								
Cystograptus vesiculosus				X	X								
Huttagraptus acinaces				X	?								
Dimorphograptus confertus s.l.				X	X								
Normalograptus tariti				cf.	cf.								
Pribylograptus sandersoni				?		?							
Atavograptus atavus				X	X	X							
Rhaphidograptus toernquisti				X	X	X	X	X	X				
Glyptograptus tamariscus s.l.				?	X	X	X	X	X				
Metaclimacograptus hughesi				X	X	?	X	X	X	X	cf.		
Metaclimacograptus undulatus s.l.				X	X	X	X	X	X	X	X	X	
Glyptograptus sinuatus s.l.					X								
Coronograptus cyphus					X								
Neodiplograptus sp. A					X								
Monograptus revolutus					X	X	X						
Monograptus sudburiae					cf.	?	X						
Coronograptus gregarius					X	X	X	X					
Demirastrites triangulatus predecipiens						cf.							
Pristiograptus concinnus						?	X						
Rastrites longispinus						X	X						
Pribylograptus incommodus						X	X						
Demirastrites triangulatus triangulatus						X	X						
"Paraclimacograptus" libycus						X	X	X	cf.				
Neodiplograptus thuringiacus						?	X	X	X				
Pseudorthograptus insectiformis						aff.	X	?	X				
Glyptograptus incertus						cf.	cf.	X	X				

Fig. 3A – stratigraphic distribution of over 150 graptolite taxa in the Qusaiba Member, Qalibah Formation

Ranges are compiled from an analysis of 1017 sample horizons. Note that the range chart identifies specimens of *Metaclimacograptus hughesi* (Nicholson), here used in the sense of Zalasiewicz (1996: text-fig. 2A–C)

Graptolite biozones and graptolite species	*cyphus*	*triangulatus*	*thuringiacus*	*leptotheca*	*convolutus*	*sedgwickii*	*halli*	*guerichi–gemmatus*	*guerichi–renaudi*
Neodiplograptus magnus			?						
Monograptus communis			?						
Monograptus toernquisti			X						
Demirastrites triangulatus separatus			X						
Monograptus pseudoplanus			X						
Demirastrites triangulatus fimbriatus			X						
Rastrites orbitus			cf.	cf.					
Pseudoglyptograptus barriei			X	X					
Pribylograptus argutus			cf.	aff.					
Petalolithus ovatoelongatus			X	X	X				
Monograptus capis			?	X	X			?	
Pseudoretiolites sp.			?	X	X	X	X	X	
Monograptus mirus				X					
Campograptus sanctgeorgensis				X					
Monograptus paradenticulatus				X					
Rastrites approximatus				X					
Normalograptus inornatus				X					
Monograptus havliceki				X					
Monograptus dracocephalus				X					
Neolagarograptus helenae				X					
Neolagarograptus sp.*(undescribed species)*				X					
Lituigraptus richteri				X					
Campograptus millepeda				X					
Torquigraptus cf. *valens*				?	?				
Monograptus limatulus inopinus				X	?				
Petalolithus folium				X	X				
Campograptus clingani				X	X				
Monoclimacis imago				?	X				
Pribylograptus leptotheca				X	X				
Monograptus capillaris (Carruthers) sensu Zalasiewicz				X	X	X			
Campograptus lobiferus				X	X	X			
Pristiograptus regularis				?	X	X	cf.		
Normalograptus scalaris				X	X	X	X	X	
Paradiversograptus rectus					X				
Petalolithus minor					X				
Monograptus limatulus limatulus					X				
Rivagraptus bellulus					X				
Lituigraptus convolutus					X				
Normalograptus normalis					X				
Neolagarograptus impolitus					X				
Neolagarograptus rickardsi					X				
Clinoclimacograptus retroversus					X				
Torquigraptus urceolinus					X				
Lituigraptus urceolus					X	X			
Neolagarograptus tenuis					X	X			
Petalolithus clandestinus					X	X			
Rastrites hybridus					X	X			
Cephalograptus cometa extrema					X	X	?		

Fig. 3B – stratigraphic distribution of over 150 graptolite taxa in the Qusaiba Member, Qalibah Formation

(Fig. 3A). The base of the biozone is defined by the first appearance of *Akidograptus ascensus* Davies, and together with the first occurrences of *Neodiplograptus lanceolatus* Štorch and Serpagli (often in abundance), *Neodiplogr. shanchongensis* (Li), *Neodiplogr*. cf. *apographon* (Štorch), *Normal. cortoghianensis* (Štorch and Serpagli) and *Normalograptus* cf. *jideliensis* (Koren' and Mikhaylova) these collectively characterize the lower subdivision of the *ascensus–acuminatus* Biozone in Saudi Arabia and this interval can be correlated with the equivalent interval in Jordan (Loydell, 2007: text-fig. 6) and continental Europe (Štorch, 1996). The upper part of the *ascensus–acuminatus* Biozone is signalled by the first occurrence of *Parakidograptus acuminatus* (Nicholson), *Normalograptus trifilis* (Manck) – often in flood proportions, *Normal. longifilis* (Manck), *Normal. rectangularis* (McCoy), together with *Neodiplograptus africanus* (Legrand), *Neodipl. parajanus* (Štorch), and *Sudburigraptus* sp. The lower part of this interval is probably comparable to the middle *ascensus–acuminatus* Biozone of Jordan (Loydell, 2007) and continental Europe (Štorch, 1996), but the Saudi Arabian interval may also overlap the upper *ascensus–acuminatus* Biozone of the European and Jordanian schemes. In Saudi Arabia, abundant *P. acuminatus* appear just above the level with *Normal. trifilis*.

Graptolite biozones and graptolite species	*thuringiacus*	*leptotheca*	*convolutus*	*sedgwickii*	*halli*	*guerichi–gemmatus*	*guerichi–renaudi*	*guerichi–utilis*
Torquigraptus decipiens			X	X	X			
Torquigraptus involutus			X	X	X	?		
Diversograptus? sp. A				X				
Oktavites contortus				?	X	X		
Stimulograptus sedgwickii				X	X	X	X	
Parapetalolithus altissimus				X	X	X	X	
Pristiograptus variabilis				X	X	X	X	X
Rastrites gracilis					X			
Pseudoplegmatograptus obesus					?			
“Spirograptus” andrewsi					X			
Parapetalolithus globosus					aff.			
Lituigraptus rastrum					?			
Streptograptus ansulosus					*X*	cf.		
Rastrites schaueri					X	?		
Pristiograptus pristinus					cf.	cf.	cf.	
Rastrites linnaei					X	X	X	
Stimulograptus halli					X	X	X	
Comograptus barbatus					X	X	X	
Paradiversograptus capillaris (Carruthers) *sensu* Loydell					X	X	X	
Torquigraptus linterni					X	cf.	aff.	aff.
Streptograptus pankhurstae						X		
Glyptograptus auritus						X		
Rastrites maximus						X		
Streptograptus tenuis						aff		
Paradiversograptus runcinatus						X		
Petalolithus palmeus						cf		
Glyptograptus elegans						?		
“Monograptus” pulcherrimus (Manck) *sensu* Přibyl and Münch						cf		
Monograptus gemmatus						X		
Pristiograptus renaudi						X	X	
Glyptograptus fastigatus						X	X	
Streptograptus filiformis						X	?	
Streptograptus plumosus						X	X	
Rastrites fugax						X	X	
Parapetalolithus conicus						X	X	
Streptograptus strachani						X	X	
Streptograptus storchi						?	X	
Monograptus marri						?	X	
Monograptus bjerreskovae						X	X	X
Spirograptus guerichi						X	X	X
Stimulograptus becki						X	X	X
Parapetalolithus elongatus							X	
Torquigraptus cavei							X	
Parapetalolithus giganteus							X	X
Pristiograptus bjerringus							cf.	cf.

Fig. 3C – Stratigraphic distribution of over 150 graptolite taxa in the Qusaiba Member, Qalibah Formation

CYSTOGRAPTUS VESICULOSUS BIOZONE

The *vesiculosus* Biozone was distinguished in the Birkhill Shales Formation of Scotland by Lapworth (1878) and is here defined by the first appearance of its eponymous species, *Cystograptus vesiculosus* (Nicholson), which is abundant. Štorch (1996) noted the co-occurrence of *C. vesiculosus* with the latest populations of *P. acuminatus*, regarding this level as the lowermost part of the *vesiculosus* Biozone. We have not been able to demonstrate such overlap. The lowermost *C. vesiculosus* in Saudi Arabia are accompanied by *Normalograptus* cf. *tariti* and normalograptids (*Normal. medius, Normal. rectangularis, Normal. ajjeri*) that range up from underlying levels. In Britain the interval represented by the *vesiculosus* Biozone was subdivided into the *Atavograptus atavus* and *Huttagraptus acinaces* biozones (see discussion in Hutt, 1974; Zalasiewicz et al., 2009), but in Saudi Arabia these subdivisions have proved unworkable, as the first appearances of *Huttagraptus* species, including *H. praestrachani* (Hutt and Rickards) and *Huttagraptus* sp. 2 of Koren’ and Bjerreskov (1997), and *Atavograptus atavus* (Jones) are effectively coincident. The *vesiculosus* Biozone assemblage includes some 25 graptolite species in Saudi Arabia (Fig. 3A). *Rhaphidograptus extenuatus* (Elles and Wood), though rare, is present in lower assemblages of the *vesiculosus* Biozone while the upper part of the biozone is characterized by the first occurrences of long-ranging *Metaclimacograptus* spp. and *Rhaphidograptus toernquisti* (Elles and Wood), and by *Dimorphograptus*

