

Supplementary information for

Late Ordovician zooplankton maps and the climate of the Early Palaeozoic Icehouse

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1. Re-plotting the early Sandbian sites using the bugPlates palaeogeography

Table S1 lists the differences between the palaeolatitudes of the sites in different palaeogeographical reconstructions. Both the maximal discrepancy between the three reconstructions under scrutiny, and the difference between the PALEOMAP (used by Vandenbroucke *et al.* 2009, 2010a) and BugPlates (this chapter) are given. The table shows that the differences in the position of our localities between the BugPlates and PALEOMAP reconstructions are usually within our defined 5° bin of palaeolatitudinal error, with the exception of site-clusters where the palaeogeographical error is systematically larger, i.e. (i) a group of localities in Laurentia; (ii) localities on Avalonia; and (iii) most localities on Gondwana. Laurentia straddles the equator in both plate reconstructions, but is rotated some degrees counter clockwise in the PALEOMAP reconstruction compared to BugPlates. This places localities from the western US into the Southern Hemisphere on the BugPlates reconstruction. The position of other localities in Laurentia, whose palaeolatitudinal position is more precisely fixed (e.g. around Quebec), but which have species of the same biotopes (i.e. C1, C2, I, see below) compensates for this error on the biotope position. The error introduced by variation on the Gondwanan localities (that are offset by 10° between PALEOMAP and BugPlates) is within the published error on the location of the Polar Front. The relative position of Avalonia in the two reconstructions causes up to 18° of variance in the inferred latitudinal position of these localities. Of the three areas, Avalonian localities thus are palaeogeographically less well constrained and these sites are not used to pinpoint the positions of important climate boundaries, such as the Polar Front.

localities	graptolite (g) or chitinozoan (c) site	Point tracker palaeolatitude (Scotese's PALEOMAP)	Cocks & Torvik (2004) palaeolatitude (°S)	Buglulates (2009) Palaeolatitudes (°S)	Max discrepancy	Difference between the Buglulates and Scotese reconstructions	large areas with palaeogeographical error > 5° bins
Australasia	g	14° N	15° N	13° N	2	1	1
Peel Rivers (Canada)	g	9° N	15° N	16° N	7	7	
Basin Ranges (California, Nevada, Utah & Idaho)	g	6° S	5° N	5° N	11	11	
Trail Creek (Idaho, USA)	g	6° S	5° N	4° N	11	10	
HD Range (Nevada, USA)	g	7° S	5° N	4° N	12	11	
Marathon(Texas, USA)	g	20° S	5° S	8° S	15	12	
Ouachitas Mountains (Oklahoma/Arkansas, USA)	g	24° S	10° S	13° S	14	11	
Tennessee (Pierce, Ridley Limestone, USA)	c	28° S	15° S	18° S	13	10	
Southern Appalachians (Lenoir – Chickamauga Limestone, and Pratt Ferry: Athens Shale Fm., USA)	c	29° S	15° S	19° S	14	10	
S. Apalachians (Alabama, Georgia, Tennessee, Virginia, USA)	g	30° S	15° S	19° to 23° S	15	9	
Quebec city area (citadel Fm, Canada)	c + g	27° S	20° S	20° S	7	7	
Southern Uplands (Scotland)	g	21° S	20° S	20° S	1	1	
Gaspé North Shore (Canada)	g	26° S	20° S	20° S	6	6	
Girvan (Superstes Mudst. /Stinchar Lmst., UK)	c	23° S	20° S	21	3	2	
Gaspé Peninsula	c	24° S	20° S	21	4	3	
Anticosti Island (NACP, Canada)	c	26° S	20° S	21	6	5	
Benan Burn and Craigmalloch Fm. (Girvan, Scotland)	g	23° S	20° S	21° S	3	2	
Curraie Formation (Southern Uplands, Scotland)	g	23° S	20° S	21° S	3	2	
Belle Brook (New Brunswick, Canada)	g	27° S	20° S	22° S	7	5	
Normanskill Shale (New York, USA)	g	30° S	20° S	22° S	10	8	
Lawrence Harbour Shale (Newfoundland)	g	26° S	23° S	24° S	3	2	
Sweden (central confacies belt)	c + g	35° S	35° S	36° S	1	1	
Fågelsång-Koängen composite (S. Sweden)	c + g	38° S	37° S	37° S	1	1	
North Estonia	c + g	34° S	38° S	37° S	4	3	
West Estonia	c	35° S	38° S	37° S	3	2	
Atocha (Bolivia)	g	43° S	35° S	37° S	8	6	
South Estonia	c + g	35° S	39° S	38° S	4	3	
Latvia	c + g	37° S	40° S	39° S	3	2	
Leba region (NW Poland)	c + g	39° S	40° S	39° S	1	0	
Chaquimayo (Peru)	g	47° S	35° S	40° S	12	7	
Koszalin-Chojnice area, Pomerania (Poland)	c	39° S	40° S	40° S	1	1	
Pomerania (Poland)	g	39° S	40° S	39° S	1	0	
Poland (Baltic compilation)	c	40° S	40° S	42° S	2	2	
Ukraine	c	42° S	42° S	45° S	3	3	
Anglo Welsh Basin and Shropshire (Shelve Inlier)	c + g	56° S	40° S	47° S	16	9	
Rügen Wells (Germany)	c + g	54° S	40° S	48° S	14	6	
Condroz Inlier (Belgium)	c	59° S	45° S	51° S	14	8	
Rheinisches Schiefergebirge (Germany)	c + g	58° S	40° S	51° S	18	7	
SE Turkey (Arabian plate)	c	44° S	55° S	54° S	11	10	
Kilgen Lake Fm (Taurides, Turkey)	c + g	51° S	60° S	58° S	9	7	
Armorican Massif (Brittany, France)	c + g	69° S	77° S	78° S	8	9	
Bucaco (Portugal)	c + g	74° S	77° S	79° S	5	5	
Iberain Ranges (NE Spain)	g	72° S	77° S	79° S	7	7	
Sueve Shale Formation (Asturias, Spain)	c	70° S	77° S	82° S	12	12	
NE Algeria (NL2 well)	c	75° S	85° S	84° S	10	9	
Anti Atlas (Morrocco)	c	82° S	85° S	87° S	5	5	
Precordillera (Los Azules Fm., Argentina)	c	-35°02	-25°		10	*	
Precordillera (Argentina)	g	-33°	-25°		8	*	

