1. SI Materials and Methods. 1.1 Time slice definition. Our time slice is
defined to enable optimum correlation of events and data associated
with the Hirnantian glacial maximum (Fig. S1). Chitinozoan
taxa have been included from (i) the Tanuchitina elongata Biozone
(Gondwana) and/or, (ii) the Belonechitina gamachiana Biozone
(Laurentia/Baltica/Avalonia?) and/or, (iii) the lower part of the
Spinachitina taugourdeaui Biozone (Laurentia/Baltica/Avalonia)
and/or, (iv) the Belonechitina reticulatus biozone (Avalonia)
and/or, (v) the Ordochitina nevadensis biozone (Laurentia)
and/or, (vi) the Nevadachitina vininica biozones biozone (Laurentia)
and/or, (vii) the Nezavellia bergstroemi Biozone (Gondwana)
and/or, (viii) the lowermost part of the Spinachitina oulebsiri
Biozone (Gondwana, i.e., where elements of the T. elongata and
the lower S. oulebsiri zones overlap). These are the time equiva-
lents of the Normalograptus extraordinarius and lower Normalo-
graptus persculptus graptolite biozones and the $^{13}$C excursion
that geochronologically characterizes the Hirnantian glaciation.
T. elongata zone chitinozoans are typically recovered from glacial
diamictites in N. Gondwana. Correlations largely follow Melchin
and Holmden (1 and references therein), with additions (2, 3).

1.2 Data and literature sources. The presence-absence chitinozoan
data is predominantly taken from the literature; the locality infor-
mation and relevant literature sources are summarized below.
This dataset is aimed at being representative, though nonexhaus-
tive, for the T. elongata species; care has been taken to select contemporary species.

The data are from Paris and Le Pochat (10, p. 409) and Paris et
al. (11) who report C. lenticularis and A. nigerica from diamictites
from the Soubirous Formation in the Aquitaine Basin.

Bou Ingarf reference section, Zagora area, Morocco.
Present-day coordinates: N 30° 35′; W 5° 33′ (Bou Ingarf,
Tazzarre trail section Morocco)
Paleolatitude (Bugplates): 70° S

The data are taken from Bourahrouh et al. (12) and Bourah-
rouh (7), which we consider to be a revision of Elaouad-Debbaj
(13). The data come from the Lower Second Bani Formation with
sedimentological evidence for glaciation, collected in the Bou
Ingarf and Route de Tazzarre sections in the central Anti-Atlas
of Morocco. An additional species reported by FP from this
section is Spinachitina sp. E.

Tazzeka Massif, NE Morocco.
Present-day coordinates: N 34° 08′; W 4° 13′ (Tazzeka Massif,
Morocco)
Paleolatitude (Bugplates): 67° S

The data are from glacial Hirnantian sediments (14); biogra-
tigraphically this assemblage remains undifferentiated between
the T. elongata and S. oulebsiri biozones.

Prague Basin, Bohemia, Czech Republic.
Present-day coordinates: N 49° 58′ 59′; E 14° 07′ 47′ (City
of Vraz)
Paleolatitude (Bugplates): 34° S (not used in analyses)
The data are taken from the Kosov Formation and from the
top of Kraluv Vur Formation, in the Levin, Vraz, and Liten
sections as described by Bourahrouh (7, p. 47, but not from Hlasa
Treban I section). These formations represent diamictites and
storm deposits (above storm wave base). The presence of the
graptolite P. ojsuensis (indicative of the N. extraordinarius bio-
zone) at base of Kosov Fm. (i.e. the “Mucronaspis” level) is noted.
The chitinozoan data is taken from fig. 46 (p. 126), which lists
the elements of the T. elongata Biozone in the Levin, Vraz and
Liten sections (l.e.2 up to l.e. 11, included).

Wells NL-2 - GD-1 Bis, NE Algerian Sahara, Algeria.
Present-day coordinates: N 33° 18′; E 3° 11′ (NL-2 borehole,
Borj Nili, NE Algeria)
Paleolatitude (Bugplates): 65° S

The chitinozoan data are taken from Paris et al. (15, p. 92,
fig. 5), from Bourahrouh (7, p. 110) and from Oulebsir and Paris
(16, figs. 5 and 6). Core NL-2 yielded chitinozoans from the
T. elongata and the lower S. oulebsiri Biozone (i.e., where elements
of the T. elongata and the lower S. oulebsiri zones overlap); core
GD-1 bis yielded data from the T. elongata Biozone.