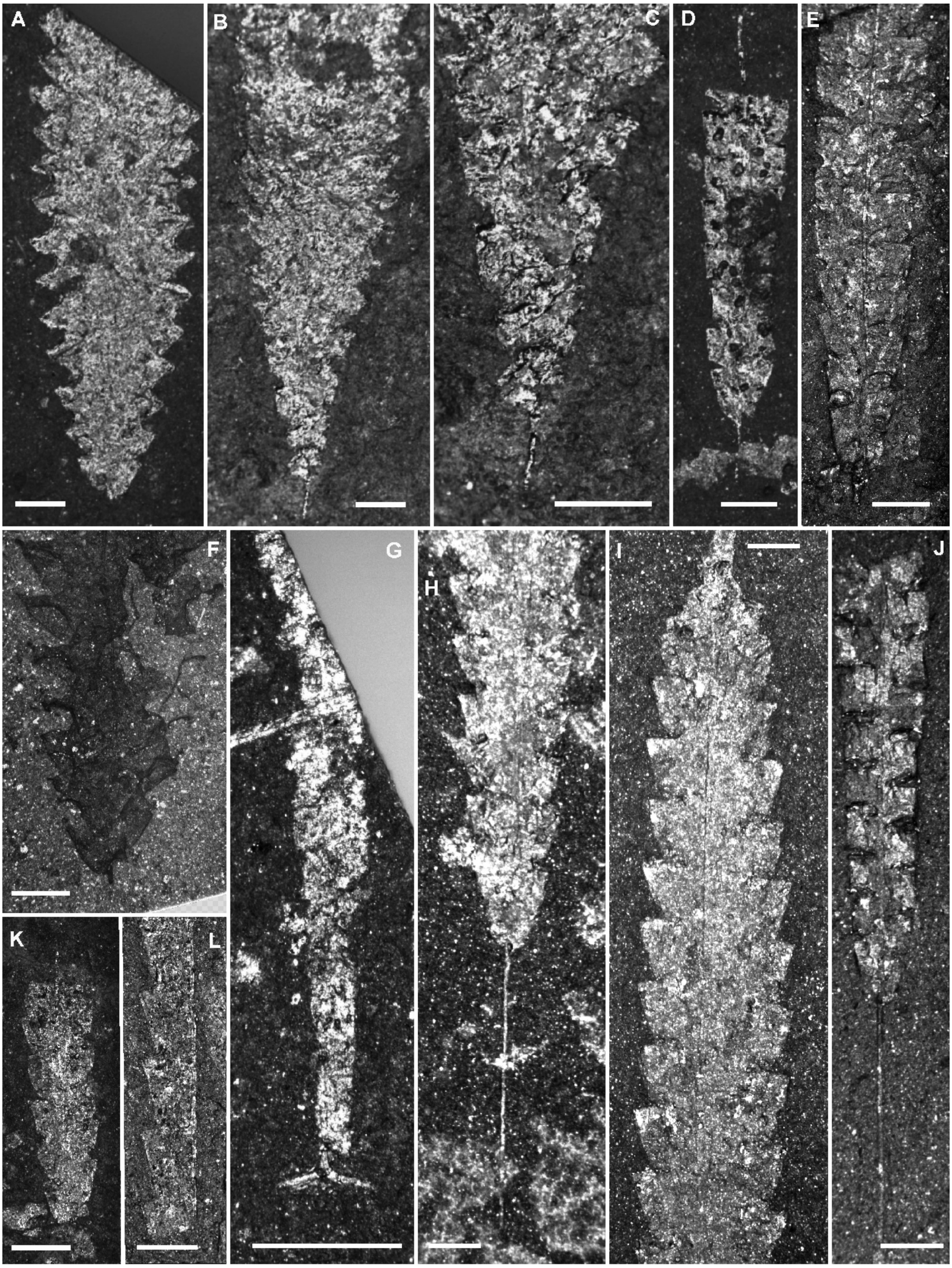

Fig. 4. Illustrative images of Rhuddanian graptolites from the Qusaiba Member of Saudi Arabia

A – *Neodiplograptus lanceolatus*; **B**, **C** – *Neodiplograptus fezzanensis*: C is a close-up of the proximal end of B; **D**, **E** – *Neodiplograptus africanus*; **F** – *Neodiplograptus lueningi*; **G** – *Akidograptus ascensus*; **H**, **I** – *Neodiplograptus parajanus*, proximal and distal part of rhabdosome respectively; **J** – *Normalograptus ajjeri*; **K** – *Normalograptus*? *parvulus*; **L** – *Atavograptus atavus*, distal fragment; scale bars are 1 mm

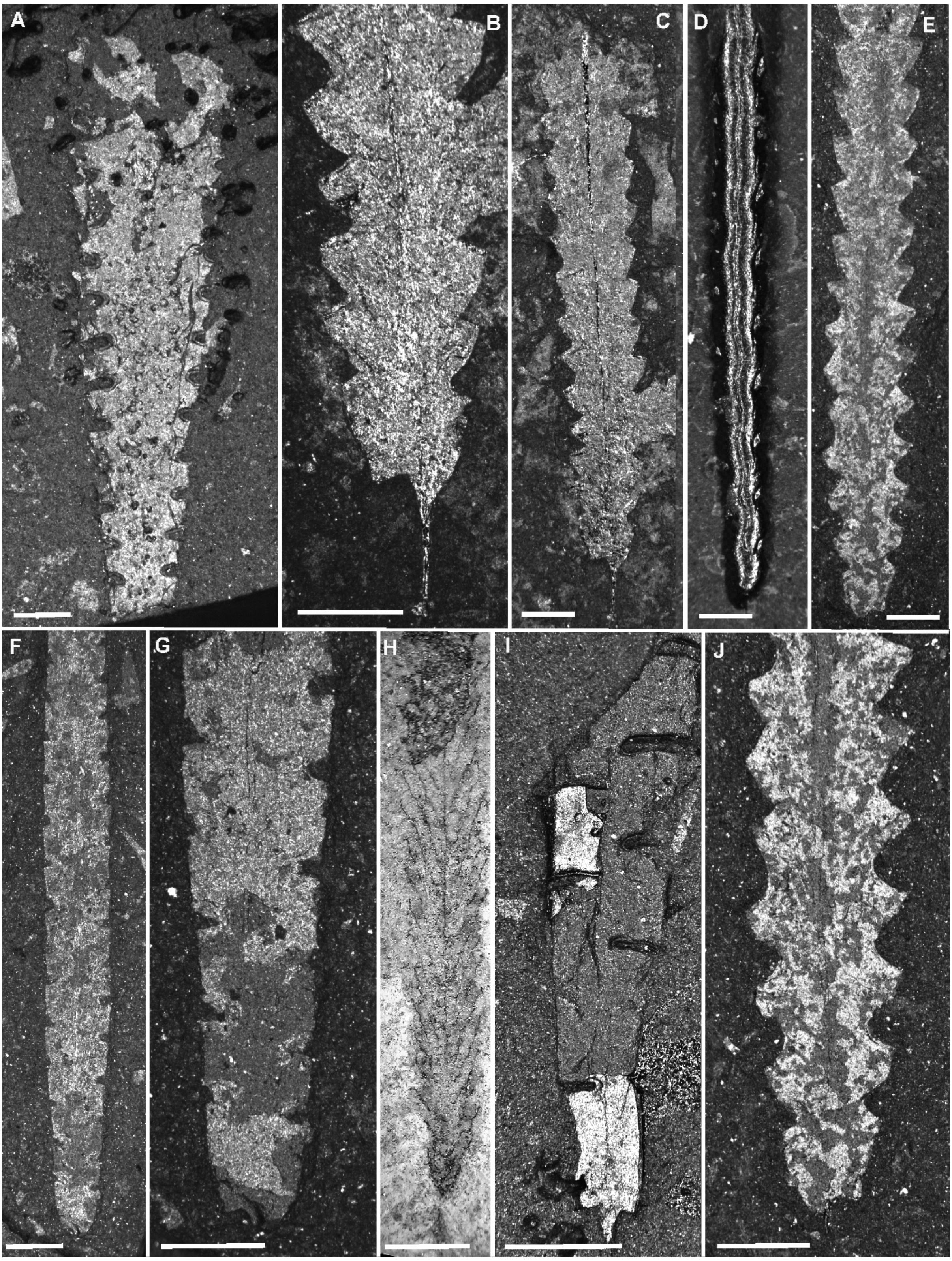

Fig. 5. Illustrative images of Rhuddanian graptolites from the Qusaiba Member of Saudi Arabia

A – “*Paraclimacograptus*” *libycus*?; **B**, **C** – *Sudburigraptus* sp: B is a close-up of the proximal end of C; **D** – *Clinoclimacograptus retroversus* Bulman and Rickards; **E**, **J** – *Neodiplograptus* cf. *apographon*: J is a close-up of the proximal end of E; **F**, **G** – *Normalograptus ajjeri*: G is a close-up of the proximal end of F; **H** – *Neodiplograptus* cf. *shanchongensis*; **I** – *Rhaphidograptus toernquisti*; scale bars are 1 mm

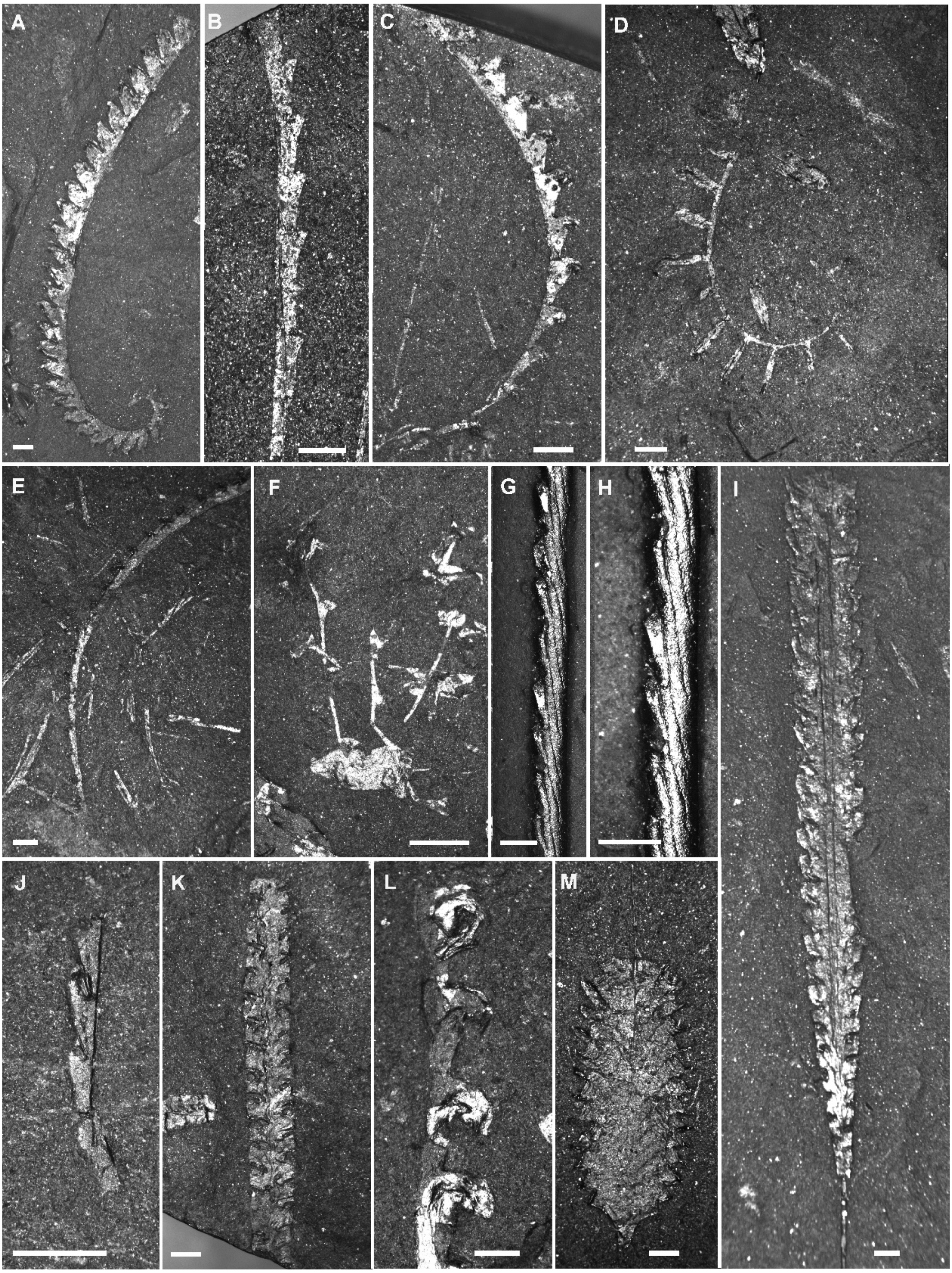

Fig. 6. Illustrative images of Aeronian graptolites from the Qusaiba Member of Saudi Arabia

