Geol. Mag. **149** (*1*), *2012, pp. 124–132.* © *Cambridge University Press 2011*
doi:10.1017/S0016756811000513

RAPID COMMUNICATION

Graptolite biozone correlation charts

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(*Received* 30 November 2010; *accepted* 5 April 2011; *first published online* 10 June 2011)

Abstract

Charts are presented showing the correlation of graptolite biozonations for the Lower Ordovician to Lower Devonian, i.e. for the entire stratigraphical range of the planktonic graptoloid graptolites. Regions chosen are those for which the most detailed biostratigraphical studies have been undertaken. For Baltica, average graptolite zone (chron) duration appears to vary from *c*. 300 000 years (Ludlow Epoch) to 2.4 Ma (Lochkovian Epoch).

Keywords: graptolite, biostratigraphy, Ordovician, Silurian, Devonian.

1. Introduction

The combination of rapid evolution, high numerical abundance, and in many cases wide geographical distribution has resulted in the planktonic graptoloid graptolites assuming pre-eminent significance in the biostratigraphical division of strata, particularly those representing outer shelf and deeper marine facies, of Ordovician to Early Devonian age.

At the 2008 meeting of the International Palaeontological Association's Graptolite Working Group (GWG) in the Czech Republic it was decided that it would be desirable and useful to produce a set of correlation charts of the graptolite biozonal schemes used on different (palaeo-)continents. The task fell to the author who distributed in the spring of 2009 preliminary versions of charts to GWG members for their comments. Minor corrections and additions were suggested and the resultant revised charts were presented at the 2009 meeting of the GWG in Sardinia. Following discussion at that meeting, a few further minor changes were made to the charts. Since the Sardinia meeting, further papers have been published (Feng *et al*. 2009; Maletz, Egenhoff & Alonso 2010; Maletz & Ahlberg, in press) and modifications made, resulting in the versions that are presented here.

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It is hoped that these charts will prove useful to both graptolite workers and all those who require precise and accurate correlations for their Palaeozoic research.

2. The charts

In the charts (Figs 1–8), columns are provided by series for those areas that have been most intensively studied; these may or may not be those with the best graptolite record. In many areas much fundamental descriptive taxonomic and biostratigraphical research remains to be done. The charts represent the current state of knowledge, to be improved upon as new research is undertaken and published.

In the majority of cases the column for any one series is a composite of biozones from a number of sections within the region indicated, e.g. for the Lower Ordovician of Laurentia (North America) the column combines the biozonations used in Newfoundland, Quebec and northern Yukon. The charts were constructed based upon data and correlations published within the references cited (and papers cited therein) in the figure captions for each chart. For Great Britain, the main source was the recent compilation by Zalasiewicz *et al*. (2009) of the published stratigraphical ranges (excluding those in abstracts) of all graptolite species. The global correlations in Gradstein, Ogg & Smith (2004) and for the Ordovician in Webby *et al*. (2004) have, where necessary, been amended and/or updated. The Chinese Ordovician columns are derived primarily from Zhan & Jin (2007) and Zhang *et al*. (2007). For the Middle Ordovician and Katian some correlations of graptolite biozones are based upon chitinozoans, using the data in Webby *et al*. (2004). Definitions of the various graptolite biozones in the charts can be found in the literature cited; the bases of the majority of graptolite biozones are defined by the first appearance of the index species: this is true, for example, of every one of the Llandovery biozones in the Avalonia+Baltica column (Fig. 4). In very rare cases an interval is defined by the disappearance of a biozonal index (at its base) and the lack of any diagnostic taxa within it. A good example is the *Pristiograptus dubius* Biozone of the