Average: 7.4 5.7

* excluded from analysis

Table 1. Differences (in degrees of latitude) between the palaeolatitudes of the sites in different palaeogeographical reconstructions – See text for full explanation

2. Re-plotting and re-interpreting biotopes using the BugPlates palaeogeography

We re-plot the groups of species obtained by TWINSPAN multivariate analyses (Vandenbroucke *et al.* 2009, 2010a) on the new BugPlates palaeogeographical reconstructions: this re-defines the latitudinal ranges of the zooplankton biotopes (based on their latitudinally short ranging species). The biotopes are then compared to a hypothetical plankton model for the Sandbian (Textfig. 4). The latter models were constructed (Vandenbroucke *et al.* 2009, 2010a) by mapping the SST-controlled boundaries of modern zooplanktonic (foraminifer) provinces (Kucera 2007) onto the SST maps derived from the Sandbian GCM at different parameterizations (Herrmann *et al.* 2004a).

In keeping with our previous studies, chitinozoan biotope IVa and generalist species groups have not been retained for the discussion (Vandenbroucke *et al.* 2009, 2010a). The other biotopes are grouped in biogeographical provinces (see text-figure 4); their overall distribution pattern fits best with the model at 8x PAL $p\text{CO}_2$ (the alternative interpretation of the climate belt attribution for the biotopes can be read from text-figure 4). This comparison allows us to interpret the patterns in terms of palaeoclimatological belts.

Equator-wards of the major divide in our plankton data, graptolite biotopes C1, C2, D1-D3 represent the Tropical biotopes. Chitinozoan biotope I, as well as graptolite biotopes C3, C4, D4 and D5 represent the Subtropical biotopes. To the south of the transition zone, wide-ranging graptolite biotope A and chitinozoan biotope III represent mixed Subpolar and Polar species. Chitinozoan biotopes IIa and IVb are Subpolar.