A – *Demirastrites triangulatus fimbriatus*; **B** – *Coronograptus gregarius*; **C** – *Monograptus pseudoplanus*; **D** – *Rastrites* cf. *orbitus*; **E** – *Monograptus sudburiae*; **F** – *Monograptus capis*; **G**, **H** – *Pribylograptus leptotheca*: H is a close-up of G; **I** – *Neodiplograptus thuringiacus*; **J** – *Pristiograptus regularis*; **K** – *Metaclimacograptus hughesi sensu* Zalasiewicz (1996); **L** – *Campograptus lobiferus*; **M** – *Petalolithus ovatoelongatus*; scale bars are 1 mm

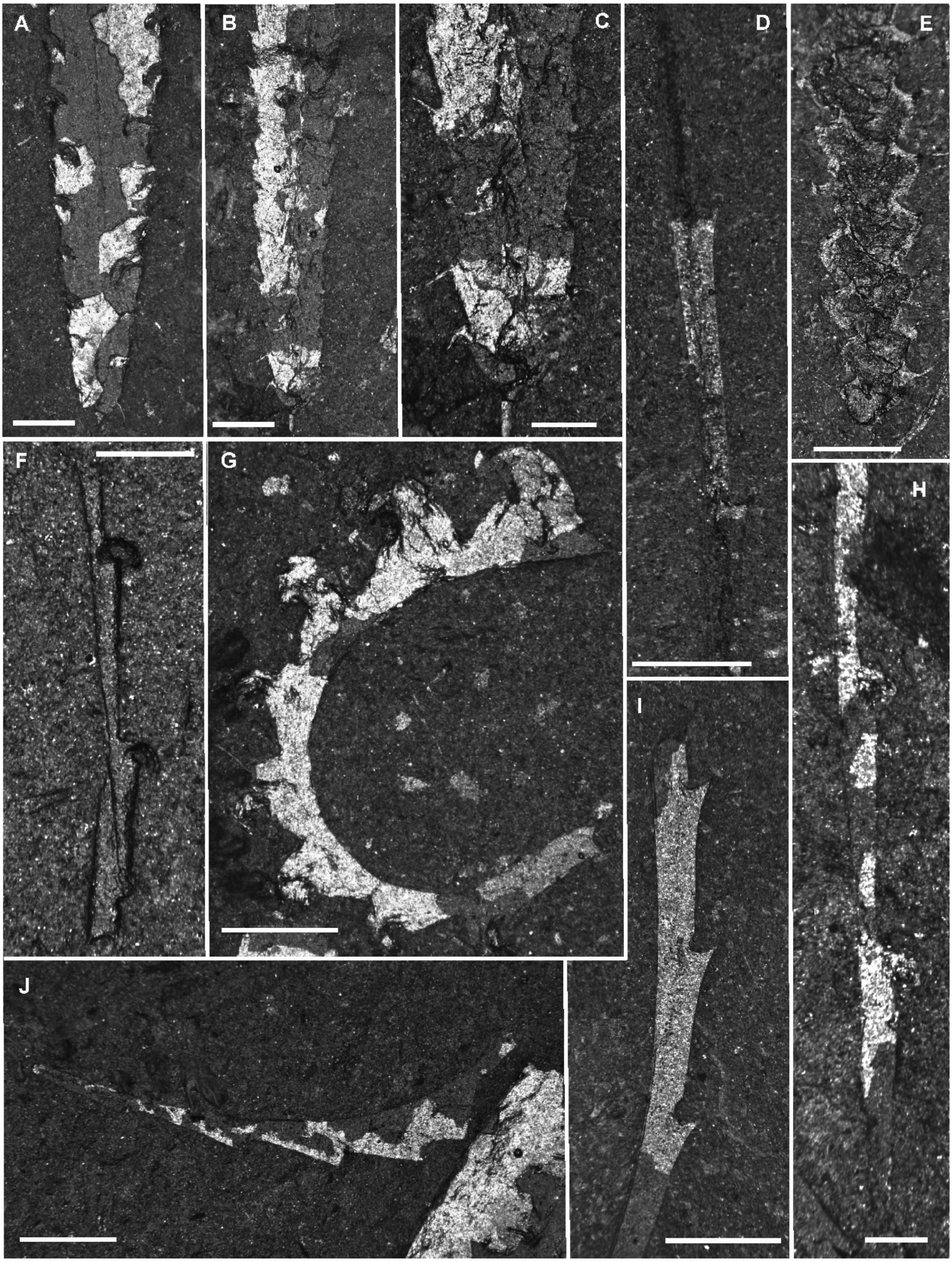

Fig. 7. Illustrative images of Aeronian graptolites from the Qusaiba Member of Saudi Arabia

A – *Pseudoglyptograptus barriei*; **B**, **C** – narrow specimen of *Rivagraptus bellulus,* approaching the dimensions of *Rivagraptus rozmanae* Koren' and Rickards: C is a close-up of the proximal end of B; **D** – *Neolagarograptus* sp. (possibly *N. helenae*); **E** – *Pseudorthograptus insectiformis*; **F** – *Campograptus sanctgeorgensis*; **G** – *Campograptus millepeda*; **H** – *Monograptus capillaris sensu* Zalasiewicz (1996); **I** – *Neolagarograptus impolitus*; **J** – *Monograptus limatulus*; scale bars are: A, B, D, E, G, I, J – 1 mm, C, F – 0.5 mm, H – 0.25 mm

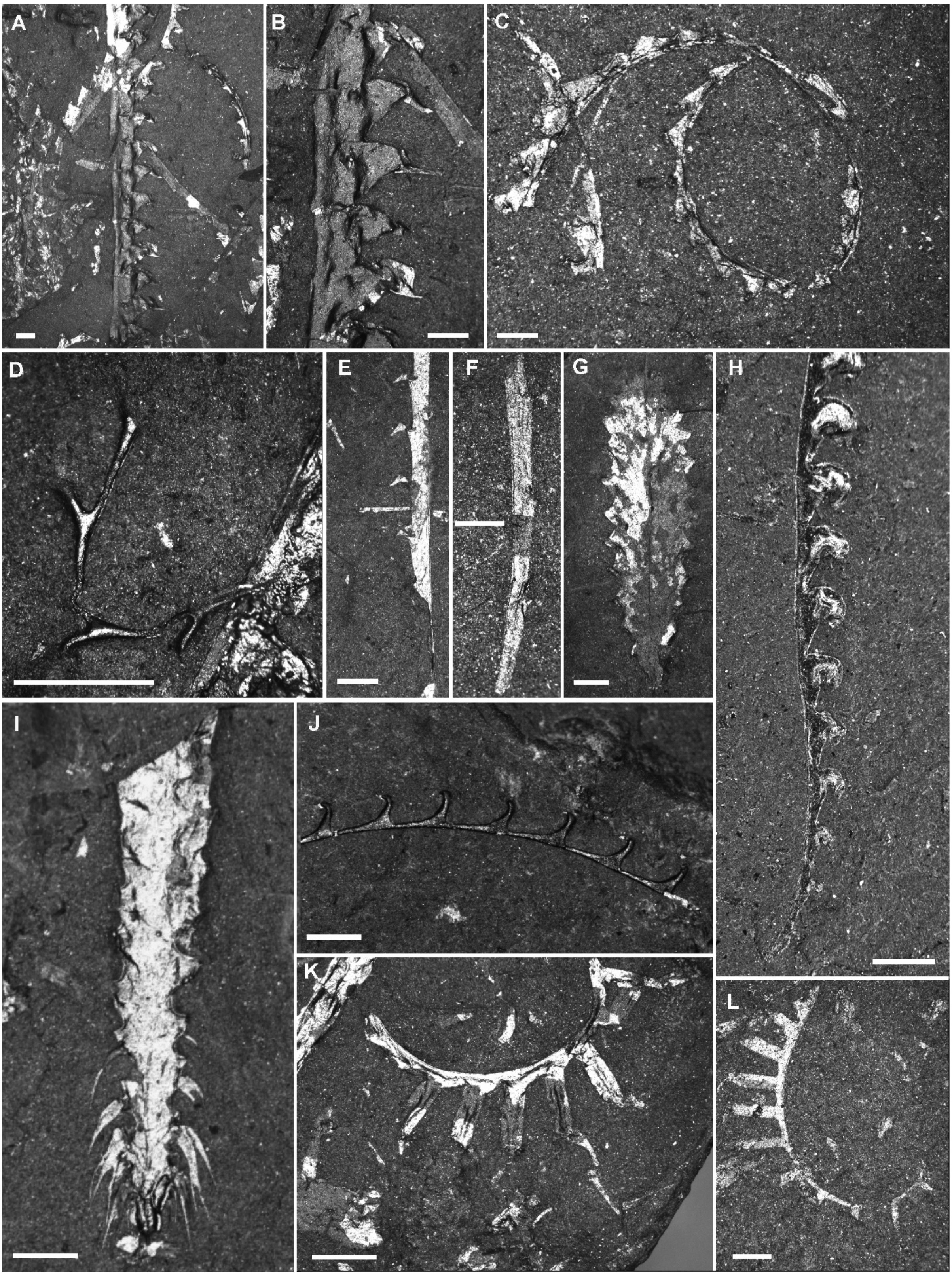

Fig. 8. Illustrative images of Aeronian (A, B, D–L) and Telychian (C) graptolites from the Qusaiba Member of Saudi Arabia

A, **B** – *Torquigraptus involutus* and *Stimulograptus sedgwickii*: B is a close-up of the thecae of *S. sedgwickii* in A; **C** – *Torquigraptus linterni*; **D** – *Torquigraptus decipiens*; **E**, **F** – *Neolagarograptus tenuis*; **G** – *Parapetalolithus altissimus*; **H** – *Campograptus lobiferus*; **I** – *Comograptus barbatus*; **J** – *Torquigraptus* sp. (possibly *T. urceolinus*); **K** – *Lituigraptus convolutus*; **L** – *Lituigraptus* sp.; scale bars are 1 mm

