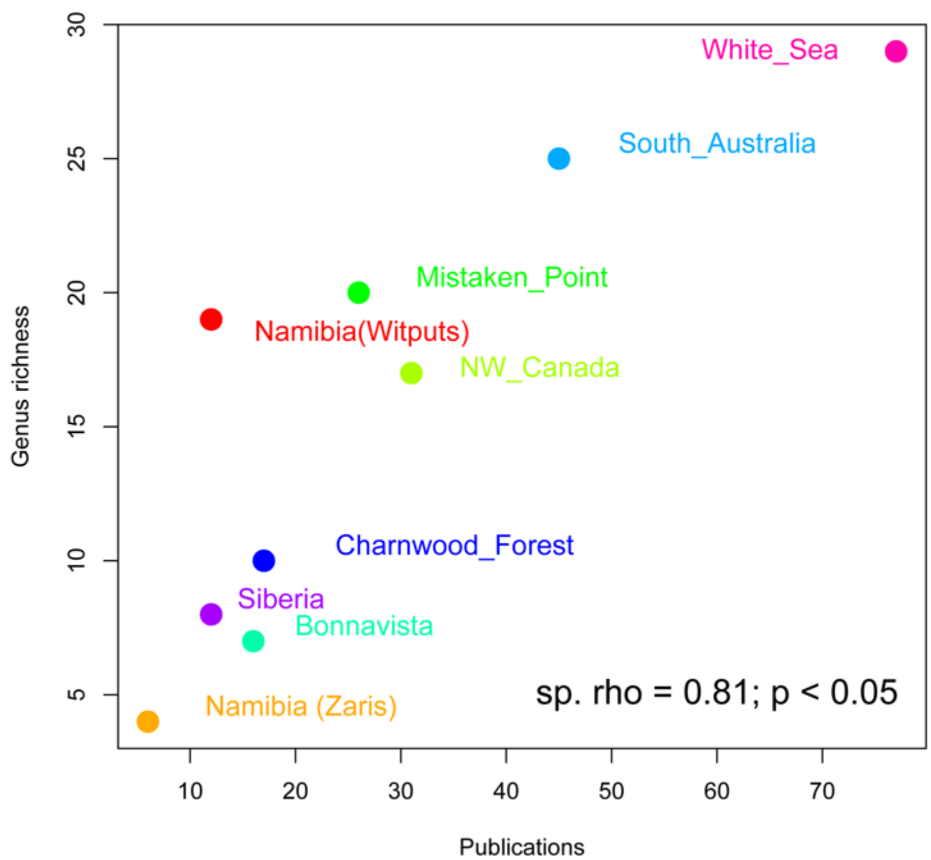
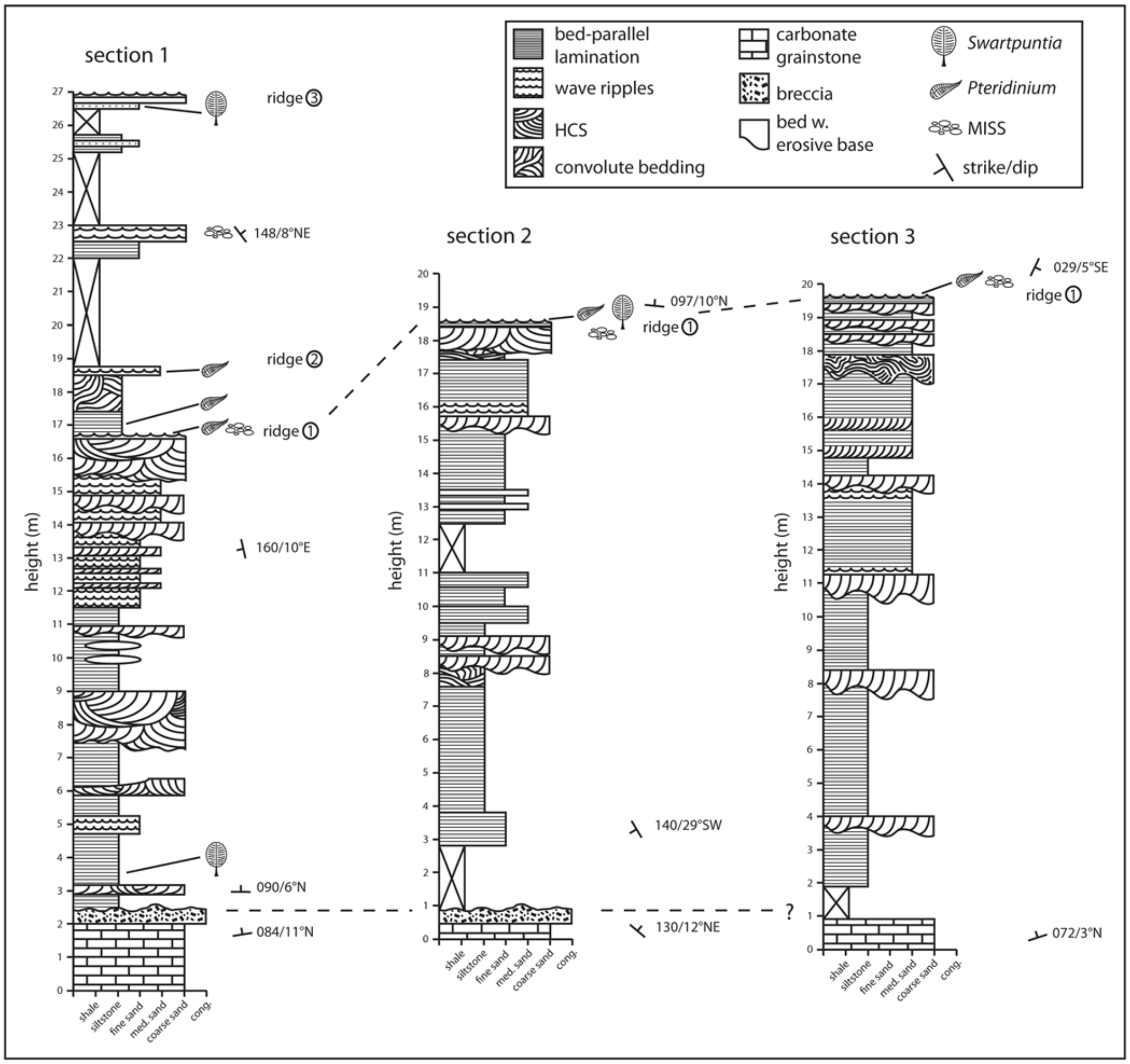
Supplementary Material for "Biotic replacement and mass extinction of the Ediacara biota"