Biotopes IVc (chitinozoans) and C7 (graptolites) are less straightforwardly attributed: they could represent either Polar or Subpolar waters. The position of this biotope is defined by the palaeogeographical position of Avalonian localities. These are, as indicated above, rather different in the various reconstructions, such that their fauna would be indicative of Subpolar waters on the maps by Cocks & Torsvik (2002; Avalonia at $\sim 40^\circ\text{S}$), of Polar waters on the maps by Scotese (PALEOMAP; Avalonia at $\sim 56^\circ\text{S}$ according to Point tracker), or of an intermediate (though rather Subpolar) position on the maps used in this study (BugPlates, Avalonia at $\sim 47^\circ\text{S}$). It follows that localities on this palaeocontinent of Avalonia might not be sufficiently reliable to pinpoint the position of the Polar Front in the Late Ordovician, so these have been given little weight in our analyses.

In contrast, chitinozoan biotope IIb represents a true Polar biotope (and could thus be used to indicate the Polar Front). However, the most equator-wards extension of this biotope can be at 44°S , 50°S or 54°S . The extension to 44°S is represented by the sole occurrence of a single species and is likely untenable. The extension to 50°S is due to a single species occurrence in an Avalonian locality, which we consider unreliable as the exact position of the Polar Front. The extension to 54°S is also due to a single species, but one that has more occurrences towards the South Pole. More Polar species appear in the database

south of 78°S, immediately south of a wide gap of 20° of latitude without chitinozoan data. As a consequence, the northerly boundary of the Polar biotope (i.e. the Polar Front) remains ill-constrained between 55°S and 80°S (but likely 55°-75°S).