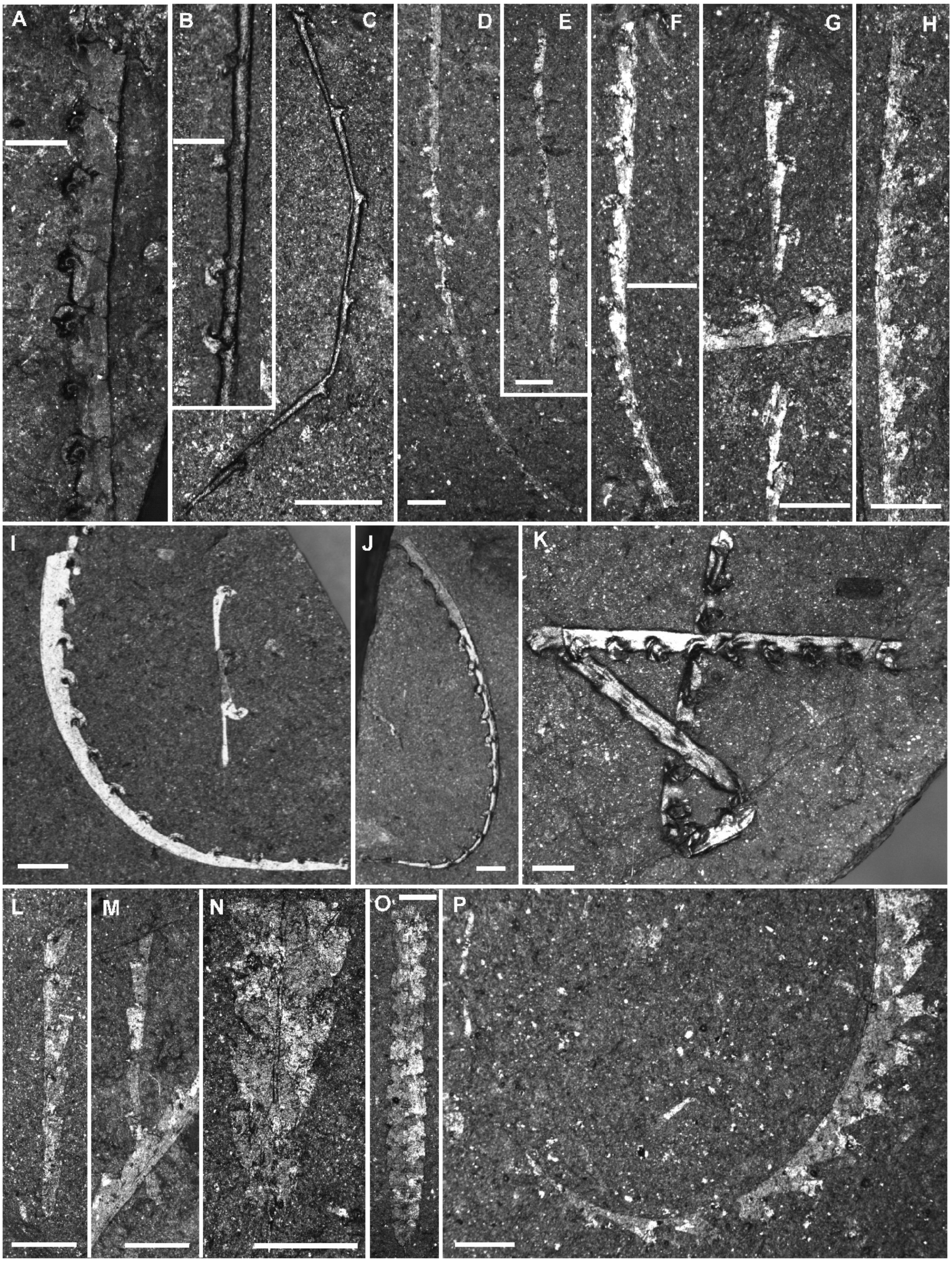

Fig. 9. Illustrative images of Telychian graptolites from the Qusaiba Member of Saudi Arabia

A – *Streptograptus storchi*?; **B**, **C** – *Paradiversograptus capillaris sensu* Loydell (1993); **D** – *Stimulograptus becki*; **E** – *Streptograptus strachani*; **F** – *Monograptus bjerreskovae*; **G** – *Monograptus gemmatus*; **H** – *Monograptus gemmatus*, distal part of rhabdosome; **I** – *Monograptus gemmatus* proximal fragment and *Streptograptus*; **J** – *Streptograptus pankhurstae*; **K** – *Monograptus bjerreskovae* that has likely been predated (hence folding of rhabdosome); **L** – *Pristiograptus variabilis*; **M** – *Pristiograptus renaudi*; **N** – *Glyptograptus auritus*; **O** – *Metaclimacograptus scalaris*; **P** – *Torquigraptus cavei*; scale bars: A, C–P – 1 mm, B – 0.5 mm

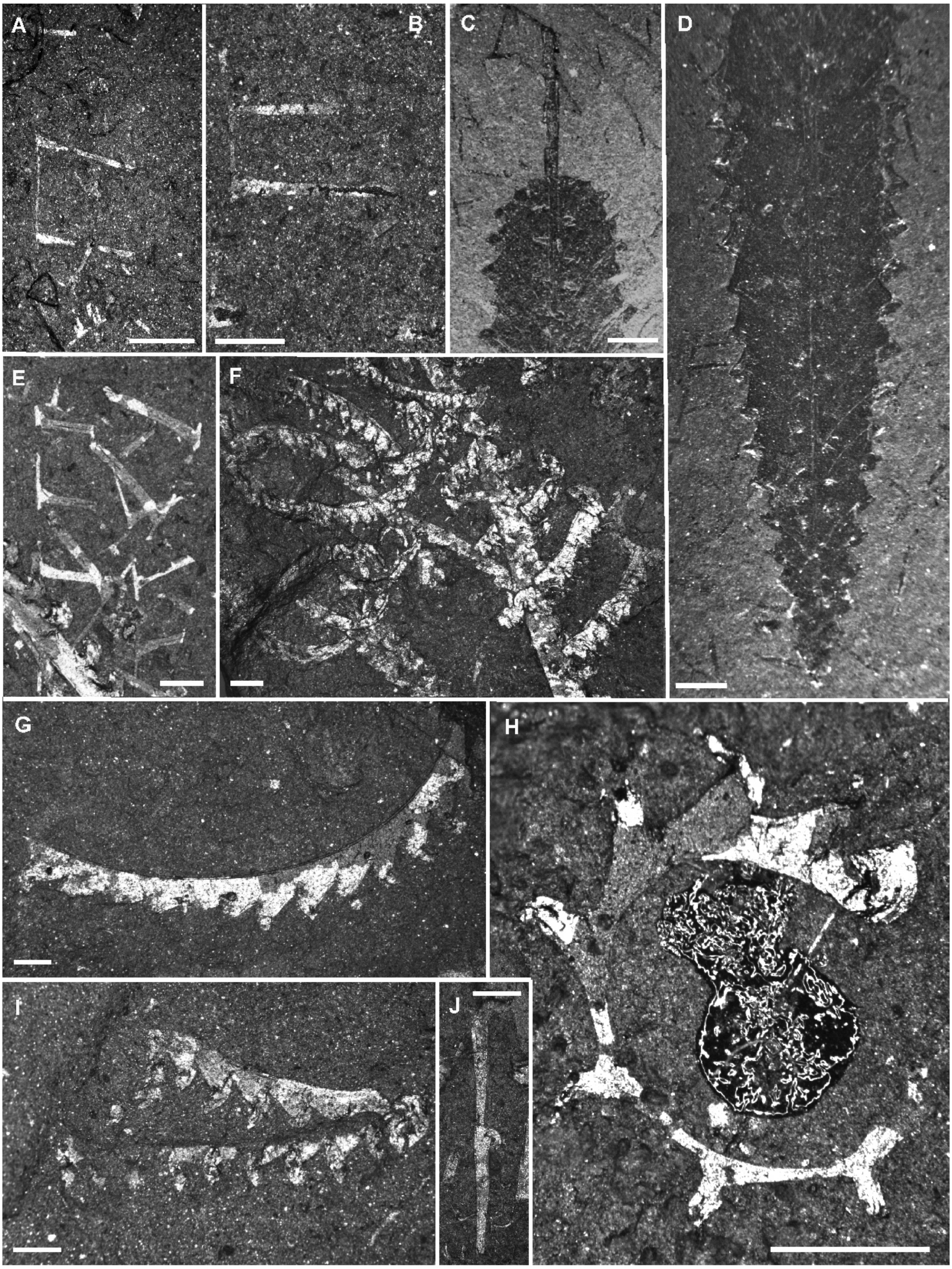

Fig. 10. Illustrative images of Late Aeronian and Telychian graptolites from the Qusaiba Member of Saudi Arabia

A, **B**, **E** – fragments of *Rastrites* spp.; **C**, **D** – *Parapetalolithus giganteus*, distal, and proximal and mesial parts of the same rhabdosome, respectively; **F** – *Spirograptus guerichi*; **G** – *Oktavites contortus*?; **H** – "*Spirograptus*" *andrewsi*?; **I** – *Oktavites contortus*?; **J** – *Streptograptus* cf. *ansulosus*; scale bars: A – 2 mm, B–I, H – 1 mm, J – 0.5 mm

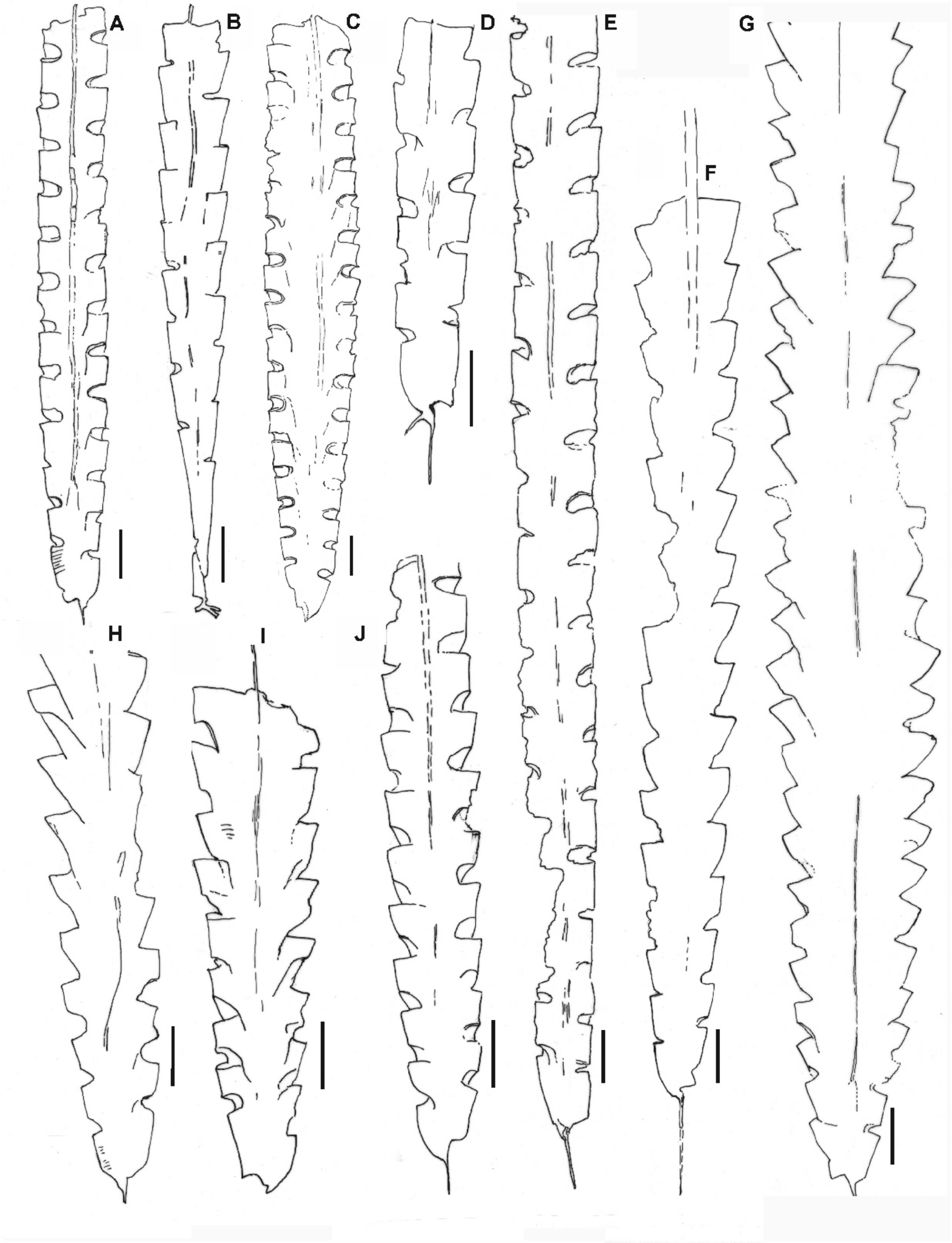

Fig. 11. Illustrative camera lucida images of Rhuddanian graptolites from the Qusaiba Member of Saudi Arabia