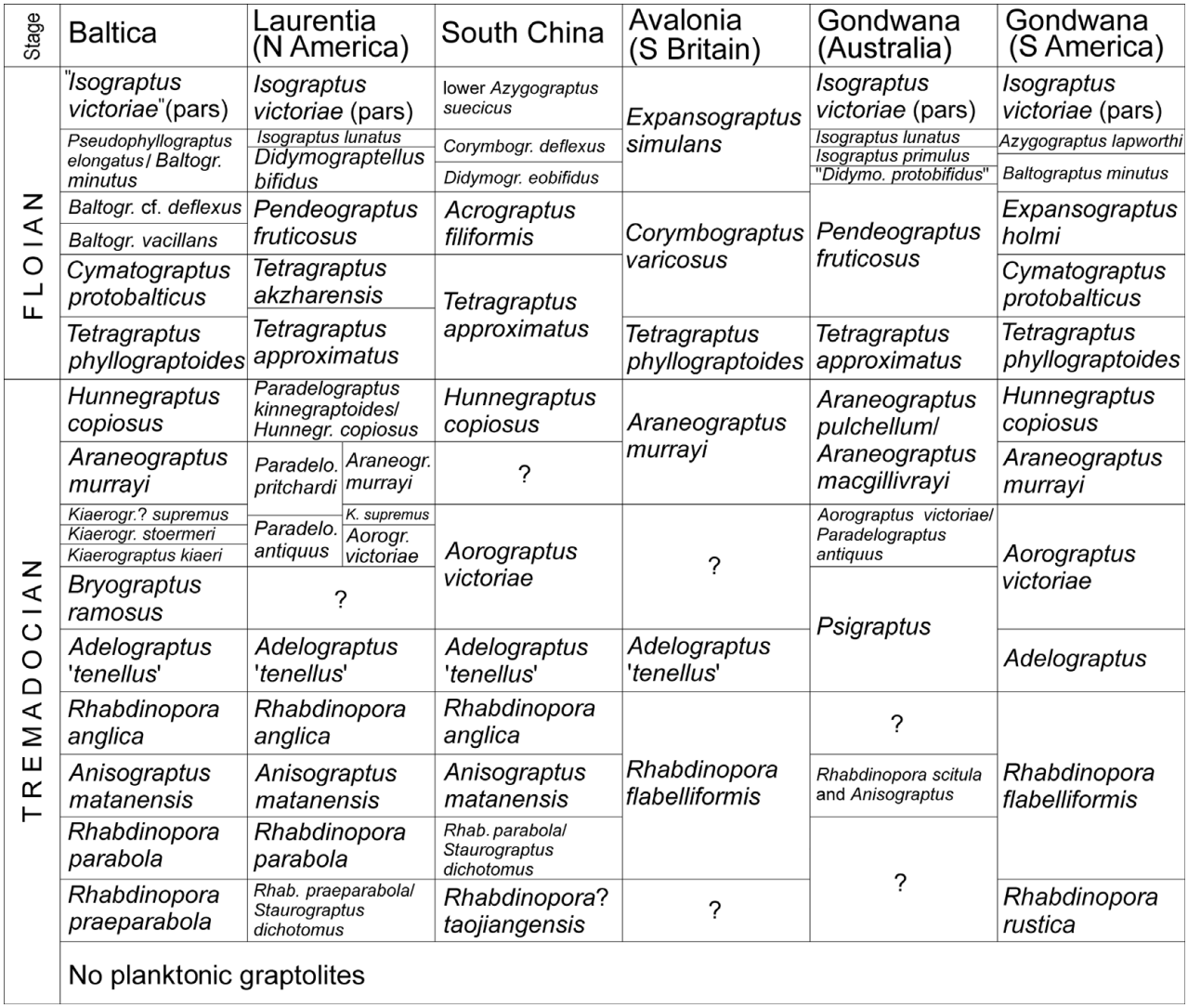

Figure 1. Correlation of Lower Ordovician graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Albanesi & Ortega (2002), Cooper (1999), Egenhoff, Maletz & Erdtmann (2004), Jackson & Lenz (2003), Lindholm (1991), Maletz & Ahlberg (in press), Maletz & Egenhoff (2001), Maletz, Egenhoff & Alonso (2010), Toro & Maletz (2008), Williams & Stevens (1988).