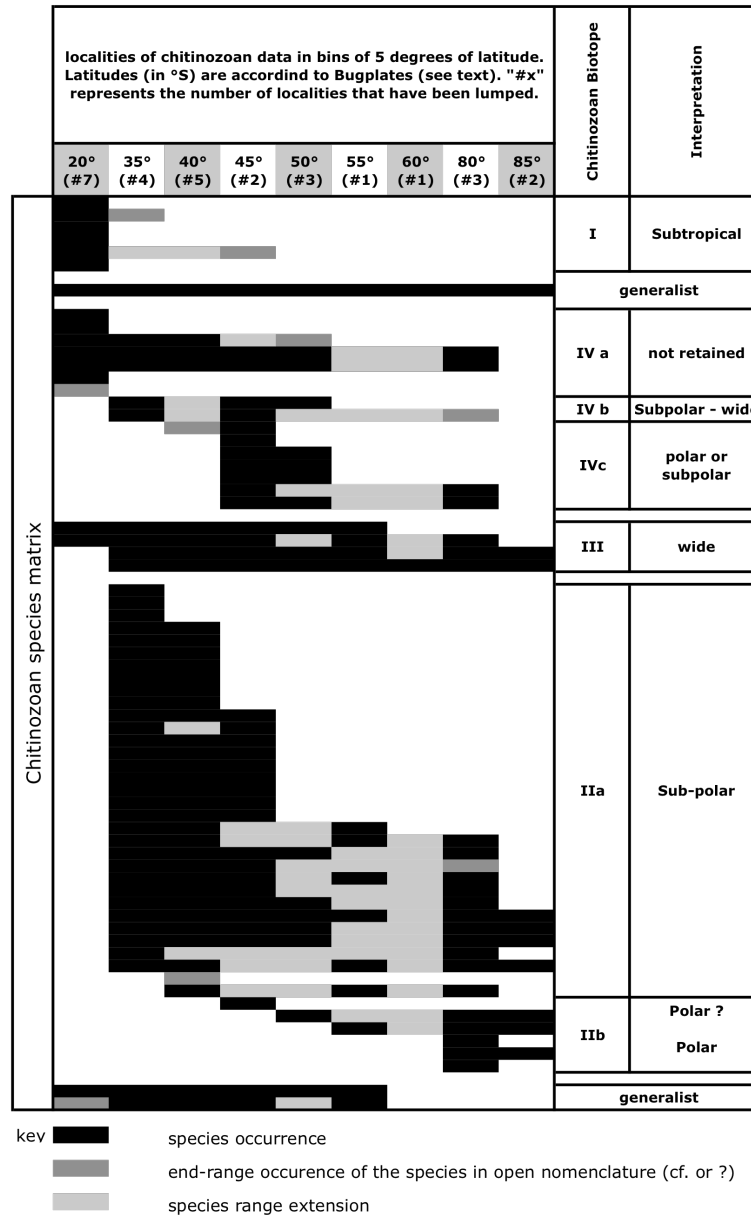


Figure S1. Chitinozoan matrix for the early Sandbian *gracilis* time-slab, with localities lumped in 5° bins. The TWINSPAN groups are those of Vandenbroucke et al. (2010a). Biotopes within the TWINSPAN groups are identified by constrained seriation. Baltoscandian ramp localities at 35°S and 40°S are not considered separate for the biotope clustering and the interpretation (cf. Vandenbroucke et al. 2010a). Each rectangle represents the occurrence of a species at a site (see legend). The species identities are not detailed here for reasons of reproducibility, but they are listed below, in section 3 of these supplementary files. Also see the supplementary material S3 for a full and scalable version of this figure, including all the localities and species. Differences between the biotopes in this figure and those in figure 7 of Vandenbroucke et al. (2010a) are listed in Table S2.