A – *Normalograptus* cf. *jideliensis*; **B** – *Akidograptus ascensus*; **C** – *Normalograptus medius*; **D** – *Normalograptus lubricus*; **E** – *Normalograptus normalis*; **F** – *Normalograptus*? cf. *lungmaensis*; **G** – *Neodiplograptus lanceolatus*; **H** – *Neodiplograptus* aff. *daedalus*; **I** –*Normalograptus*? cf. *persculptus*; **J** – *Normalograptus*? *parvulus*; scale bars are 1 mm

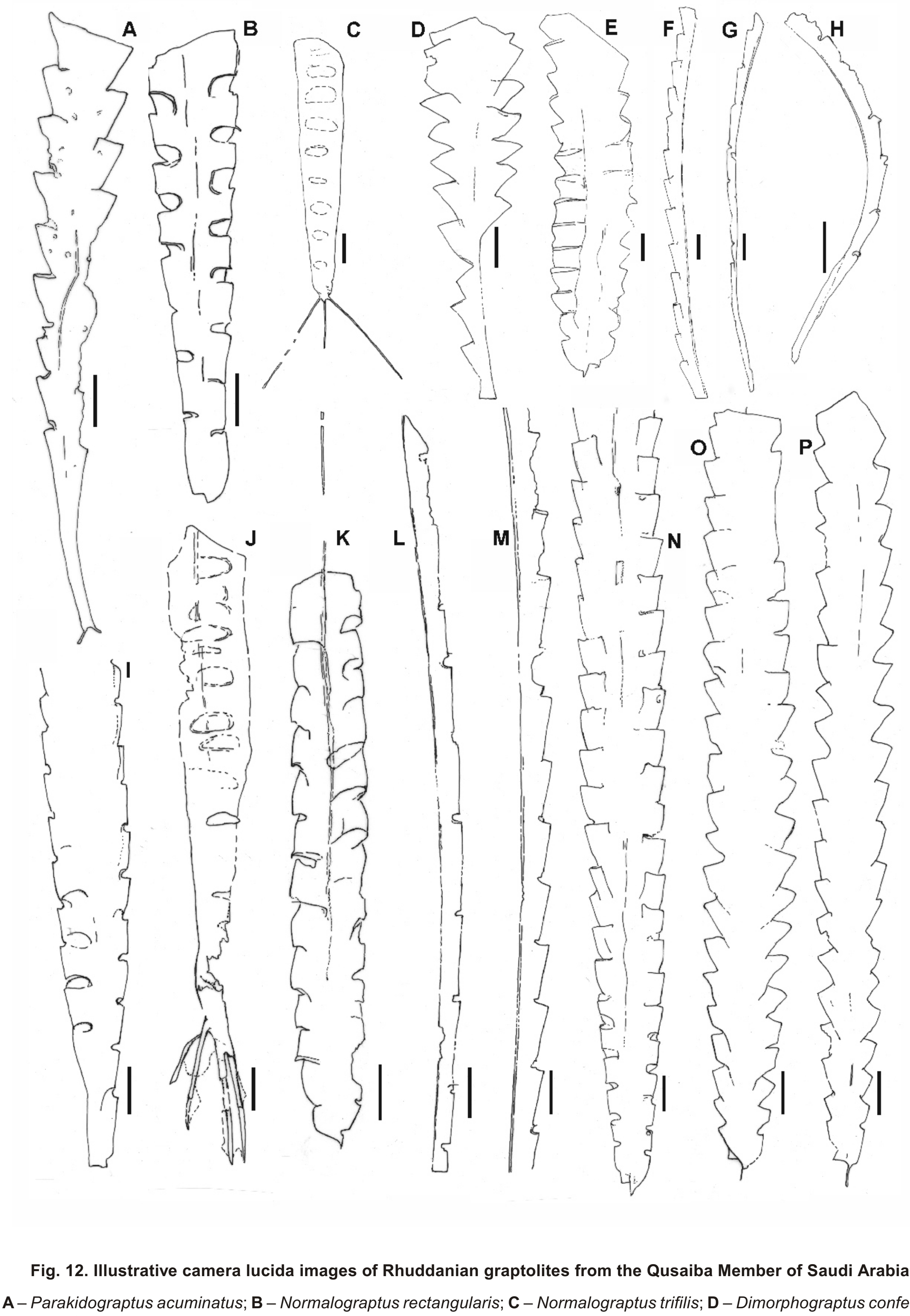

Fig. 12. Illustrative camera lucida images of Rhuddanian graptolites from the Qusaiba Member of Saudi Arabia

A – *Parakidograptus acuminatus*; **B** – *Normalograptus rectangularis*; **C** – *Normalograptus trifilis*; **D** – *Dimorphograptus confertus* s.l.; **E** – *Cystograptus vesiculosus*; **F** – *Atavograptus* sp.; **G** – *Huttagraptus praestrachani*; **H** – *Huttagraptus incurvus*?; **I** – *Rhaphidograptus toernquisti*; **J** – *Normalograptus longifilis*; **K** – *Metaclimacograptus hughesi sensu* Zalasiewicz (1996); **L**, **M** – *Huttagraptus* sp. 2 of Koren' and Bjerreskov; **N** – *Neodiplograptus parajanus*; **O** – *Neodiplograptus* cf. *apographon*; **P** – *Normalograptus* cf. *tariti*; scale bars are 1 mm

Fig. 13. Flow-aligned *Normalograptus* from the *Neodiplograptus thuringiacus* Biozone, Qusaiba Member, Saudi Arabia

The graptolite bottom right is 10 mm long (not including the nema)

confertus (Nicholson) s.l. and *Neodiplograptus fezzanensis* (Desio): the earliest occurrence of *Glyptograptus tamariscus* (Nicholson) s.l. is just below these three taxa in cores. The uppermost interval of this biozone probably overlaps with the lower part of the *fezzanensis* Biozone of Libya (see Štorch and Massa, 2006).

CORONOGRAPTUS CYPHUS BIOZONE

The *cyphus* Biozone was originally distinguished in the Rhayader area of central Wales by Lapworth (1900; see Zalasiewicz et al., 2009). In Saudi Arabia the biozone is defined by the total range of *Coronograptus cyphus* (Lapworth). In Britain *C. cyphus* is known to occur in assemblages of the *acinaces* Biozone (Hutt and Rickards, 1970; Zalasiewicz et al., 2009: 829), equivalent to the upper part of the *vesiculosus* Biozone of Saudi Arabia. We have found *C. cyphus* to be a good marker for an interval between the ranges of *C. vesiculosus* and the earliest *Demirastrites triangulatus* s.l. in Saudi Arabia, and the species demarcates a similar interval in Bohemia (Štorch, 1994). In total, the *cyphus* Biozone yields about 20 graptolite taxa (Fig. 3A) including the earliest occurrences of *Coronograptus gregarius* (Lapworth), *Glyptograptus sinuatus* (Nicholson) s.l., and graptolites of the *Monograptus revolutus* group including *Monograptus sudburiae* Hutt. The biozone typically occupies only a very thin succession of black mudstones with a maximum thickness of 0.3 m and in many cores the *cyphus* Biozone is missing or unrecorded. The small thickness of the *cyphus* Biozone would likely preclude its recognition in most Arabian surface exposures. The *cyphus* Biozone of Saudi Arabia likely correlates with the upper part of the *N. fezzanensis* Biozone of Libya (Štorch and Massa, 2006) and approximately with the *revolutus* Biozone of Britain *sensu* Zalasiewicz et al. (2009).

DEMIRASTRITES TRIANGULATUS BIOZONE

The *triangulatus* Biozone represents the lowermost interval of the “*Monograptus gregarius* zone” of Lapworth (1878), later subdivided into *triangulatus, magnus* and *leptotheca* biozones (for history, see Sudbury, 1958; Zalasiewicz et al., 2009). In Saudi Arabia the *triangulatus* Biozone is characterized by 19 graptolite taxa (Fig. 3A) and is identified by the first occurrence of *Demirastrites triangulatus* (Harkness) s.l., which is abundant at some horizons, together with *Pribylograptus incommodus* (Törnquist) and “*Paraclimacograptus*” *libycus* (Desio). *Rhaphidograptus toernquisti* is commonly found. The base of the *triangulatus* Biozone and of the Aeronian Stage is often readily identifiable from this assemblage in the continuous core, even where the eponymous biozonal fossil is absent. The lower part of the biozone includes *Demirastrites* cf. *triangulatus predecipiens* Sudbury, while *Rastrites longispinus* Perner appears in the upper part. In some boreholes the thickness of the combined *triangulatus* and overlying *thuringiacus* biozones is <1 m, though the *triangulatus* Biozone more typically occupies a succession of about 2 m of black mudstones in Saudi Arabia. It is equivalent, at least in part, to the *gregarius–libycus* Biozone of Libya (Štorch and Massa, 2006) indicated by the first occurrence of “*P.*” *libycus* at this level. While the *gregarius–libycus* Biozone assemblage is of low diversity in North Africa, in Saudi Arabia the *triangulatus* Biozone assemblage is diverse, possibly reflecting greater Silurian marine-shelf water-depths in the Arabian succession. The first occurrence of *Demirastrites triangulatus* s.l. and *Rastrites* at this level in Saudi Arabia also indicates correlation with the *triangulatus* Biozone in Britain (see Hutt, 1975).

NEODIPLOGRAPTUS THURINGIACUS BIOZONE

The *thuringiacus* Biozone takes its name from *Neodiplograptus thuringiacus* (Kirste) and this biostratigraphic interval appears to be equivalent to the *magnus* biozone of Britain, first recognized in the Rheidol Gorge of Wales by Jones (1909). In Saudi Arabia this biozone is characterized by 28 graptolite taxa (Fig. 3A, B), including the first definite occurrence of *Neodipl. thuringiacus*, and of *Monograptus pseudoplanus* Sudbury, and by abundant *Monograptus sudburiae, Demirastrites triangulatus fimbriatus* (= *D. pectinatus* of some authors) and *Rhaphidograptus toernquisti*. Above the base of the biozone the interval is associated with the earliest occurrences of retiolitids (possible *Pseudoretiolites* and petalolithids (*Petalolithus ovatoelongatus* (Kurck)), and with the incoming of the distinctive *Pseudoglyptograptus barriei* Zalasiewicz and Tunnicliff, possible *Monograptus capis* Hutt, and definitive *Pseudorthograptus insectiformis* (Nicholson). The top of the biozone is identified by the last occurrence of *Demirastrites triangulatus* s.l. The *thuringiacus* Biozone occupies a succession of strata between about 0.3 and 9 m thick in black graptolitic mudstones. As both "*P.*" *libycus* and *C. gregarius* range through this interval, at least part of the *thuringiacus* Biozone of Saudi Arabia correlates with an interval in the upper part of the *libycus–gregarius* Biozone of Libya (Štorch and Massa, 2006). As strata bearing *D. triangulatus fimbriatus* are succeeded immediately in Saudi Arabia by those bearing *Lituigraptus richteri* (Perner) that denote the *leptotheca* Biozone, it is not certain whether an interval equivalent to the *simulans* Biozone – recognized in Bohemia (see Štorch, 1994) – may be differentiated in the Qusaiba Member.