Wenlock (Fig. 5), characterized by extremely low diversity graptolite assemblages of long-ranging species (*P. dubius* itself appears in the *Monograptus firmus* Biozone). It is in intervals such as these that other fossil groups, particularly chitinozoans, have the potential to provide more precise biostratigraphical subdivision of graptolitic strata. Both of these types of graptolite biozones are interval zones as defined by the *International Stratigraphic Guide* (Salvador, 1994). A few, less precisely defined assemblage zones still exist, for example the *Diplograptus foliaceus* Biozone of the Sandbian (Fig. 3), but these are very much in the minority.

Where columns are split vertically (e.g. in Fig. 1, Laurentia; Fig. 2, South China), two different biozonal schemes, of different resolution, are used in the region concerned. A slash (/) is used to indicate biozones of approximate biostratigraphical equivalence. Single quotation marks around species' names and double quotation marks around taxon names indicate that taxonomic revision of the material upon which the biozone is based in the region concerned is required or that the biozonal index species is absent or identification is uncertain. Sub-biozones are not included in the charts: in some regions, at some stratigraphical levels (e.g. the Telychian), several of the biozones can be divided into a number of sub-biozones (see Zalasiewicz *et al*. (2009) for examples).

As research progresses, the stratigraphical resolution of graptolite biozones and precision in correlation will undoubtedly improve.

https://doi.org/10.1017/S0016756811000513 Published online by Cambridge University Press

Stage	Baltica	Laurentia (N America)	South China		Avalonia (S Britain)	Gondwana (Australia)	Peri-Gondwana (C+S Europe)
DARRIWILIAN	*Hustedograptus teretiusculus*	*Hustedograptus teretiusculus*	*Gymnograptus linnarssoni*		*Hustedograptus teretiusculus*	*Archiclimacograptus riddellensis*	*Hustedograptus teretiusculus*
	Pseudamplexograptus distichus	?	*Didymograptus murchisoni/ Pterograptus elegans*		*Didymograptus murchisoni*		*Didymograptus clavulus - Didymograptus murchisoni*
	Pterograptus elegans	*Pterograptus elegans*				*Pseudoclimacograptus? decoratus*	
	Nicholsonograptus fasciculatus	*Nicholsonograptus fasciculatus*	*Didymo. artus*	*Nichol. fascicul.*	*Didymograptus artus*		*Jenkinsograptus spinulosus - Didymograptus artus*
	Holmograptus lentus	*Holmograptus lentus*		*Acrogr. ellesae*		*Undulograptus intersitus*	
	?	*Undulograptus dentatus*	*Undulograptus intersitus*		*Aulograptus cucullus*		*Corymbograptus retroflexus*
	Undulograptus sinicus	*Undulograptus austrodentatus*	*Undulograptus austrodentatus*			*Undulograptus austrodentatus*	*Expansograptus hirundo*
	Arienigraptus zhejiangensis						
DAPINGIAN	"*Arienigraptus dumosus*"	*Oncograptus*	*Exigraptus clavus*		?	*Cardiograptus morsus*	
						Oncograptus upsilon	
	Maeandrograptus schmalenseei	*Isograptus maximus*	*Expansograptus hirundo/Isograptus imitatus*		*Isograptus gibberulus*	*Isogr. maximodivergens*	
						Isograptus maximus	*Azygograptus ellesae-Tetragraptus reclinatus abbreviatus*
	"*Isograptus victoriae*"(pars)	*Isograptus victoriae*	upper *Azygograptus suecicus*		*Isograptus victoriae* (pars)	*Isograptus victoriae*	

Figure 2. Correlation of Middle Ordovician graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Gutiérrez-Marco *et al*. (2002), Kraft & Kraft (1999), Maletz (1997*a,b*, 2005), Maletz & Egenhoff (2001), Maletz & Ahlberg (in press).