Western Sahara, Algeria.
Present-day coordinates: N 29° 30′; W 02° 12′ (Ougarta, West
Algeria); N 27° 16′; E 5° 5’ (southern limb of the Tindouf basin,
W Algeria)
Paleolatitude (Bugplates): 69° to 71° S
This represents a previously unpublished dataset from shallow
cores from water wells in the Tindouf Basin available through
F. Paris and previously unpublished data from the El Kseib
glacio-marine El Kseib Member (diamictites) of the Djebel Seraf
Formation in Ougarta, West Algeria.
Illizi Basin, AMA, Algeria.
Present-day coordinates: N 28° 43’ 10”; E 7° 9’ 60” (Amissak “AMA-1” borehole, SE Algeria)
Paleolatitude (Bugplates): 67° S
This represents a previously unpublished dataset from F. Paris, from Hirnantian levels immediately above the limestone bed (with bryozoans) in the AMA core.

Tripolitaine area, W Libya.
Present-day coordinates: N 31° 33’; E 13° 12 (borehole A2-70, 150 km South of Tripoli, W Libya)
Paleolatitude (Bugplates): 61° S
This entry concerns data from the Djefarra Formation in Tunisia and W Libya (17, in 18) together with additional previously unpublished data (F. Paris) from W Libya, Tripolitaine area, core A2-70 (c. 150 km South of Tripoli in W Libya) and a very similar (if not exactly the same) fauna in core M1–66 at c. 500 km south of Tripoli.

Cyrenaica, NE Libya.
Present-day coordinates: N26°45; E 24°15 (Well E1-81, Cyrenaica, NE Libya)
Paleolatitude (Bugplates): 56° S
Data from Molyneux and Paris (19) and Paris (6). Paris (6) only mentions the nigerica biozone fauna, but after revision, this represents the T. elongata biozone, now defined from the FAD of the index species upwards. Data have been included from well E1-81 and from well JIA-1. The synonymy used for the data from Paris (6) is as follows: Plectochitina spongiosa = Plectochitina sylvanica; Spinachitina bulmuni = Spinachitina fragilis; Spinachitina sueccica = Spinachitina sp.; Tanuchitina bergstroemi = Tanuchitina elongata; Tanuchitina oantierensis = Tanuchitina elongata; Tanuchitina antiscosis = Tanuchitina elongata. E1-81 is a fully cored well, in contrast with JIA-1 which are samples from cutting samples (of not exactly the same) fauna in core M1–66 at c. 500 km south of Tripoli.

Kourneida 1 (Kr. 1) Core, Nigerian Sahara, Niger.
Present-day coordinates: approx. N 21° 30’; E 13° (Kourneida Kr-1 borehole, Niger)
Paleolatitude (Bugplates): 67° S
Data is taken from Bouchez (20), who lists two assemblages, a lower “A” and an upper “B” assemblage. These have been reinterpreted in terms of modern taxonomy, where assemblage “B” and part of “A” belong to the T. elongata biozone, which have been added to the database. The synonymy used for the data (20) is as follows: Conochitina conulus = Euconochitina sp.; Cyathochitina cf. campanulaeformis = Cyathochitina caputii (Silurian species ~ cutting samples); Cyathochitina koumeidaenensis = Spinachitina koumeidaensis; Lagenochitina brevicolis = Lagenochitina baltica; Lagenochitina cylindrica = Conochitina sp.; Cyathochitina fusiformis = Cyathochitina sp. 1 = Tanuchitina bergstroemi = Rhabdochitina magna = Tanuchitina elongata.

Border Folds area, SE Turkey.
Present-day coordinates: N 37° 19’; E 40° 10’ (Derek-Mardin area (loc. 5 in 21) fig. 1, i.e. 50 km due west of Mardin, Turkey)
Paleolatitude (Bugplates): 40° S
The data (21) were collected in the Border folds area, SE Turkey (representing the northern part of the Arabian plate, 22). The chitinozoans are from surface samples (Derek-Mardin region) from the Halevikdere Formation (21, p. 95–97) and from cutting samples from the Bedinan area (“Bedinan Group”—fig. 7 of ref. 21). Belonechitina sp. 1 (21) is identical to Belonechitina sp. 11 (4) and to Belonechitina reticulatus (3).