PRIBYLOGRAPTUS LEPTOTHECA BIOZONE

This biozone was originally recognized in the English Lake District by Marr and Nicholson (1888) as the *Monograptus argenteus* Zone, named after one of its definitive species. Later, Elles and Wood (1901–1918) noted the incoming of *Pribylograptus leptotheca* (Lapworth) at this level, a species that is more widely recorded than *M. argenteus*. In Saudi Arabia the *leptotheca* Biozone is characterized by 36 graptolite taxa, the base of the biozone being demarcated by the first occurrence of its two most distinctive species, *Lituigraptus richteri* and *P. leptotheca* (Fig. 3B). The *leptotheca* Biozone has a distinctive fauna that includes the first occurrences of an undescribed new species of *Neolagarograptus*, *N. helenae* (Štorch), *Monograptus havliceki* Štorch, *M. imago* Zalasiewicz, *M. limatulus inopinus* Törnquist, *Campograptus clingani* (Carruthers), *C. lobiferus* (McCoy), *C. millepeda* (McCoy), *C. sanctgeorgensis* Štorch and *Petalolithus folium* (Hisinger) (Fig. 3B). The top of the biozone is characterized by the last occurrence of *Li. richteri*. The most commonly occurring taxon of the *leptotheca* Biozone is *C. lobiferus*, present in both low- and high-diversity assemblages. Based on the first occurrence of *P. leptotheca* this interval in Saudi Arabia is the equivalent of the *leptotheca* Biozone in Britain (Hutt, 1975; Zalasiewicz et al., 2009), but the Arabian assemblage shows the most striking similarity to the *leptotheca* assemblages of the Czech Republic described by Štorch (1998). The *leptotheca* Biozone of Saudi Arabia is probably equivalent to the "*leptotheca*" Biozone in Libya (Štorch and Massa, 2006), though in the latter area the biozone is characterized by a low-diversity assemblage that includes *Neolagarograptus helenae* (Štorch): we regard similar faunas as indicative of more shallow-water marine lithofacies in Saudi Arabia (see below). The *leptotheca* Biozone may occupy as little as 1 m of black graptolitic mudstone in Saudi Arabia, but can be expanded to >40 m of strata.

LITUIGRAPTUS CONVOLUTUS BIOZONE

This biozone was originally recognized by Marr and Nicholson (1888) in the English Lake District and is equivalent to the "*clingani* Zone" and "*cometa* band" of Lapworth (1878). In Saudi Arabia the biozone yields over 30 graptolite taxa, many of them ranging from the preceding *leptotheca* Biozone (Fig. 3B). It is characterized by the first appearances of *Lituigraptus convolutus* (Hisinger), *Torquigraptus decipiens* (Törnquist), *Monograptus limatulus limatulus* Törnquist, *Neolagarograptus impolitus* Štorch, *Rastrites hybridus* Lapworth, *Torquigraptus urceolinus* (Stein), *Rivagraptus bellulus* (Törnquist), and *Pristiograptus regularis* (Törnquist). *Paradiversograptus rectus* (Manck) and *Torquigraptus involutus* (Lapworth) also have their first occurrences in this biozone, but above the base. Small fragments of *Li. convolutus* are often difficult to distinguish from *Li. richteri* in core material and in many instances the *convolutus* Biozone has been distinguished from the preceding *leptotheca* interval by the distinctive *T. decipiens*. *Pribylograptus leptotheca* ranges through much of this biozone, but disappears at a level approximately coincident with the incoming of *Neolagarograptus rickardsi* El Khayal, a species that informally identifies a discrete "*rickardsi* interval" in the uppermost *convolutus* Biozone. The neolagarograptids provide a subdivision more widely, as *N. impolitus* Štorch occurs in the lower part of the biozone, while *N. tenuis* (Portlock) appears just before the top of the biozone. This evolutionary lineage of *Neolagarograptus* is more useful here than the well-known succession of *Cephalograptus* species (Snelling et al., 2011), as the latter are rare in Saudi Arabia. The top of the *convolutus* Biozone seems generally coincident with the last occurrence of *Li. convolutus*, though the similar taxon, *Lituigraptus urceolus* (Richter) (distinguished by more closely spaced thecae), ranges up into the *sedgwickii* Biozone. At some levels, *Normalograptus scalaris* (Hisinger) dominates the assemblages.

Based on the first occurrences of *T. decipiens* and *Li. convolutus*, this interval is the stratigraphic equivalent of the *convolutus* Biozone in Libya (Štorch and Massa, 2006), the Czech Republic (Štorch, 1998) and Britain (Zalasiewicz et al., 2009). In some regions of Saudi Arabia thin rock successions bearing *convolutus* Biozone assemblages (3 to 4 m thick) sit unconformably atop Late Ordovician successions of the Sarah Formation. At its maximum extent, in deep-water graptolite shale facies, the *convolutus* Biozone occupies an interval of black mudstones that are more than 20 m thick.

STIMULOGRAPTUS SEDGWICKII BIOZONE

This biozone was distinguished by Lapworth (1878) in the Birkhill Shales Formation of southern Scotland and is typified by the first occurrence of *Stimulograptus sedgwickii* (Portlock). In Saudi Arabia the *sedgwickii* Biozone comprises about 19 taxa, mostly ranging from the preceding *convolutus* Biozone. The lowermost interval of the *sedgwickii* Biozone is characterized by *Neolagarograptus tenuis* (Portlock) that is characteristic of the *N. tenuis* assemblage Biozone in Libya (Štorch and Massa, 2006; see also Pannell et al., 2006): this interval also includes the first occurrence of *Parapetalolithus altissimus* (Elles and Wood). The earliest *N. tenuis* slightly precedes *S. sedgwickii* in Saudi Arabia, but the two graptolites overlap in the lower part of the biozone (through circa 4 m of stratigraphic thickness in one core). *Cephalograptus cometa extrema* Bouček and Přibyl, a taxon most often associated with the uppermost *convolutus* Biozone, occurs sporadically (and indeed, possibly ranges into the overlying *halli* Biozone). The *sedgwickii* Biozone occurs in a relatively narrow interval of typically 2 to 5 m of strata, but possibly as much as 8 m of black graptolitic mudstone in one core. It is a correlative of the lower part of the *sedgwickii* Biozone of Libya, including the *tenuis* interval (Štorch and Massa, 2006), but not of the whole of the Libyan interval that includes graptolites with a younger aspect (e.g., *Pristiograptus* cf. *renaudi*). The *sedgwickii* Biozone of Saudi Arabia is the correlative of the same biozone in Britain (Zalasiewicz et al., 2009).

STIMULOGRAPTUS HALLI BIOZONE

The *halli* Biozone was recognized in Wales by Jones and Pugh (1916) and revitalized by the studies of Loydell (1991, 1992, 1993). The nominate species of the biozone, *Stimulograptus halli* (Barrande), is distinguished from the contemporaneous *S. sedgwickii* by its broader dorso-ventral width (see Loydell, 1993), though in practice the dimensions of *halli* and *sedgwickii* overlap (see discussion of the history of this biozone in Zalasiewicz et al., 2009). The *halli* Biozone represents a distinctive interval in Saudi Arabia characterized by 25 taxa, and associated with the first definitive occurrence of *Oktavites contortus* (Perner), and of *Comograptus barbatus* (Elles and Wood), *Rastrites schaueri* Štorch and Loydell, *R. linnaei* Barrande, *R. gracilis* Přibyl, *Streptograptus ansulosus* (Törnquist) and *Torquigraptus linterni* Williams et al. (see Fig. 3C). These indicate its correlation with the *halli* Biozone of Britain. There is a distinct upper part of the biozone in Saudi Arabia, probably reflecting an interval which is commonly barren of graptolites elsewhere, and which includes the Aeronian–Telychian boundary (see also Štorch and Fryda, 2012). It includes taxa such as "*Spirograptus*" *andrewsi* (Sherwin) and possible *Lituigraptus rastrum* (Richter), though assemblages are commonly of low diversity, with swarms of *S. ansulosus* being locally common. Further study of this interval could provide a clearer definition of the Aeronian–Telychian boundary, particularly given the problems with the boundary stratotype clearly demonstrated by Davies et al. (2013). The *halli* Biozone assemblage of graptolites has not been recorded from Libya (Štorch and Massa, 2006), and the *halli* Biozone probably equates to an unspecified interval in the upper part of the *sedgwickii* Biozone there. The first occurrence of *R. linnaei* in the *halli* Biozone indicates that this level in Saudi Arabia equates to the lower part of the *linnaei* Biozone of the Czech Republic (Štorch and Loydell, 1992). The *halli* Biozone is present through up to 7 m of black graptolitic mudstones in Saudi Arabia.

SPIROGRAPTUS GUERICHI BIOZONE

The *guerichi* Biozone was defined by Loydell et al. (1993) and represents the lower part of the *turriculatus* Biozone s.l. of former usage (see for e.g., Rickards, 1976). In Saudi Arabia the biozone contains over 40 taxa and is identified by the incoming of *Spirograptus guerichi* Loydell, Štorch and Melchin (Fig. 3C). The top of the biozone is uncertain in Saudi Arabia, as the biozonal fossil of the succeeding *turriculatus* Biozone has not been recorded in the Qusaiba Member. In Wales the *guerichi* Biozone has been subdivided into four subzones: the *runcinatus, gemmatus* and *renaudi* subzones, and the lower part of the *utilis* Subzone (Loydell, 1992, 1993). We do not recognize a separate *runcinatus* Biozone in Saudi Arabia, as taxa typical of the *gemmatus* Biozone (*Monograptus gemmatus* (Barrande) itself, *Glyptograptus fastigatus* Haberfelner, *Pristiograptus renaudi* (Philippot), and *Streptograptus pankhurstae* (Sherwin) soon succeed a low-diversity and regionally variable unit up to 5 m thick that seems mostly assignable to the underlying *halli* Biozone. Some of these graptolites seem to precede the appearance of *Spirograptus guerichi* itself, though this needs further study, as *S. guerichi* is sporadic in its distribution early in its range. The total thickness of strata in which the *guerichi* Biozone is developed exceeds 30 m of black mudstone in the continuous core.

The *guerichi* Biozone of Saudi Arabia records essentially the same succession of graptolites, and is an equivalent of the *guerichi* Biozone in Britain. The overall suite of graptolites, and the common occurrence of *Rastrites linnaei* Barrande and *R. maximus* Carruthers through this interval, also indicate equivalence to the middle and upper part of the *linnaei* Biozone in the Czech succession (Štorch and Loydell, 1992).

***Monograptus gemmatus* Subzone**. In Saudi Arabia this subzone is distinguished by the total range of *Monograptus gemmatus*. In continuous core the base of this interval is recognized by the first occurrence of the characteristic early Telychian *Monograptus bjerreskovae* Loydell, the most common species at this level, and by *Glyptograptus fastigatus*. The *gemmatus* Subzone is also characterized by the first occurrence of a suite of *Streptograptus* species (Fig. 3C), including *S. plumosus* (Baily), *S. strachani* Loydell and *S. filiformis* Chen, while another distinctive member of this assemblage is *Streptograptus pankhurstae*. The top of the subzone is defined as the interval immediately preceding the first occurrence of a suite of robust *Parapetalolithus* graptolites that define the base of the succeeding *renaudi* Subzone. In practice the sub-zonal boundary is often difficult to establish, as *M. gemmatus* is rare in its upper range.