Stage	Baltica	Laurentia (Scotland)	South China	Laurentia (USA)	Gondwana (Australia)	Peri-Gondwana (C+S Europe)
HIRNANTIAN	'post-*persculptus*'	*Normalograptus persculptus*	*Normalograptus persculptus*	*Normalograptus persculptus*	*Normalograptus persculptus*	*Normalograptus persculptus*
	Normalograptus persculptus					
	?		*Normalograptus extraordinarius*	*Normalograptus extraordinarius*	*Normalograptus extraordinarius*	*Norm. extraordinarius - Norm. ojsuensis*
KATIAN	?	*Dicellograptus anceps*	*Paraorthograptus pacificus*	*Paraorthograptus pacificus*	*Paraorthograptus pacificus*	?
			Dicellogr. complexus	*Dicellograptus ornatus*	'pre-*pacificus*'	*Dicellograptus laticeps*
						?
	Dicellograptus complanatus	*Dicellograptus complanatus*	*Dicellograptus complanatus*	*Dicellograptus complanatus*	*Climacograptus uncinatus*	'*Diplograptus*' *vulgatus - Orthograptus lingulitheca*
	Pleurograptus linearis	*Pleurograptus linearis*	?	*Climacogratus tubuliferus*	*Dicellograptus gravis*	
					Dicranograptus kirki	
	Dicranograptus clingani	*Dicranograptus clingani*		*Diplacanthograptus caudatus*	*Diplacantho. spiniferus*	?
					Diplacantho.lanceolatus	
SANDBIAN	*Diplograptus foliaceus*	*Climacograptus bicornis*		*Climacograptus bicornis*	'*Orthograptus calcaratus* Group'	
	Nemagraptus gracilis	*Nemagraptus gracilis*	*Nemagraptus gracilis*	*Nemagraptus gracilis*	*Nemagraptus gracilis*	*Oepikograptus bekkeri*

Figure 3. Correlation of Upper Ordovician graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Finney *et al*. (1999), Goldman *et al*. (2007), Gutiérrez-Marco *et al*. (2002), Koren', Ahlberg & Nielsen (2003), Pålsson (2001, 2002), Štorch & Leone (2003), Štorch & Loydell (1996), VandenBerg & Cooper (1992). The Avalonian graptolite biozonation (Zalasiewicz *et al*. 2009, fig. 1) combines elements of the biozonations used in Baltica (*Nemagraptus gracilis* to *Pleurograptus linearis* biozones), in Scotland (*Dicellograptus anceps* Biozone) and globally (*Normalograptus persculptus* Biozone).