Darroch et al. (submitted)

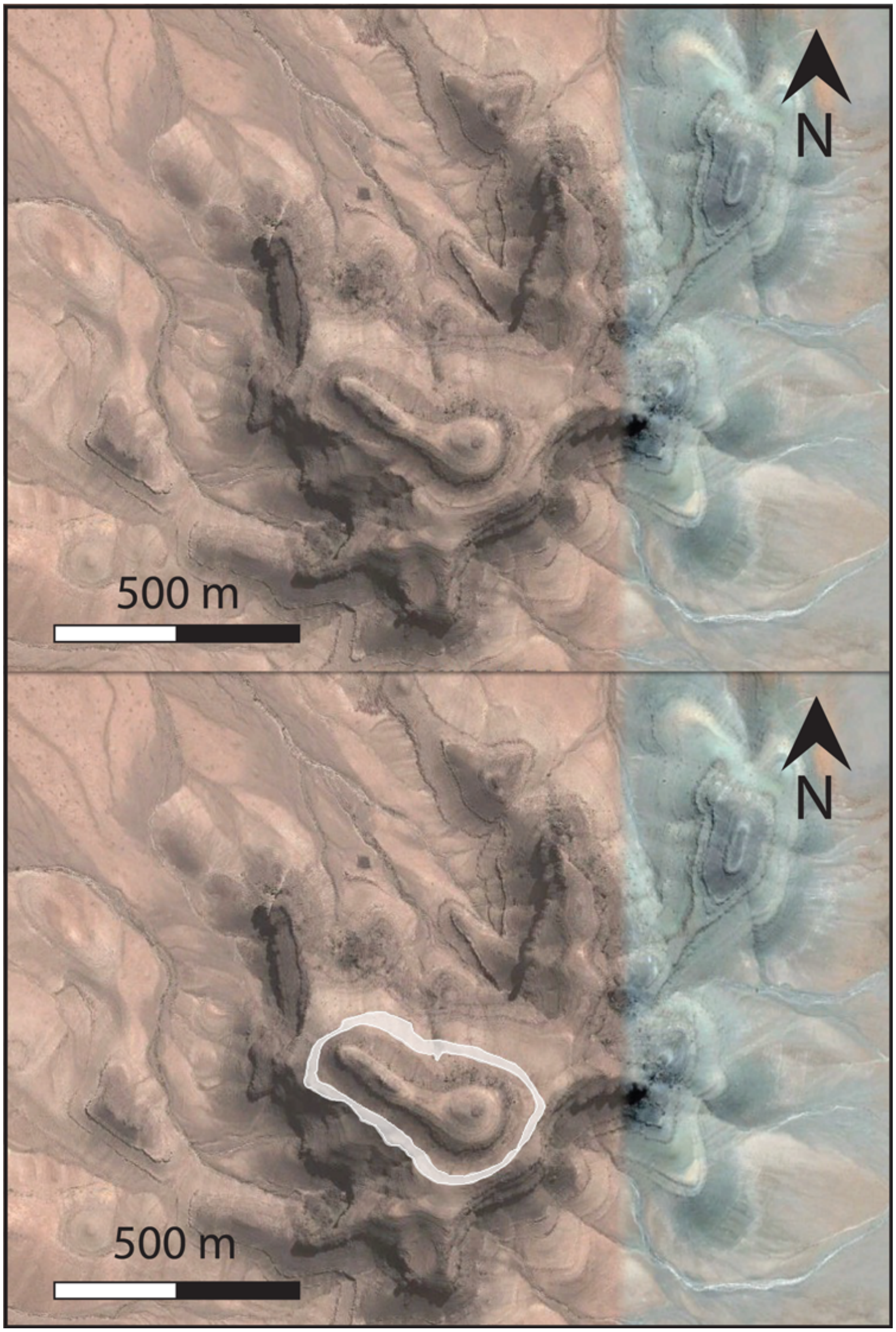
S1 - Scatterplot illustrating positive correlation (spearman rho) between 'worker effort' (quantified as the number of original taxonomic papers), and overall generic richness for Ediacaran fossil localities. Note that we include skeletal fossils (e.g., *Namacalathus* and *Cloudina*), likely form taxa (e.g., *Aspidella*), and enigmatic tubular taxa (e.g., *Shaanxilithes*) in counts.



S2 – Measured sections (see also Fig. 1), showing the stratigraphic distribution of Ediacaran fossils encountered during measurement. Strata exposed as three prominent ridges or breaks in slope, which are interspersed with scree material, can be traced around the top of the koppe. The first ridge is equivalent to fossil bed 'A' of Narbonne et al. (1997) while the second ridge (located stratigraphically ~ 2 m above Bed 1) is equivalent to fossil bed 'B' (of Narbonne et al. 1997) The third ridge is located ~8.5 m above ridge 2, and to our knowledge has not previously been identified as a fossiliferous horizon. *In situ* Ediacaran macrofossils were recovered from five individual horizons within the siliciclastic deposits (including the three ridges). From our section 1 in particular, we recovered *in-situ* fossils from ~1 m above the base of the siliciclastic horizons (thin-bedded green siltstone), the top surface of ridge 1 (weakly rippled coarse sandstone with abundant microbial mat texture), ~50 cm above ridge 1 (thin-bedded green siltstone), the top surface of ridge 2 (rippled medium sandstone), and within ridge 3 (thin yellow-green medium sandstone horizons with minor carbonate). Fossils recovered from float material occurred in a number of different lithologies, suggesting the existence of numerous other fossiliferous horizons not identified in this survey. Microbial mat textures are developed throughout the section, but particularly well on the top surface of ridge 1 where a large proportion of *in-situ* fossils are recorded. Similar to previous studies, we find a dramatic change in bedding, from horizontal to sub-horizontal/sub-vertical at the contact between fossil-bearing siliciclastic horizons and underlying carbonate, interpreted by Narbonne et al. (1997) as a 'mega slump'. Due to the discovery of Ediacaran macrofossils preserved in-situ on bedding planes (i.e., not jumbled and/or preserved in 3 dimensions, similar to transported assemblages elsewhere in Namibia – see e.g., Vickers-Rich et al., 2013) immediately above the basal contact, we agree with these previous workers that deformation was likely not syn-depositional, but rather the result of faulting or relatively recent slumping. Consequently, fossils are most likely autochthonous (or parauthocthonous) rather than transported as part of mass-flow facies.