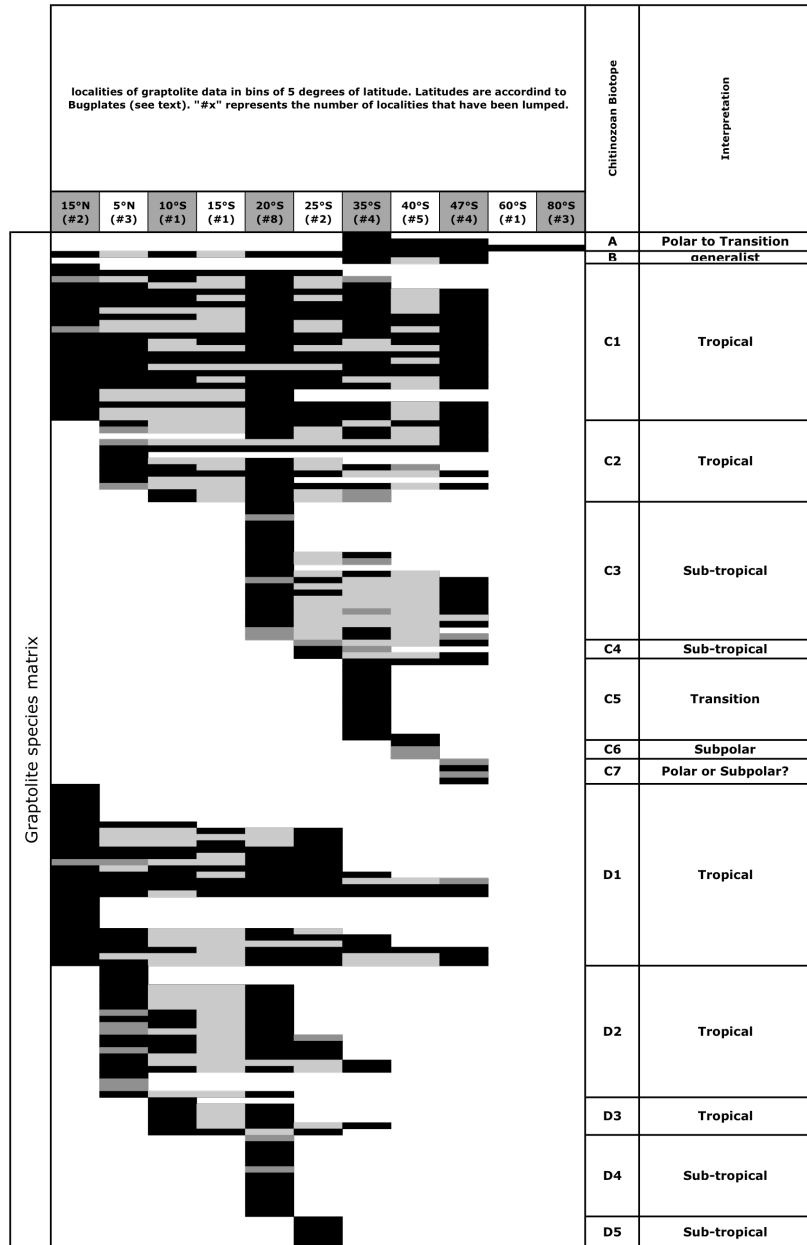


Figure S2. Simplified graptolite matrix for the early Sandbian *gracilis* time-slab. TWINSPAN groups are those of *Vandenbroucke et al. (2009)*. See *Figure S1* for key. See section 3 of these supplementary files for the species identifications and see supplementary materials *S4* for a full and scalable version of this figure, including all the localities and species. Differences between the biotopes in this figure and those of *Vandenbroucke et al. (2009)* are listed in *Table S2*.

Chitinozoan species	biotope Vandenbroucke et al. 2010	biotope this study
<i>Desmochitina angulata</i>	IIa	IIb
<i>Lagenochitina ponceti</i>	IIa	IIb
<i>Conochitina homoclaviformis</i>	IVb	IVc
<i>Hercochitina volkheimerii</i>	I	-
Graptolite species	biotope Vandenbroucke et al. 2009	biotope this study
<i>Dicellograptus patulosus</i>	C3	C2
<i>Leptograptus validus incisus</i>	C3	C2
<i>Ensigraptus caudatus</i>	C4	C3
<i>Dicranograptus kirki</i>	C5	-
<i>Dicranograptus spiniferus</i>	C5	-
<i>Nanograptus phylloides</i>	C5	C6
<i>Amplexograptus rugosus</i>	C6	C5
<i>Azygograptus mobergi</i>	C6	C5
<i>Climacograptus haddingi</i>	C6	C5
<i>Climacograptus putillus</i> (Hadding non Hall)	C6	C5
<i>Dicellograptus pumilus</i>	C6	C5
<i>Diplograptus propinquus</i>	C6	C5
<i>Diplograptus toernquisti</i>	C6	C5
<i>Glossograptus scanicus</i>	C6	C5
<i>Janograptus laxatus</i>	C6	C5
<i>Lasiograptus spinatus</i> Hadding	C6	C5
<i>Nemagraptus gracilis remotus</i>	C6	C5
<i>Orthograptus truncatus truncates</i>	D5	D4
<i>Azygograptus simplex</i>	D5	D4
<i>Climacograptus phyllophorus</i>	D5	D4
<i>Dicellograptus divaricatus rectus</i>	D5	D4
<i>Dicellograptus mensurans</i>	D5	D4
<i>Dicranograptus furcatus exilis</i>	D5	D4
<i>Dicranograptus nicholsoni diapason</i>	D5	D4
<i>Dicranograptus spinifer geniculatus</i>	D5	D4
<i>Glossograptus ciliatus</i> 'var.' <i>debilis</i>	D5	D4

Table S2. Differences between the species content of biotopes in this study and those of Vandenbroucke et al. (2009, 2010a).

3. Biotopes & provinces

A. Chitinozoan biotopes

TWINSPAN group I = Biotope I (Subtropical province)

Belonechitina nevellensis, *Calpichitina megastrophica*, *Lagenochitina* sp. A sensu Achab, *Cyathochitina jenkinsi*, *Belonechitina hirsuta* sensu Achab, *Kalochitina multispinata*.

TWINSPAN group II

Biotope IIa (Subpolar province): *Belonechitina pellifera*, *Conochitina tigrina*, *Cyathochitina jaanussoni*, *Cyathochitina latipatagium*, *Spinachitina tvaerensis*, *Calpichitina lecaniella*, *Belonechitina cactacea*, *Conochitina tuberculata*, *Calpichitina complanata*, *Conochitina savalaensis*, *Conochitina viruana*, *Desmochitina amphorea*, *Desmochitina rugosa*, *Pistillachitina ex gr differens*, *Pterochitina retracta*, *Spinachitina suecica*, *Desmochitina elongata*, *Laufeldochitina* sp. A aff. *striata*, *Angochitina curvata*, *Armoricochitina granulifera*, *Laufeldochitina stentor*, *Lagenochitina* sp. A aff. *capax* sensu Grahn et al. (1996), *Eisenackitina rhenana*, *Desmochitina ovulum*, *Desmochitina erinacea*, *Desmochitina piriformis*, *Lagenochitina deunffi*, *Euconochitina primitiva*, *Lagenochitina dalbyensis*, *Cyathochitina hunderumensis*, *Desmochitina nodosa*, *Eisenackitina* sp. 1 sensu Vandenbroucke (2004) and *Spinachitina bulmani*.