***Pristiograptus renaudi* Subzone**. This subzone is often difficult to recognize in cores, as the nominate species, *P. renaudi*, is long-ranging from the earliest Telychian. The first occurrences of *Rastrites fugax* Barrande and *Streptograptus storchi* Loydell equate to a level in the uppermost *gemmatus* Subzone or lower *renaudi* Subzone. Decisive indication of the *renaudi* Subzone is given by *Parapetalolithus elongatus* (Bouček and Přibyl), *Parapetalolithus conicus* (Bouček), and *Parapetalolithus giganteus* (Bouček and Přibyl), in tandem with abundant *P. renaudi*. The upper part of the subzone is characterized by *Torquigraptus cavei* Loydell.

***Stimulograptus utilis* Subzone (lower part)**. This subzone is only tentatively identified in Saudi Arabia, based on the occurrence of *Pristiograptus* cf. *bjerringus* (Bjerreskov) at two horizons in one core, co-occurring with *Stimulograptus becki* (Barrande) and *Spirograptus guerichi*: *P.* cf. *bjerringus* succeeds an interval with *P. giganteus* and *T. cavei* that is typical of the upper *renaudi* Subzone. In Spain, *P. bjerringus* is known from the *palmeus* Subzone (Guitiérrez-Marco and Štorch, 1998) that probably correlates to the same stratigraphical level as the *renaudi* Subzone.

REGIONAL SIGNIFICANCE OF THE SAUDI ARABIAN GRAPTOLITE BIOZONATION

Correlation of the graptolite biozonation for the Early Silurian of Saudi Arabia with the biozonal schemes in North Africa, the Czech Republic and the UK is shown in Figure 14. Differences in the ranges of individual taxa between regions have been noted in the discussion of the biozones above. Here we comment on differences in the definition of particular intervals of the Arabian biozonal scheme where they are important for interregional correlation.

CORRELATION OF THE *ASCENSUS–ACUMINATUS* AND *VESICULOSUS* BIOZONES

The earliest *N. lubricus* Biozone interval of Saudi Arabia appears equivalent to the locally distinguished *lubricus* Subzone of Uzbekistan, the lowermost interval of the *ascensus–acuminatus* Biozone as defined there (Koren' and Melchin, 2000). In Saudi Arabia the succession of graptolites in the early Rhuddanian is essentially comparable with that recognized in peri-Gondwanan Europe and Jordan (see Štorch, 1996; Loydell, 2007), there being an early *ascensus–acuminatus* Biozone characterized by abundant *Akidograptus ascensus*, while *Normalograptus trifilis* and abundant *Parakidograptus acuminatus* appear at younger levels in the biozone. The base of the succeeding *vesiculosus* Biozone is here taken at the first appearance of the eponymous species, as generally elsewhere (Štorch, 1994: fig. 2): overlapping ranges for *P. acuminatus* and *Cystograptus vesiculosus* are not recorded in Saudi Arabia (cf. Štorch, 1996).

Chronostratigraphy Epoch	Stage	Age [Ma]	Saudi Arabia	North Africa	Czech Republic	United Kingdom
Llandovery (pars)	Telychian (pars)		*Spirograptus turriculatus*	*S. turriculatus–S. guerichi interval*	*Spirograptus turriculatus*	*Spirograptus turriculatus*
		436	*Spirograptus guerichi*		*Rastrites linnaei*	*Spirograptus guerichi*
	Aeronian		*Stimulograptus halli*	*Stimulograptus sedgwickii*	*Stimulograptus sedgwickii*	*Stimulograptus halli*
			Stimulograptus sedgwickii			*Stimulograptus sedgwickii*
			Lituigraptus convolutus	*Lituigraptus convolutus*	*Lituigraptus convolutus*	*Lituigraptus convolutus*
			Pribylograptus leptotheca	*“Pribylograptus leptotheca”*	*Pribylograptus leptotheca*	*Pribylograptus leptotheca*
			Neodiplograptus thuringiacus	*C. gregarius–P. libycus*	*D. simulans*	*Neodiplograptus magnus*
		439	*Demirastrites triangulatus*		*D. pectinatus–D. triangulatus*	*Demirastrites triangulatus*
	Rhuddanian		*Coronograptus cyphus*	*N. fezzanensis*	*Coronograptus cyphus*	*Monograptus revolutus*
			Cystograptus vesiculosus	*Neodiplograptus africanus*	*Cystograptus vesiculosus*	*Huttagraptus acinaces*
						Atavograptus atavus
			A. ascensus–P. acuminatus	*N. imperfectus to N. tilokensis*	*A. ascensus–P. acuminatus*	*A. ascensus–P. acuminatus*
		443.7	*N. lubricus*			

Fig. 14. Correlation of graptolite biozones for the Early Silurian (Llandovery) of Saudi Arabia with the graptolite biozonal schemes in North Africa (Libya, Štorch and Massa, 2006), United Kingdom (Zalasiewicz et al., 2009), and the Czech Republic (Štorch, 1994, 1996); data are also compiled from Loydell (2012)

CORRELATION OF THE *FEZZANENSIS* BIOZONE OF NORTH AFRICA

The graptolite assemblages of Saudi Arabia contain *Neodiplograptus fezzanensis* from the upper part of the *vesiculosus* Biozone, co-occurring with the earliest *Rhaphidograptus toernquisti, Metaclimacograptus undulatus* and *Glyptograptus tamariscus*. *N. fezzanensis* is widespread, occurring in the succession of North Africa (e.g., Legrand, 1979) and Central Europe (Štorch, 1996). Occurrence of *N. fezzanensis* within the *vesiculosus* Biozone suggests that in part, the *fezzanensis* Biozone of North Africa (see Štorch and Massa, 2006) correlates with the upper *vesiculosus* Biozone (Fig. 14). Štorch and Massa (2006) recorded *N. fezzanensis* with graptolites of the *cyphus* Biozone, though this has not been replicated in Saudi Arabia, and they considered the total range of *N. fezzanensis* to extend into the earliest Aeronian.

SUBDIVISION AND CORRELATION OF THE *SEDGWICKII* BIOZONE

Pannell et al. (2006) identified a discrete stratigraphical interval at the base of the *sedgwickii* Biozone in Scotland that was characterized by several peaks of abundance of *Neolagarograptus tenuis*. They suggested that these peaks might represent widely correlatable events. Elsewhere the interval of the lower *sedgwickii* Biozone has been identified as a discrete *tenuis* Subzone that is characterized by the abundance of the eponymous species, and which is recognized in Bohemia and North Africa (Štorch and Massa, 2006), and also in the lower part of the *sedgwickii* Biozone in Saudi Arabia. Pannell et al. (2006) suggested that this interval represented about 0.2 Ma, being of comparable duration to the subzones of the Telychian *guerichi* Biozone. This provides a highly resolved stratigraphy that allows correlation from palaeocontinental Gondwana at high southern palaeo-latitude to palaeocontinental Laurentia in the palaeo-tropics.

CORRELATION OF THE EARLY TELYCHIAN

The *guerichi* Biozone of the early Telychian is well-developed in Saudi Arabia, the interval being characterized by the common occurrence of the biozonal index species *Spirograptus guerichi*. This graptolite occurs in strata succeeding those of a well-defined *halli* Biozone that indicate its correlation with the *guerichi* Biozone of Wales (see Loydell, 1991, 1992, 1993). Strata bearing *S. guerichi* in Saudi Arabia succeed those with the earliest *Rastrites linnaei*, providing correlation with successions in continental Europe that identify a *linnaei* Biozone at this stratigraphic level (see Štorch and Loydell, 1992; Gutiérrez-Marco and Štorch, 1998). The lowermost part of the *guerichi* Biozone in Saudi Arabia does not usually bear the subzonal index fossil *Paradiversograptus runcinatus* (Lapworth). *P. runcinatus* has been found in low-diversity assemblages in lithofacies that seem to represent more inshore conditions. *P. runcinatus* is known from Wales (Loydell 1993), though Gutiérrez-Marco and Štorch (1998) noted the rarity of this graptolite in the Spanish succession, and chose to identify a combined *runcinatus–gemmatus* Subzone as the lowermost interval of the *linnaei* Biozone. We suggest that part of the low-diversity interval at the base of the *guerichi* Biozone in Saudi Arabia may equate to the *runcinatus* Subzone in Wales; in both areas it is succeeded by rocks that bear abundant *Monograptus gemmatus*, with this graptolite effecting a clear subzonal correlation between the Welsh and Arabian successions. Above the *gemmatus* Subzone in Saudi Arabia the *renaudi* Subzone can be recognized and this is probably an equivalent biostratigraphic level to the eponymous subzone in Wales (Loydell, 1992). As the *renaudi* Subzone in Saudi Arabia also contains *Parapetalolithus elongatus*, this suggests correlation with the *palmeus* Subzone of the *linnaei* Biozone in Spain (Gutiérrez-Marco and Štorch, 1998).

GRAPTOLITE BIOTOPES

Analysis of the temporal and spatial distribution of the graptolites in over 130 cores from Saudi Arabia identifies a persistent pattern of Llandovery age depth-stratified marine assemblages. These have been interpreted from their associated fauna and lithofacies and from knowledge of palaeo-basin bathymetry (Konert et al., 2001). These distribution patterns resemble those synthesized for Ordovician graptolites by Cooper and Sadler (2010 and references therein), who identified a surface-dwelling biotope occupying the euphotic zone of Ordovician oceans, analogous to the mixed layer of modern oceans, and, a deeper water biotope the distribution of which may have been controlled by oxygen-level and food supply, occupying the oxygen-minimum zone of Ordovician oceans, and bearing the typical assemblages of graptolitic black mudstones.

In general, boreholes from north-west Saudi Arabia (Fig. 2) penetrate black shale successions that record continuous deposition on a distal marine shelf, through several graptolite biozones. These cores preserve little evidence of burrowing benthos, or of shelly fauna. Typical associates of the graptolites are orthoconic nautiloids and small (pseudoplanktonic?) lingulate brachiopods. The graptolites in these marine settings are typically high-diversity assemblages, sometimes reaching 15 species on a single lamination surface in core. In the Aeronian and Telychian such assemblages are characterized by spirally and helically coiled species of *Lituigraptus* (*Li. richteri* and *Li. convolutus*), *Torquigraptus* (*T. involutus, T. linterni*), *Spirograptus* (*S. guerichi*) and *Rastrites* (*R. linnaei, R. maximus*). Graptolites of this assemblage are not found in more near-shore facies, or in regions of elevated basin topography where seawater depth shoaled.

Graptolites of a low-diversity, presumed surface-dwelling graptolite biotope are preserved with their deep-water counterparts in deep basin settings. That they were near-surface dwellers is suggested by their presence in more near-shore shelf environments of central and eastern Saudi Arabia, where a range of sand-dominated successions indicates the influence of prograding deltas active from the Early Silurian. They are preserved with an extensive benthic faunal assemblage (including trilobites, bivalves, brachiopods, burrows) on topographic highs within deeper basin settings in the northwestern area, where they can be used to determine palaeo-basin topography. These shallow biotope graptolites typically comprise species of *Normalograptus*, *Neodiplograptus* (*N. fezzanensis*), *Stimulograptus* (e.g., *S. sedgwickii, S. becki*), *Neolagarograptus* and *Coronograptus* (especially *C. gregarius*), with a diversity of generally one or two taxa at each horizon. Štorch and Massa (2006) have described similar assemblages from North Africa, contrasting these with the more richly diverse assemblages of peri-Gondwanan Europe. Graptolites of the presumed surface-dwelling biotope are often present as flow-aligned assemblages on lamination surfaces, presumably deposited from turbidity or storm-driven currents that formed on the shelf, transporting the graptolites basin-wards (Fig. 13).