bed-parallel lamination
wave ripples
HCS
convolute bedding
carbonate grainstone
breccia
bed w. erosive base
Swartpuntia
Pteridinium
MISS
strike/dip
section 1
section 2
section 3
ridge ③
ridge ②
ridge ①
148/8°NE
160/10°E
090/6°N
084/11°N
097/10°N
140/29°SW
130/12°NE
029/5°SE
072/3°N
?
height (m)
shale
siltstone
fine sand
med. sand
coarse sand
cong.

S3 – Google Earth image of the koppe at Farm Swartpunt (top), and showing the approximate outline of surveyed area shaded in white (bottom).



S4 – Fossil database and description of sampling methods. Our database was built through intensive survey of the fossiliferous horizons at Farm Swartpunt, over three days in June 2014 (4 dedicated spotters, working 5 hours per day; equivalent to ~60 hours total). The identities and contexts of all identifiable fossils are listed in Supplementary Table 1. The total surveyed area at Farm Swartpunt, within the relevant horizons is estimated at 20358.68 meters^2 (= 0.02 km^2) (based on calculations using the polygon tool in Google Earth) – see S3.

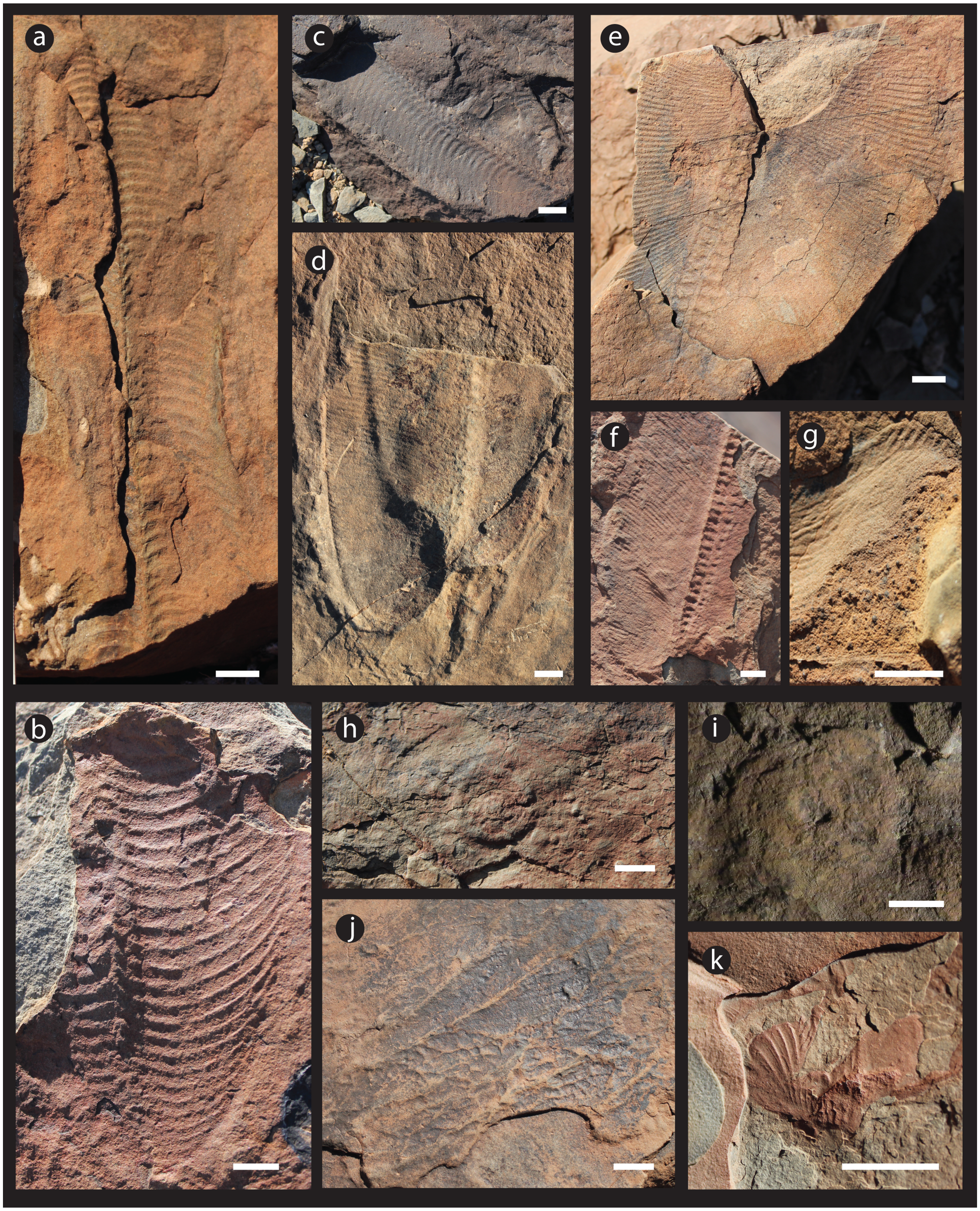
Specimen	ID	Context	Notes
SWP-1	Aspidella	float; laminated siltstone/mudstone facies	bulbous, at base of koppe; Multiple holdfasts
SWP-2	Aspidella	float; laminated siltstone/mudstone facies	bulbous, at base of koppe; holdfasts
SWP-7	Swartpuntia	float, fine SST with ripple cross laminations	NA
SWP-15	Ernietta?	float, fine SST	Scallop-shaped form; prob. Ernietta
SWP-37	Swartpuntia	float, med SST	complex stem/vane structure
SWP-38	Swartpuntia	float, med-coarse SST	3D preservation from above main surface
SWP-40	Pteridinium	float, med-coarse SST	very small & fractured
SWP-41	Pteridinium	float	1 long PT, likely fell from cliff
SWP-43	Aspidella	float? (but cemented in place); SST	very big 1st concentric rings w/ faint radial traces extending ~5 cm from center
SWP-44	Swartpuntia	float, coarse cross-bedded sandstone	preserved flat on curved bedding surface w. petaloids visible; incomplete specimen (edges obscured); zigzag raised stalk
SWP-45	Aspidella	float	NA
SWP-46	Pteridinium	in place (top of bed 1 - coarse sandstone)	very faint & poorly preserved; only see central ridge + one petaloid (edge not fully resolved)
SWP-47	Pteridinium	float, coarse sandstone	incomplete but w/ 3D preservation (w-in bed) can see 1 vane clearly w/ mid-ridge and faint 2nd vane