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<table>
<tr><th>Stage</th><th>Avalonia + Baltica</th><th>Peri-Gondwana (C+S Europe)</th><th>Laurentia (Arctic Canada)</th><th>Gondwana (NE Africa)</th><th>South China</th></tr>
<tr><td rowspan="14">TELYCHIAN</td><td>Cyrtograptus centrifugus</td><td>Cyrtograptus centrifugus</td><td>Cyrtograptus centrifugus</td><td rowspan="5">?</td><td rowspan="3">?</td></tr>
<tr><td>Cyrtograptus insectus</td><td>Cyrtograptus insectus</td><td>Cyrtograptus insectus</td></tr>
<tr><td>Cyrtograptus lapworthi</td><td>Cyrtograptus lapworthi</td><td>Cyrtograptus sakmaricus</td></tr>
<tr><td rowspan="2">Oktavites spiralis</td><td rowspan="2">Oktavites spiralis</td><td rowspan="4">"Monoclimacis griestoniensis"</td><td>Cyrtogr. lapworthi</td></tr>
<tr><td>Monoclimacis geinitzi</td></tr>
<tr><td>Monoclimacis crenulata</td><td>Torquigraptus tullbergi</td><td rowspan="4">Metaclimaco-graptus flamandi - Parapetalolithus meridionalis</td><td>Oktavites spiralis</td></tr>
<tr><td>Monoclimacis griestoniensis</td><td>Monoclimacis griestoniensis</td><td>Torquigraptus tullbergi</td></tr>
<tr><td>Streptograptus sartorius</td><td rowspan="2">Streptograptus crispus</td><td>"Monoclimacis griestoniensis"</td></tr>
<tr><td>Streptograptus crispus</td><td>Streptograptus crispus</td><td>Streptograptus exiguus</td></tr>
<tr><td>Spirograptus turriculatus</td><td>Spirograptus turriculatus</td><td>Spirograptus turriculatus</td><td rowspan="2">Spirograptus turriculatus + Spirograptus guerichi</td><td>Streptograptus crispus</td></tr>
<tr><td>Spirograptus guerichi</td><td rowspan="2">Rastrites linnaei</td><td>Spirograptus guerichi</td><td>Spirograptus turriculatus</td></tr>
<tr><td rowspan="6">AERONIAN</td><td>Stimulograptus halli</td><td rowspan="3">Stimulograptus sedgwickii</td><td rowspan="3">Stimulograptus sedgwickii</td><td rowspan="3">Stimulograptus sedgwickii</td><td>Spirograptus guerichi</td></tr>
<tr><td>Stimulograptus sedgwickii</td><td rowspan="3">?</td></tr>
<tr><td>Lituigraptus convolutus</td><td>Lituigraptus convolutus</td><td>Lituigraptus convolutus</td><td>Lituigraptus convolutus</td></tr>
<tr><td>Pribylograptus leptotheca</td><td>Pribylograptus leptotheca</td><td rowspan="3">Campograptus curtus</td><td>Pribylograptus leptotheca</td><td rowspan="3">Coronograptus gregarius</td></tr>
<tr><td>Neodiplograptus magnus</td><td>Demirastrites simulans</td><td rowspan="2">Coronograptus gregarius - Paraclimacograptus libycus</td></tr>
<tr><td>Demirastrites triangulatus</td><td>Demirastrites pectinatus - D.triangulatus</td></tr>
<tr><td rowspan="6">RHUDDANIAN</td><td>'Monograptus' revolutus</td><td rowspan="2">Coronograptus cyphus</td><td rowspan="2">Coronograptus cyphus</td><td>Neodiplograptus fezzanensis</td><td rowspan="2">Coronograptus cyphus</td></tr>
<tr><td rowspan="2">Cystograptus vesiculosus</td><td rowspan="2">Neodiplograptus africanus</td></tr>
<tr><td>Cystograptus vesiculosus</td><td>Huttagraptus acinaces</td><td rowspan="2">Cystograptus vesiculosus</td></tr>
<tr><td rowspan="2">Parakidograptus acuminatus - Akidograptus ascensus</td><td rowspan="2">Parakidograptus acuminatus</td><td rowspan="2">Parakidograptus acuminatus</td><td>Atavograptus atavus</td></tr>
<tr><td>Neodiplo. imperfectus</td><td rowspan="2">Parakidograptus acuminatus</td></tr>
<tr><td>Akidograptus ascensus</td><td>Akidograptus ascensus</td><td>Akidograptus ascensus</td><td>Neodiplo. incommodus</td></tr>
<tr><td></td><td></td><td></td><td></td><td>'Paraclimaco.' kiliani</td><td rowspan="2">Akidograptus ascensus</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Normalo. tilokensis</td></tr>
</table>

Figure 4. Correlation of Llandovery (Silurian) graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Chen (1984), Chen, Rong & Fan (2003), Fu, Zhang & Geng (2000), Legrand (2003), Loydell, Männik & Nestor (2003), Melchin (1989), Štorch (1994), Štorch & Massa (2006).