Cooper and Sadler (2010) noted the overall stability of the surface-dwelling epipelagic graptolite biotope and its lower susceptibility to environmental perturbation from climatically induced changes to ocean circulation. By contrast, they noted that the deep-water biotope was susceptible to change, being widespread in stratified oceans during greenhouse climates, but disrupted by a thermohaline circulation during icehouse climate states. They noted the temporal longevity of taxa from the surface epipelagic biotope and equated this to environmental stability, a pattern that may also be present in some of the Silurian graptolites. Thus, graptolites of the surface-dwelling biotope recognized in Saudi Arabia include the long-lived *Coronograptus gregarius* (spanning five graptolite biozones), "*Paraclimacograptus*" *libycus* (spanning four), and *Stimulograptus sedgwickii* (spanning three). This biotope also contains short-lived, but closely related *Neolagarograptus* species such as *N. rickardsi* and *N. tenuis*.

GRAPTOLITE BIOGEOGRAPHY

Here we compare the biogeographical signature of the Saudi Arabian graptolites with contemporaneous faunas in North Africa, continental Europe and the UK. These areas represent palaeogeographical entities that were Gondwanan and peri-Gondwanan (e.g., the Perunica micro-continent for Bohemia), Avalonian and Laurentian, and which provide a latitudinal gradient from the southern high palaeo-latitudes to the palaeo-tropics (Fig. 15): this distribution can be used to assess some of the possible environmental and geographical control

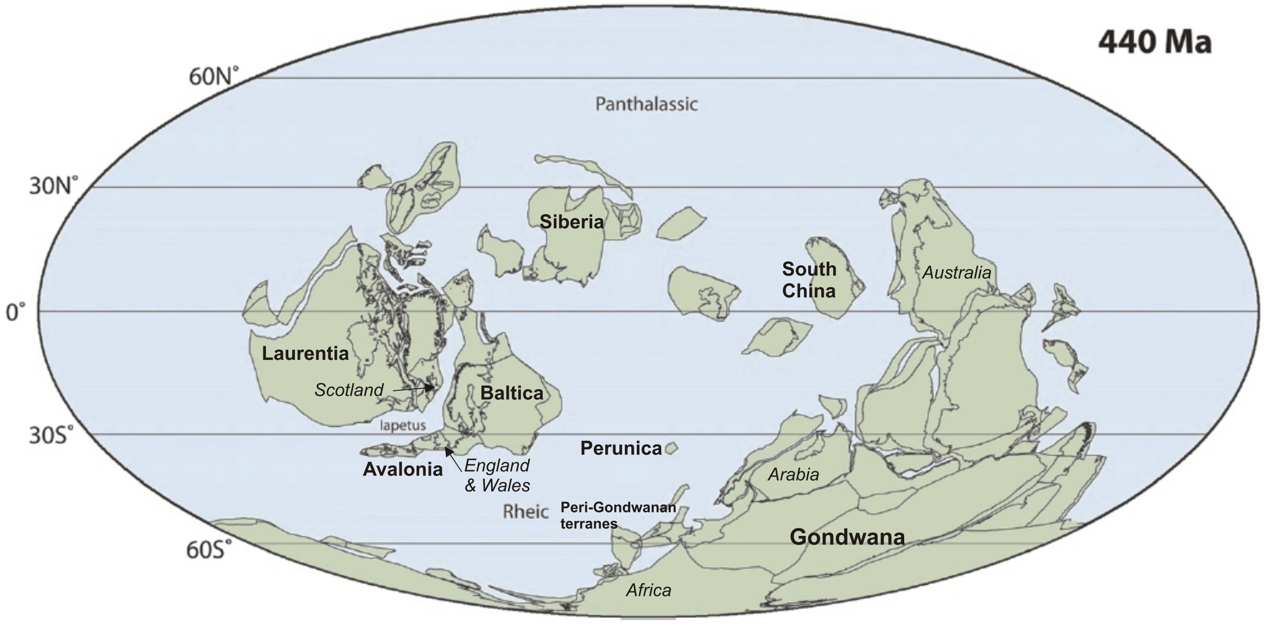

Figure 15. Early Silurian (Llandovery) palaeogeography (base map from Torsvik and Cocks, 2013)

Palaeocontinents are labelled in bold. Geographical areas are labelled in italics. The Iapetus, Rheic and Panthalassic oceans are also marked. Peri-Gondwanan terranes include Iberia, Armorica, Saxo-Thuringia and Perunica mechanisms on graptolite distribution. During the Silurian, Gondwana formed a large southerly landmass composed of Africa, South America, India, Australia, Antarctica and the Arabian Peninsula. This supercontinent straddled the palaeogeographical South Pole, but extended into mid-latitudes (Fig. 15): Saudi Arabia was situated at mid southern palaeo-latitude, between 30° to 50°S.

The early Rhuddanian graptolites of Saudi Arabia show a remarkably similar biogeographical motif to assemblages of peri-Gondwanan Europe (see Štorch, 1996). Especially at the level of the *ascensus–acuminatus* Biozone, these assemblages are often dominated by large *Neodiplograptus* species, particularly *N. parajanus, N. africanus, N. lanceolatus* and *N.* cf. *apographon*. Graptolites of this assemblage are well-documented from Jordan (Loydell, 2007), Spain, Germany, Austria and Bohemia (Štorch 1996: fig. 5). But, they are absent from the early Rhuddanian graptolite assemblages of Britain (e.g., Toghill, 1968; Zalasiewicz and Tunnicliff, 1994). Nevertheless, much of the graptolite fauna of the lowermost Rhuddanian in Saudi Arabia comprises taxa that occur also at lower palaeo-latitudes, including *Akidograptus ascensus, Normalograptus*? *parvulus, Normalograptus trifilis* and *Parakidograptus acuminatus*. These graptolites are used to zone the same interval in the Southern Uplands of Scotland, and therefore occupied the southern, ocean-facing margin of palaeo-tropical Laurentia (Fig. 15). Either these graptolites were deep-water forms whose distribution was not controlled by the surface-water temperature gradient; or they were eurythermic and not affected by this gradient; or, there was a low thermal gradient from the tropics to the poles in the deglacial interval following the Hirnantian icehouse. The latter scenario seems unlikely, as the distinct high to mid latitude *Neodiplograptus*-dominated assemblage present in Saudi Arabia and peri-Gondwanan Europe suggests a cool water surface assemblage adapted for these palaeo-latitudes, and this is not present at (warmer?) lower latitudes. Štorch (1996) has discussed distinct differences between the Gondwanan assemblages of the *ascensus–acuminatus* Biozone and other palaeogeographical entities including South China, Siberia and Kazakhstan, noting for example the abundance of metaclimacograptids in the assemblages of the Gorny Altai.

The persistence of a distinctive Gondwanan fauna in Saudi Arabia continues into the *vesiculosus* and *cyphus* biozones and is typified by *Neodiplograptus fezzanensis*, and in the early to mid Aeronian by "*Paraclimacograptus*" *libycus*. Nevertheless, this high latitude fauna is associated with post-*ascensus–acuminatus* cosmopolitan graptolites, that include at the level of the *vesiculosus* Biozone the pan-latitude species *Cystograptus vesiculosus, Rhaphidograptus toernquisti* and *Metaclimacograptus undulatus*, and in the *cyphus* Biozone, *Coronograptus cyphus, C. gregarius* and the *revolutus*-group monograptids. Distinctive Saudi Arabian faunas can still be identified within the Aeronian, and include at the level of the *leptotheca* Biozone an undescribed (apparently new) *Neolagarograptus* species. Biogeographical differences are also exemplified by the absence of *Campograptus harpago* (Törnquist) from Saudi Arabia (see Chopey-Jones et al., 2003: fig. 5) a taxon thought to characterize mid-latitude regions at this time. Nevertheless, much of the mid-Aeronian graptolite fauna of Saudi Arabia is indistinguishable at the species-level from the contemporaneous faunas of Bohemia (Štorch, 1994), Wales (e.g., Zalasiewicz, 1996) and Scotland (e.g., Chopey-Jones et al., 2003).

The incoming of *Neolagarograptus tenuis* characterizes the beginning of a late Aeronian and early Telychian interval in Saudi Arabia that is essentially composed of cosmopolitan taxa, which also occur at lower palaeo-latitude. Thus, the Saudi Arabian graptolite assemblage of the *sedgwickii* Biozone contains species that are also present in southern Scotland (Pannell et al., 2006; Williams et al., 2003), England (e.g., Hutt, 1975), Wales (Loydell, 1992, 1993) and Bohemia (Štorch, 1994). This pattern continues into the *halli* and *guerichi* biozones, enabling sub-zonal correlation between Wales and Saudi Arabia. More inshore shelf depositional successions in Saudi Arabia do not record graptolites in the *sedgwickii* Biozone (Zalasiewicz et al., 2007; Page et al., 2007), but this is not reflected in the continuous depositional successions of distal shelf settings in north-west Saudi Arabia where the *sedgwickii* Biozone is richly fossiliferous and contiguous with preceding *convolutus* and succeeding *halli* intervals. This adds weight to the suggestion of Loydell (1998: 454) that the lack of *sedgwickii* Biozone faunas in some areas (e.g., Bornholm, palaeocontinental Baltica, see Bjerreskov, 1975) may not represent a global sea level fall in the earliest *sedgwickii* Biozone, and this is counter to the idea of a *sedgwickii* Biozone glaciation (cf. Page et al., 2007). Instead, the absence of *sedgwickii* Biozone faunas from some areas may relate to local basin evolution. In Wales, as in Saudi Arabia, the *sedgwickii* Biozone is partly in black shales and is graptolitic (Zalasiewicz, 1990). But, the *sedgwickii*-bearing succession in Wales probably represents only part of the *sedgwickii* Biozone, with much of the rock interval in oxic, grey mudstones.

CONCLUSIONS

Analysis of graptolites from the Qusaiba Member, Qalibah Formation of Saudi Arabia, provides a refined graptolite biostratigraphy for the Arabian Peninsula. Over 150 graptolite species characterize 11 biozones from the base of the Llandovery to the lower Telychian *guerichi* Biozone. Graptolite spatial distribution suggests persistent depth-stratified assemblages, with low-diversity surface-dwelling assemblages characterized by species of *Neodiplograptus*, *Coronograptus*, *Neolagarograptus* and *Stimulograptus*, and higher diversity (up to 15 species per horizon), deeper marine assemblages typified by dorsally curved and helically coiled species of *Spirograptus, Demirastrites*, *Lituigraptus*, *Rastrites* and *Torquigraptus*. Biogeographically, the graptolite assemblages of Saudi Arabia are remarkably similar to contemporaneous faunas from peri-Gondwanan Europe and, from the mid-Rhuddanian onwards, with Avalonian and Laurentian faunas.

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