SWP-48	Pteridinium	bed top 1 in place	2 vanes; primary visible, 3rd vane? 2D (bed top); largest vane incomplete, min width recorded
SWP-49	Pteridinium	in place - bed top 1	poss. PT w/ 3D preservation poorly preserved

SWP-50	Pteridinium	in place - bed top 1	small incomplete PT - only 1 vane visible - preserved 2D
SWP-51	Pteridinium	in place - bed top 1 (coarse sandstone)	small PT - incomplete 2 vis. vanes, preserved in 2D
SWP-52	Pteridinium	float (coarse SST)	small PT - 2 vanes & central axis, possible 3D preservation, 1 vane along axis upwards
SWP-53	Pteridinium	float - bed top 1 - coarse SST	2 visible vanes with central axis
SWP-54	Pteridinium	in place - bed top 1	incomplete sp - 1 vane complete; 2 vanes + central axis visible; 2D preservation
SWP-55	Pteridinium	float bed top 1	poorly preserved, in rippled trough, 2-3 vanes visible, branches on 2nd vane oriented differently
SWP-56	Bradgatia?	in place - bed top 1	Faint (but visible) rangeomorph elements extending from several vanes; Bradgatia?
SWP-57	Pteridinium	in place - bed top 1	possible 3D preservation, very poor, all vanes incomplete
SWP-59	Aspidella	in place - bed top 1	7 individuals; 2D preservation
SWP-60	Pteridinium	in place - bed top 1	2 vanes visible, both incomplete w/ central ridge
SWP-61	Pteridinium	in float - top of bed 1	large PT, 2 vanes w/ distinct center ridge, 1 vane complete
SWP-62	Pteridinium	float (coarse SST)	2 vanes incomplete, 3rd vane actually visible!
SWP-63	Pteridinium	float (med-coarse SST)	2 vanes both incomplete visible
SWP-64	Swartpuntia	float	1 vane complete, 2nd pet has no visible structure
SWP-65	Pteridinium	in place	twisted - good center ridge, all ?? Incomplete
SWP-66	Pteridinium	float	2D preservation, L/W incomplete
SWP-67	Pteridinium	float	incomplete - 1 vanes visible, 2D preservation
SWP-68	Pteridinium	in place - top of bed 1	incomplete - 2 vanes
SWP-69	Pteridinium	float - thick, dark red SST	1 petaloid only w/ no central ridge; 2D preservation
SWP-70	Pteridinium	coarse grained in place top of bed 1	all incomplete - mid petaloid visible, 2D preservation
SWP-71	Pteridinium	in place top of bed 1	incomplete- 2 petaloids
SWP-72	Pteridinium	float	2 spec. on slab, both incomplete
SWP-73	Pteridinium	float (coarse SST)	2nd sp. on slab incomplete
SWP-74	Pteridinium	in place - top of bed 1	2D preservation, 2 vanes, poorly