Kilgen Lake area, Taurus range, SE Turkey.
Present-day coordinates: N 37° 27’; E 35° 49’ (Just E of Kozan, Kilgen lake area, Turkey)
Paleolatitude (Bugplates): 43° S
The data were collected in the central and eastern Taurus range (21). This formed part of the Anatolia microplate. Chitinozoan data are from the glacial deposits of the Halevikdere Formation (21, p. 93) and belong to the elongata Biozone.

Cardigan to Llandovery transect, S Wales, United Kingdom.
Present-day coordinates: N 52° 08’; W 04°32’ (samples TJ d979 and upwards in 3, Cardigan—Llandovery area, United Kingdom)
Paleolatitude (Bugplates): 32° S
Data from two range charts (3) in (1) the Cardigan-Llanrangon area (Basin) and (2) the Llandovery area (shelf). The B. gamachiana zone in the Cardigan-Llanrangon district is reported from the pre-Hirnantian Nantmel mudstones (ancestral graptolite Biozone), below the Hirnantian, glacial Yr-Allt Formation. However, the recognition of the gamachiana biozone is only based on poorly identified specimens of B. cf. gamachiana, so we only used the fauna from the glacial Yr-Allt Formation. In the Llandovery area, the gamachiana biozone is of Hirnantian age.

Bala Area/Cwm Hirnant, N Wales, United Kingdom.
Present-day coordinates: N 52°51’; W 03°33’ (Hirnant Quarry, a small abandoned quarry [SH 951 296] on the western slopes of Cwm Hirnant, due west of Cwm-yr-Aethnen Farm, N Wales)
Paleolatitude (Bugplates): 32° S
Data from Vandenburgoucke et al. (23) from the S. taugoudeauii Biozone in the Cwm Hirnant Limestone and associated species and genera in the adjacent strata of the Moelfryn Mudstone Formation and the Foel-y-dinias Mudstone Formation. The synonymy of spinachitiniids in Vandenburgoucke et al. (23) with S. oulesisi and S. verniersi as suggested (24) has been followed herein.

Cerrig Gwynion Quarry/Claerwen Valley, Central Wales, United Kingdom.
Present-day coordinates: N 52°17’; W 03°31’ (Cerrig Gwynion Quarry, local grid reference [SN 969 656], Rhayadar area, Cerrig Gwynion Quarry/Claerwen Valley, Central Wales, United Kingdom)
Paleolatitude (Bugplates): 32° S
Data from Vandenburgoucke et al. (23); the Belonechitina reticulatus zone is present (index fossil identified as Belonechitina sp. 11 in 23).

Type Ashgill area, north of Sedbergh, N. England, United Kingdom.
Present-day coordinates: N 54°23’; W02°28’ (the confluence of Sp en and Stockless Gill in the Cautley district, sandy intercalation in the Ashgill mudstones)
Paleolatitude (Bugplates): 30° S
Data from the Murtwhaite, Taythes, and Westerdale inliers (8). B. reticulatus occurs in the Hirnantian samples (as Belonechitina sp. 6 in 8 and as Belonechitina sp. 11 in 4), together with Spinachitina verniersi (=Spinachitina sp. 3 in 8 — Spinachitina sp. 5 = Spinachitina sp. aff. oulesisi in 4) and associated taxa. Only species co-occurring with B. reticulatus have been included, i.e. in samples 03–025, 03–026 and 02–100 (8).

Brabant Massif, Belgium.
Present-day coordinates: N 50°50’; E 03°19’ (Harelbeke Borehole, “Provinciaal Domein de Gavers,” Deerlijk, Belgium)
Paleolatitude (Bugplates): 34° S
These are data from Vanmeirhaeghe (25, p. 183–183) from the Harelbeke Unit (outer shelf to upper slope/turbidites; 25, fig. 74) collected from the Harelbeke Borehole (West
Monitor Range composite, central Nevada, USA.