Biotope IIb (Polar): *Desmochitina angulata*, *Lagenochitina ponceti*, *Pistillachitina pistillifrons*, *Conochitina claviformis*, and *Linochitina mayensis*.

TWINSPAN group III (wide-ranging Subpolar-Polar province)

Conochitina elegans, *Cyathochitina kuckersiana*, *Belonechitina capitata*, *Conochitina lepida* and *Desmochitina cocca*.

TWINSPAN group IV

Biotope IVa (excluded): *Belonechitina wesenbergensis brevis*, *Belonechitina micracantha*, *Belonechitina seriespinosa*, *Calpichitina lata*, *Conochitina tribulosa*, *Belonechitina wesenbergensis*, *Belonechitina robusta*.

Biotope IVb (wide-ranging Subpolar-Polar province): *Eisenackitina ?rhenana*, *Eisenackitina inconspicua*.

Biotope IVc (Subpolar of Polar province?): *Belonechitina vulgaris*, *Conochitina parviverter*, *Conochitina homoclaviformis*, *Belonechitina brittanica*, *Cyathochitina sp.1*, *Conochitina aff. homoclaviformis sensu Vandenbroucke (2008)*, *Conochitina chydaea*.

B. Graptolite biotopes

TWINSPAN group A

Climacograptus brevis mutabilis, *Orthograptus uplandicus* and *Oepikograptus bekkeri*.

TWINSPAN group B

Dicellograptus divaricatus salopiensis, *Diplograptus molestus*.

TWINSPAN group C

Biotope C1: *Corynoides serpens*, *Dicellograptus divaricatus rigidus*, *Dicellograptus moffatensis alabamensis*, *Dicranograptus nicholsoni longibasalis*, *Glossograptus armatus*, *Orthograptus calcaratus calcaratus*, *Cryptograptus tricornis schaeferi*, *Cryptograptus tricornis tricornis*, *Dicellograptus divaricatus divaricatus*, *Dicellograptus intortus*, *Dicellograptus sextans sextans*, *Dicranograptus irregularis*, *Nemagraptus gracilis gracilis*, *Normalograptus brevis*, *Acrograptus superstes*, *Amplexograptus arctus*, *Climacograptus antiquus antiquus*, *Climacograptus bicornis bicornis*, *Dicranograptus nicholsoni nicholsoni*, *Glossograptus hincksii fimbriatus*, *Glossograptus hincksii hincksii*, *Lasiograptus harknessi costatus*, *Normalograptus euglyphus euglyphus*, *Pseudoclimacograptus scharenbergi scharenbergi*, *Reteograptus geinitzianus*.

Biotope C2: *Dicranograptus ziczac*, *Thamnograptus capillaris*, *Hallograptus bimucronatus*, *Archiclimacograptus modestus*, *Dicranograptus rectus*, *Hustedograptus teretiusculus*, *Orthograptus quadrimucronatus whitfieldi*, *Amplexograptus perexcavatus*, *Corynoides curtus curtus*, *Lasiograptus pusillus*, *Dicellograptus patulosus*, *Leptograptus validus incisus*.

Biotope C3: *Dicranograptus cyathiformis*, *Dicranograptus tardiusculus*, *Diplograptus compactus*, *Hallograptus mucronatus nobilis*, *Leptograptus ascendens*, *Nemagraptus pertenus*, *Thamnograptus scoticus*, *Dicranograptus celticus*, *Lasiograptus harknessi harknessi*, *Leptograptus flaccidus flaccidus*, *Leptograptus grandis*, *Diplograptus notabilis*, *Climacograptus antiquus lineatus*, *Dicellograptus geniculatus*, *Dicranograptus brevicaulis*, *Diplograptus foliaceus*, *Diplograptus leptotheca*, *Leptograptus validus validus*, *Nemagraptus subtilis*, *Ensigraptus caudatus*, *Orthograptus apiculatus*, *Dicranograptus furcatus minimus*.