			preserved, all measurements incomplete
SWP-75	Pteridinium	in place - top of bed 1	very poorly preserved, 2D preservation, 2 vanes visible
SWP-76	Pteridinium	in place? See notes, top bed 1	may have been some block rotation...??
SWP-77	Aspidella	in place, top bed 1	raised central area & raised outer rim
SWP-78	Pteridinium	in place, top bed 1 (1 m higher)	incomplete - 2 vanes visible
SWP-79	Pteridinium	in place near top bed 1 in "wavy" SST roller	2D preservation 2 vanes visible & central axis
SWP-80	Pteridinium	in place - top of bed 1 - much thinner here - not big cliff forming unit?	incomplete - 2D preservation, 3 Vanes & midline
SWP-81	Pteridinium	in place	incomplete - poor preservation
SWP-82	Pteridinium	in place	same bed as large ?? 1 pet poor complete pic of ??? Taken
SWP-83	Pteridinium	in place, top of bed 1 - above ? lithology	2 in same place, elements curve in different directions
SWP-84	Pteridinium	in place, top of bed 1 - above ? lithology	2nd specimen (84) both with 3 vanes
SWP-85	Pteridinium	in place	this individual bent - two orientations taken; incomplete
SWP-86	Pteridinium	in place - top of bed 1	nice one - 1 PW complete, 2 PW visible
SWP-87	Pteridinium	in place	PW's look complete
SWP-88	Pteridinium	in place	Very highly twisted, measurements incomplete, poor preservation
SWP-89	Pteridinium	in place	measured separate but next 3 sp all in same spot, 3D preservation
SWP-90	Pteridinium	in place	2 vanes visible - central axis v. visible
SWP-91	Pteridinium	in place	none
SWP-92	Pteridinium	in place	small + poorly preserved
SWP-93	Pteridinium	in place	sp broken down middle front piece may be lost
SWP-94	Pteridinium	in place	1 vane nearly complete, the other weathered off
SWP-95	Pteridinium	in place	2 vanes, 1 w/ complete width
SWP-96	Pteridinium	in place	poor preservation
SWP-97	Swartpuntia	in place	1 common PW
SWP-98	Pteridinium	float - top of bed 1	big specimen on fallen block -

			scree slope below classic locality; 1 complete petaloid
SWP-99	Aspidella	float	taken from fine siltstone horizon, 4 holdfasts
SWP-100	Swartpuntia	float	Found in float and end of day 2
SWP-101	Swartpuntia	float	Found in float and end of day 2
SWP-101b	Pteridinium	float	Found in float and end of day 2
SWP-102	Pteridinium	float	Found in float and end of day 2
SWP-103	Pteridinium	float	Found in float and end of day 2
SWP-104	Pteridinium	float	Found in float and end of day 2

S5 – Representative Ediacara biota recovered from Farm Swartpunt: a-c) *Pteridinium simplex*; d-f) *Swartpuntia germsi*; g) *Nasepia* sp.; h-i) *Aspidella*-type holdfasts, possibly belonging to *Swartpuntia* (see S5b); j) unidentified rangeomorph taxon, provisionally assigned to *Bradgatia*; k) unidentified Erniettomorph taxon, provisionally assigned to *Ernietta*.