Present-day coordinates: N 39° 14′; W 116° 26′ (Copenhagen Canyon, Nevada)

Paleolatitude (Bugplates): 3° S

These data are from the Copenhagen Canyon and Martin Ridge sections in the Monitor range of central Nevada (26). The time slice has been recognized by means of the graptolites from the *extraordinarius* and *persculptus* biozones described from these sections (27).

Vinini Creek section, central Nevada, USA.

Present-day coordinates: N 39° 54′; W 116° 14′ (Vinini Creek section, Nevada)

Paleolatitude (Bugplates): 3° S

These data are from the Vinini Creek section in the Robert Mountains of central Nevada (26). The time slice has been recognized by means of the good graptolite control on the section (27).

Anticosti Island, Canada.

Present-day coordinates: N 49° 49′; W 64° 23′ (Ellis Bay, Cap Henri, Loc A-2B of 28)

Paleolatitude (Bugplates): 21° S

Data are from Soufliane and Achab (28) who discuss the upper part Ellis Bay Formation and from Achab (29, fig. 6, p. 7, and text p. 6) who discusses the lower part of the same Ellis Bay Formation. This represents a “shallow, subtidal environment” (28). The time slice is recognized by *B. gamachiana* (occurring throughout the formation) and *S. taugourdeaui* (and their biozones). For the new graptolite data and correlation chart, we follow Melchin (30). The *A. ellisbayensis* biozone has not been included in our time slice. A revision of the correlation of Ellis Bay Formation deposits between various outcrop areas on Anticosti Island (31) has little influence on the data used for this compilation. The chitinozoans at the base of the Ellis Bay Formation (e.g. in member 1) have not been included as these represent a mix of *B. gamachiana* with species typical of older deposits (Vauereal Formation, Katian).

Latvia.

Present-day coordinates: N 56° 57′; E 24° 06′ (Riga, Latvia)

Paleolatitude (Bugplates): 26° S

The data are taken from the compilation made by J.N. for the Webby et al. volume (32, time slice 6C) and from the Rickstini section in Brenchley et al. (33, fig. 8, p. 96).

N. Estonia.

Present-day coordinates: N 59° 15′; E 25° 00′ (central N Estonian confacies belt)

Paleolatitude (Bugplates): 24° S

The data are taken from the compilation made by J.N. for the Webby et al. volume (32), which contained data from North Estonia and the “Rapla 1” borehole. It contains limited data as to the very shallow water to emergent settings of this area in the Hirnantian.

Sweden.

Present-day coordinates: N 58° 46′; E 17° 25′ (Tvären crater, central Sweden)

Paleolatitude (Bugplates): 25° S

The data are taken from the compilation made by J.N. for the Webby et al. volume (32); it contains limited data and probably only represents the *C. scabra* biozone.

West Estonia.

Present-day coordinates: N 58° 25′; E 22° 30′ (Eikla, Estonia)

Paleolatitude (Bugplates): 25° S

The data are taken from the compilation made by J.N for the Webby et al. volume (32, time slice 6C), from the Kaugatuma core (33, fig. 9, p. 97) and from the Tamme (K-38) core (33, fig. 11, p. 99).

South Estonia.

Present-day coordinates: N 58°; E 26° (center between Tallinn and Riga; Estonia)

Paleolatitude (Bugplates): 25° S

The data are taken from the compilation made by J.N (32, time slice 6C), from the Kardla core (33, fig. 10, p. 98), the Ruhnu core (33, fig. 6, p. 94), the Taagepera core (33, fig. 7, p. 95), the Tartu core (34) and the Valga-10 core (35). Nõlvak (in ref. 36) shows some more occurrences of *B. gamachiana* and *S. taugourdeaui* but not the full assemblages

In all the above sites, the following species were considered to be reworked: *Lagenochitina deunffi*, *Linochitina pissaotensis*, *Si-phonochitina formosa*, *Desmochitina juglandiformis*, *Eremochitina brevis*, *Fungochitina fungiformis*, *Hyalochitina fistulosa*, *Anryochi- tina spongiosa*, *Velatichitina cf. veligera*, *Conochitina homoclavi- formis*, *Lagenochitina cf. ponceti*, *Eisenackitina inconspicua*, *Eisenackitina rhennana*, *Belonechitina robusta*, *Euconochitina tanvillensis* and *Calpichitina complanata*.