Biotope C4: *Corynoides curtus pristinus*, *Dicellograptus cambriensis*, *Haddingograptus eurystoma*.

Biotope C5: *Leptograptus flaccidus macer*, *Normalograptus kuckersianus*, *Amplexograptus rugosus*, *Azygograptus mobergi*, *Climacograptus haddingi*, *Climacograptus putillus* (Hadding non Hall), *Dicellograptus pumilus*, *Diplograptus propinquus*, *Diplograptus toernquisti*, *Glossograptus scanicus*, *Janograptus laxatus*, *Lasiograptus spinatus Hadding*, *Nemagraptus gracilis remotus*.

Biotope C6: *Nanograptus lapworthi*, *Normalograptus minimus*, *Nanograptus phylloides*.

Biotope C7: *Archiclimacograptus caelatus*, *Climacograptus cf. putillus* (Hall), *Climacograptus sheldoni*, *Didymograptus euodus*.

TWINSPAN group D:

Biotope D1: *Climacograptus brevis strictus*, *Climacograptus cruciformis*, *Corynoides australis*, *Glossograptus acanthus*, *Glossograptus ovatus*, *Lasiograptus asiaticus*, *Nicholsonograptus fasciculatus*, *Orthograptus expansus*, *Paraglossograptus tentaculatus*, *Pseudoclimacograptus scharenbergi angulatus*, *Reteograptus speciosus*, *Pseudoclimacograptus riddellensis*, *Archiclimacograptus stenostoma*, *Azygograptus incurvus*, *Dicellograptus bispiralis bispiralis*,

Kalpinograptus lyra, *Dicranograptus furcatus*, *Dicranograptus ramosus longicaulis*, *Dicellograptus gurleyi gurleyi*, *Leptograptus flaccidus trentonensis*, *Climacograptus bicornis tridentatus*, *Corynoides calicularis*, *Orthograptus calcaratus vulgatus*, *Dicellograptus sextans exilis*, *Dicranograptus ramosus ramosus*, *Dicranograptus ramosus spinifer*, *Glossograptus ciliatus ciliatus*, *Hallograptus mucronatus mucronatus*, *Orthograptus calcaratus acutus*.

Biotope D2: *Climacograptus spiniferus*, *Dicranograptus nicholsoni whitianus*, *Trigonograptus martelii*, *Dicranograptus nicholsoni geniculatus*, *Glossograptus horridus*, *Neurograptus margaritatus*, *Orthograptus calcaratus basilicus*, *Climacograptus bicornis peltifer*, *Climacograptus eximius*, *Dicellograptus divaricatus bicurvatus*, *Dicellograptus smithi*, *Dicranograptus contortus*, *Didymograptus serratulus*, *Diplograptus multidens* 'var.' *diminutus*, *Nemagraptus exilis exilis*, *Nemagraptus exilis linearis*, *Nemagraptus gracilis* 'var.' *surcularis*, *Normalograptus euglyphus pygmaeus*, *Orthograptus calcaratus incisus*, *Diplograptus multidens multidens*, *Corynoides incurvus*.

Biotope D3: *Orthograptus calcaratus alabamensis*, *Climacograptus modestus meridionalis*, *Dicellograptus gurleyi exilis*, *Dicranograptus nicholsoni parvangulus*, *Didymograptus subtenuis*, *Corynoides tricornis*.

Biotope D4: *Amphigraptus divergens*, *Climacograptus parvus*, *Didymograptus sagitticaulis*, *Dicellograptus sextans* 'var.' *perexilis*, *Orthograptus truncatus truncatus*, *Azygograptus simplex*, *Climacograptus phyllophorus*, *Dicellograptus divaricatus rectus*, *Dicellograptus mensurans*, *Dicranograptus furcatus exilis*, *Dicranograptus nicholsoni diapason*, *Dicranograptus spinifer geniculatus*, *Glossograptus ciliatus* 'var.' *debilis*,

Biotope D5: *Corynoides americanus*, *Cryptograptus marcidus*, *Dicranograptus clingani*, *Nemagraptus linmassiae*, *Pseudoclimacograptus angulatus angulatus*.

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