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Stage	Avalonia and Baltica	Peri-Gondwana (Europe)	Laurentia (Arctic Canada)
HOMERIAN	*Colonograptus ludensis*	*Colonograptus ludensis*	*Colonograptus ludensis*
	Colonograptus deubeli + C. praedeubeli	*Colonograptus deubeli + C. praedeubeli*	*Colonograptus deubeli + Co. praedeubeli*
	Gothograptus nassa	*Gothograptus nassa*	*Pristiograptus dubius/ Gothograptus nassa*
		Pristiograptus parvus	
	Cyrtograptus lundgreni	*Cyrtograptus lundgreni*	*Cyrtograptus lundgreni*
SHEINWOODIAN	*Cyrtograptus perneri*	*C. perneri/ C. ramosus*	*Cyrtogr. perneri/ Monogr opimus*
	Cyrtograptus rigidus	*C. rigidus/ M. belophorus*	*Monograptus instrenuus/ Cyrtograptus kolobus*
	Pristiograptus dubius	*"Pristiograptus dubius"*	
	Monograptus riccartonensis	*Monograptus riccartonensis*	
	Monograptus firmus	*Cyrtograptus murchisoni*	?
	Cyrtograptus murchisoni		

Figure 5. Correlation of Wenlock (Silurian) graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Lenz & Kozłowska-Dawidziuk (2002), Lenz & Melchin (1991), Loydell, Männik & Nestor (2003), Piras, Simonetto & Corradini (2008), Štorch (1994), Urbanek & Teller (1997). The base of the Wenlock Series is taken here for convenience as the base of the *Cyrtograptus murchisoni* Biozone. Based on chitinozoan evidence, the base of the Wenlock Series lies somewhere within the upper *Cyrtograptus centrifugus* to lower *Cyrtograptus murchisoni* Biozone interval (Mullins & Aldridge 2004).

3. Average graptolite zone (chron) duration

There are very few reliable radiometric dates for the Ordovician–Early Devonian interval. Using the timescale in Ogg, Ogg & Gradstein (2008) and the biozonation for Baltica as an example, approximate average graptolite zone (or chron) durations for each epoch/age are as follows: Early Ordovician: *c*. 1 Ma; Middle Ordovician: *c*. 1 Ma; Late Ordovician: *c*. 2 Ma; Llandovery: *c*. 800 000 years; Wenlock: *c*. 500 000 years; Ludlow: *c*. 300 000 years; Přídolí: *c*. 350 000 years; Lochkovian: *c*. 2.4 Ma; Pragian: *c*. 1 Ma. It is not known the extent to which these apparent variations in duration are a result of inadequacies in the construction of the time scale used and radiometric age dates upon which it is based, the amount of work conducted on graptolites from the series concerned, variations in rates of graptolite evolution, ease of identifying biostratigraphically useful taxa, and/or eustatic sea-level change, which in part controls the geographical extent of graptolite-bearing strata available for study.

Acknowledgements. The members of the Graptolite Working Group are thanked for their comments on earlier versions of the charts presented here. I thank also three anonymous referees for their constructive reviews.

<table>
<tr><th>Stage</th><th>Baltica</th><th>Peri-Gondwanan Europe</th><th>Laurentia (Arctic Canada)</th><th>Central Asian microplates</th></tr>
<tr><td rowspan="12">LUDFORDIAN</td><td>Uncinatograptus spineus</td><td rowspan="3">Pristiograptus fragmentalis</td><td rowspan="4">Formosograptus formosus</td><td rowspan="4">Formosograptus formosus/ Uncinatograptus spineus</td></tr>
<tr><td>Unicinatograptus protospineus</td></tr>
<tr><td>Uncinatograptus acer</td></tr>
<tr><td>Pseudomonoclimacis latilobus/ Slovinograptus balticus</td><td>Pseudomonoclimacis latilobus/ Slovinograptus balticus</td></tr>
<tr><td>Neocucullograptus kozlowskii</td><td>Neocucullograptus kozlowskii</td><td rowspan="5">Bohemograptus tenuis/ Bohemograptus praecornutus</td><td rowspan="2">Polonograptus podoliensis</td></tr>
<tr><td>Neocucullograptus inexpectatus</td><td>Neocucullograptus inexpectatus</td></tr>
<tr><td>Neolobograptus auriculatus</td><td rowspan="3">Bohemograptus tenuis</td><td rowspan="3">Bohemograptus tenuis</td></tr>
<tr><td>Bohemograptus cornutus</td></tr>
<tr><td>Bohemograptus praecornutus</td></tr>
<tr><td>Cucullo. aversus/ S. leintwardinensis</td><td>Saetograptus linearis</td><td>Saetograptus linearis/ 'Monograptus' ceratus</td><td>Saetograptus linearis</td></tr>
<tr><td rowspan="6">GORSTIAN</td><td>Cucullograptus hemiaversus</td><td rowspan="3">Lobograptus scanicus/ Saetograptus chimaera</td><td rowspan="3">Lobograptus scanicus</td><td rowspan="3">Lobograptus scanicus/ Saetograptus chimaera</td></tr>
<tr><td>Lobograptus invertus</td></tr>
<tr><td>Lobograptus parascanicus</td></tr>
<tr><td>Lobograptus progenitor</td><td>Lobograptus progenitor</td><td rowspan="2">Lobograptus progenitor</td><td rowspan="2">Lobograptus progenitor/ Colonograptus colonus</td></tr>
<tr><td>Neodiversograptus nilssoni</td><td>Neodiversograptus nilssoni</td></tr>
</table>