1.3 Paleogeography of the localities. Sites are limited to the Southern hemisphere and more in particular, to the *circum* Iapetus oceanic realm. For each site, the paleolatitude is derived from the Torsvik and Cocks “Bugplates” reconstructions. These represent the most recently revised reconstructions for the Ordovician, and are based on paleomagnetic and (predominantly benthonic) paleobiogeographic data (37). The base maps used in these reconstructions are updated versions of those published (38, 39); these revisions and the data they are based on are largely published in paleocontinental case studies for e.g. Baltica (40) or Siberia (41). The accessibility of the scientific arguments for the reconstructions, their recent update, and their availability in a user-friendly, digital format, now makes these reconstructions the most appropriate ones for our objectives. We accept the paleolatitudinal difference with earlier reconstructions, i.e., maps from PALEOMAP (using Point Tracker software, 42) as defining the paleogeographical error flags on or data points (see Fig. 3 of the main text). Variance between both reconstructions is relatively small (and below our 5° margin of paleogeographical error) for localities equatorward of 35° S. However, a discrepancy between both reconstructions concerns variance of up to 15° latitude (typically ~10°) for the Northern Gondwanan localities south of 35° S. It is introduced by differences in estimates of movement of the Gondwana continent between both reconstructions compared to earlier times (37, 42). This introduces a sampling gap in the PALEOMAP (42) reconstruction (between 35° and 50° S) and a larger error flag on the position of the Polar Front.

1.4 Analytical methods. Our methodology follows Vandenbroucke et al. (43) and is briefly summarized here. Datasets with considerable species turnover require unimodal ordination methods such as Correspondence Analysis (CA), or methods based on unimodal ordination methods, such as TWINSpan. Our species presence/absence matrix was subjected to TWINSpan, “two way indicator species analysis” (44) resulting in the dendrogram shown in Fig. S2. TWINSpan differs from other clustering methods more generally used in the Ordovician in that each dichotomy is based on an initial sample ordination. In addition, it simultaneously provides a hierarchical classification of both species and sites. The data were also subjected to detrended correspondence
analysis (DCA) to construct an ordination diagram (Fig. S3). Where possible, the TWINSPLAN species clusters were then used in a constrained seriation analysis (45). The paleolatitude of the localities was constrained allowing a reordering of species into biotopes. This produces latitudinally restricted biotopes, and we use the species with the narrowest latitudinal ranges [i.e., a limited sea surface temperature (SST) tolerance] to define them. These biotopes are then compared to a hypothetical plankton model (46 for further details). The latter represents the hypothetical distribution of modern planktonic foraminifer provinces, by mapping their present-day SST-controlled boundaries (47) onto the SST maps of Hirnantian GCMs (48). The comparison of the chitinozoan patterns with the hypothetical model allows the application of modern day terminology (Tropic to Polar) to the Ordovician biotopes.

2. Si Results. TWINSPLAN analysis (down to the third division level) divides our chitinozoan data into five species groups (Figs. S2–S4). Three of these are useful for paleobiogeographical interpretation. These TWINSPLAN groups can be further subdivided into subgroup(s) or biotopes using constrained seriation. The low and mid latitude biotopes and their inferred climate belts conform best to the patterns predicted by the SST model at 8x PAL pCO₂ at low sea levels, but for a perfect fit, the modeled SST gradient would need to be steeper still (see main text Figs. 1 and 3). The overall close similarity justifies the use of modern terminology in the Ordovician, and we have hence been able to identify Tropical to Polar chitinozoan biotopes in the Hirnantian.

TWINSPLAN Group I includes the following species: Hercocithina minuta, Nevadachitina vininica, Tanuchitina laurentiana, Belonechitina parvispinata, Calpichitina scabiosa, Eisenackithina ripae, Ordnochitina nevadensis and Kalochitina multispinata. They have a range within 5° of latitude from the equator. This group is not further subdivided using constrained seriation and represents thus the Tropical TWINSPLAN group and the Tropical biotope.

TWINSPLAN Group II. This group represents the Polar fauna or TWINSPLAN group, although three species range into subpolar latitudes. The TWINSPLAN group includes two biotopes. Biotope IIa is the truly Polar biotope and includes the following species: Acanthochitina atrox, Anryochitina prima, Spinachithina bulma, Calpichitina lenticularis, Euconochitina lepta, Lagenochitina, Acanthochitina barbata, Anyrochitina prima, Spinachitina bulbilla.

TWINSPAN Group III comprises three biotopes, i.e., the Subtropic, Transition and Subpolar biotope. The Subtropic Biotop has narrowly ranging species Belonechitina sena, Conochitina dolosa, Hercocithina crikcikvy, Tanuchitina antigonioides and Tanuchitina bergstroemi, restricted around 20° S, and wide(r) ranging species Belonechitina gamachiana, Spinachithina taugouaridae, Belonechitina micrancanata typica, Cyathochitina kuckerianana and Belonechitina micrancanata. The Transitional Biotop has Calpichitina complanata tunica, Conochitina scabn, Rhabdochitina gracilis and Conochitina minuta. The Subpolar Biotop contains the following species: Belonechitina americana, Belonechitina reticularis, Belonechitina ceredigionensis, Cyathochitina salis, Belonechitina sp. 12 (4), Belonechitina wesenbergensis, Spinachithina corona, Conochitina nata and Acanthochitina atrox.

3. Si Discussion. In the second part of the main text we use our biogeographical data to evaluate Hirnantian pCO₂ estimates. The development of large continental-scale ice sheets in the Polar regions during the Cenozoic has also been marked by significant drops in pCO₂ (e.g. 49). However, atmospheric pCO₂ levels in the Late Ordovician have generally been estimated much higher than those of today, and range from an implausibly high x22 to x8 PAL. These values are largely based on modeling, though rare values for atmospheric CO₂ calculated from proxy data are published: Yapp & Poths (50) obtained results of ~16x PAL pCO₂ from goethites from the Neda Formation in the latest Ordovician (~440 Ma). Tobin & Bergström (51) modeled atmospheric CO₂ during the early Sandbian (~460 Ma) to be likely between 14x and 22x PAL based on data from fibrous calcite from the Eiffna Formation. The GECARB I to III models (52–54) showed a very high Late Ordovician pCO₂, in the order of 13–16x PAL. Crowley & Baum (55) were able to reconcile a Late Ordovician glaciation (i.e. permanent summer snow cover) with GENESIS GCM boundary conditions of 14x PAL pCO₂, solar luminosity reduced by 4.5% and an elevated topography on Gondwana of 300–500 m. Gibbs et al. (56) modeled an ice-free Late Ordovician world above pCO₂ levels of 14x PAL and a runaway icehouse below values of 8x PAL pCO₂. Other GCM experiments (48, 57) with 18 to 8x PAL pCO₂ suggested that a drop to 8x PAL pCO₂, together with changes in other environmental conditions (drop in sea level, changing paleogeography) can cause glaciation in the Late Ordovician. In the main text, we address the paradox of Early Paleozoic glaciation at these supposed elevated levels of pCO₂. This paradox is now exacerbated due to growing support for views that the Early Paleozoic Icehouse (EPI) could have been similar to the Cenozoic in duration, timing and likely causal mechanisms (58, 59).
A Chronostrat. overview

B Schematic definition of the timeslice

1. Graptolite biostratigraphy
2. N. Gondwanan chitinozoan biozones
3. Baltoscandian chitinozoan biozones
4. Avalonian chitinozoan biozones
5. Laurentian (Anticosti) chitinozoan biozones
6. Laurentian (Nevada) chitinozoan biozones
7. Schematic diamictite distribution in N. Gondwana
8. Simplified δ¹³C curve

Fig. S1. Definition of the Hirnantian (HICE) time slice (shaded).
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<th>Group I: Tropical</th>
<th>Group II: Generalists</th>
<th>Group III: Subtropical to Subpolar</th>
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<td><strong>T. winspan</strong></td>
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<td><strong>Group II: Polar</strong></td>
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<td><strong>Group III: Subtropical to Subpolar</strong></td>
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**Fig. S2.** Results of the TWINSPAN analysis and the significance of the major groups.
Fig. S3. Detrended correspondence analysis analysis of the HICE time slice chitinozoan data: clusters of species (black font, gray points), localities (blue font and dots) are shown; interpretation is in green (e.g. Tropic, Polar; see text for a justification).
Fig. S4. Totality of the preserved-abundance chitinozoan data for the HICE time slice, used in this study, structured according to the results of the TWINSPAN and constrained seriation analysis.