Figure 6. Correlation of Ludlow (Silurian) graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Koren' & Sujarkova (2004), Lenz & Kozłowska-Dawidziuk (2004), P. Štorch (pers. comm.), Urbanek & Teller (1997).

https://doi.org/10.1017/S0016756811000513 Published online by Cambridge University Press

Baltica (East European Platform)	Peri-Gondwanan Europe	Laurentia (Arctic Canada)	Central Asian microplates
Istrograptus transgrediens	*Istrograptus transgrediens*	*Istrograptus transgrediens*	*Istrograptus transgrediens sensu lato*
'*Monograptus*' *perneri*	'*Monograptus*' *perneri*		
'*Monograptus*' *bouceki*	'*Monograptus*' *bouceki*	'*Monograptus*' *bouceki*	
Istrograptus samsonowiczi	?	?	
Istrograptus chelmiensis			
Neocolonograptus lochkovensis	*Neocolonograptus lochkovensis*	*Neocolonograptus branikensis*	*Neocolonograptus branikensis*
Neocolonograptus ultimus	*Neocolonograptus ultimus* + *Neocolonograptus parultimus*	*Neocolonograptus ultimus*	*Neocolonograptus ultimus*
Neocolonograptus parultimus		*Neocolonograptus parultimus*	*Neocolonograptus parultimus*

Figure 7. Correlation of Přídolí (Silurian) graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Koren' & Sujarkova (1997), Kříž *et al*. (1986), Lenz & Kozłowska-Dawidziuk (2004), Urbanek & Teller (1997).

Stage	Baltica (East European Platform)	Peri-Gondwanan Europe	Laurentia (Yukon)	Central Asian microplates
PRAGIAN	?	'*Monograptus*' *yukonensis* + '*Monograptus*' *atopus*	'*Monograptus*' *yukonensis*	'*Monograptus*' *yukonensis*
	'*Monograptus*' *craigensis*			'*Monograptus*' *craigensis*
	'*Monograptus*' *fanicus*	?	'*Monograptus*' *fanicus*	'*Monograptus*' *fanicus*
	'*Monograptus*' *falcarius*		?	'*Monograptus*' *falcarius*
LOCHKOVIAN	'*Monograptus*' *hercynicus*	'*Monograptus*' *hercynicus*	'*Monograptus*' *hercynicus*	'*Monograptus*' *hercynicus*
	'*Monograptus*' *uniformis*	'*Monograptus*' *praehercynicus*	?	?
		'*Monograptus*' *uniformis*	'*Monograptus*' *uniformis*	'*Monograptus*' *uniformis*

Figure 8. Correlation of Lower Devonian graptolite biozones. Key references used in construction of the chart, in addition to those mentioned in the text: Chlupáč *in* Chlupáč *et al*. (1998), Koren' (1975, 1978), Lenz (1988), Lenz *et al*. (1996), Porębska (1984).

https://doi.org/10.1017/S0016756811000513 Published online by Cambridge University Press

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