S5 (cont.) – Collected slab preserving specimens of *Aspidella* (SWP-99); holdfast structure ('Hf'), *Swarptuntia*-type segmented stem ('St'), and *Swartpuntia*-type petaloid ('Pet') are clearly visible. The positions of multiple other suspected holdfast structures are marked with 'x'. A poorly preserved additional petaloid, possibly belonging to another *Swartpuntia*, is circled.

S6 – Facies, taphonomic, and geochronologic summaries for analysed assemblages

Farm Swartpunt (southern Namibia)

Palaeoenvironmental and stratigraphic setting – The fossil-bearing horizons at Farm Swartpunt are part of the latest Ediacaran Nama Group, Urusis Formation (Spitskopf Member), deposited into the southernmost (Witputs) of two subbasins. Fossil beds are contained within siliciclastic horizons overlying brecciated horizons that contain slumped intervals, interpreted as a post-depositional 'megaslump' by Narbonne et al. (1997; see also S2). Fossils occurring above the slumped horizons are preserved in-situ (our 'Bed 1' – see S2); within the slumped horizons fossils may have been moved from their original positions, but are most likely parautocthonous (rather than allocthonous). The palaeoenvironment is interpreted as a quiet and open-marine setting at or near fair weather wave base, and shows evidence for occasional disruption by storms (Narbonne et al., 1997).

Taphonomic mode – Fossils from all horizons are preserved as 2D casts and molds on the top- and bottom-surfaces of beds. Fossiliferous horizons frequently also preserve evidence for microbial mats, and thus were likely preserved in the "death mask" style common to many other Ediacaran localities, including Mistaken Point (Narbonne, 2005), and South Australia (Gehling, 1999). The 3D taphonomic mode, characterized by moldic infills (which can be isolated from the surrounding matrix) is not evident here, despite being frequently seen elsewhere in Namibia (see e.g., Vickers-Rich et al., 2013), reinforcing inference that these organisms represent an autocthonous accumulation.

Geochronology – An ash bed in the lower carbonate package of the Urusis Formation has been dated by U-Pb geochronology at 545.1 ± 1 Ma (recalculated to 542.58 ± 1.25 Ma by Schmitz, 2012), and an ash bed ~85 meters below the investigated fossil beds at 543.3 ± 1 Ma (Grotzinger et al., 1995 - see Fig. 1; recalculated to 540.61 ± 0.67 Ma by Narbonne et al., 2012). Strata from the overlying Nomtsas Formation in the Swartkloofberg Farm directly north of Swartpunt contain an ash bed dated to 539.4 ± 1 Ma (i.e., Cambrian; Grotzinger et al., 1995; recalculated to 538.18 ± 1.11 Ma by Narbonne et al., 2012).

Nilpena (southern Australia)

Palaeoenvironmental and stratigraphic setting – Fossils from Nilpena occur within the Ediacara member of the Rawnsley Quartzite (Flinders Ranges), broadly consisting of a variety of shallow marine and deltaic facies, preserving evidence for wave action and occasional storms (Gehling and Droser, 2013). More detailed sedimentological studies (Droser et al., 2006; Gehling and Droser, 2013) have identified a complex series of taxon-restricted paleoecosystems representing distinct sedimentary facies (i.e. paleoenvironments) including shoreface sands, wave-base sands, delta-front sands, sheet-flow sands, and mass-flow sands. The shoreface-, wave-base-, and delta-front sands are all interpreted to reflect in-situ and untransported assemblages. By contrast, the sheet-flow- and mass-flow sands preserve (largely) transported assemblages.

Taphonomic mode – Ediacaran preservation across the Flinders Ranges is typically represented by 2D casts and molds (i.e., 'death mask' preservation; Gehling, 1999) on the bottom surfaces of coarse-grained sandy storm event beds. However, rare sedimentary facies from Nilpena have resulted in 3D-preservation of large Ediacaran fronds (Gehling and Droser, 2013).

Geochronology – The fossil assemblages from Nilpena are most similar to assemblages from Russia, Siberia, Ukraine, and northwestern Canada, and so assignment to the 'White Sea' assemblage (i.e., 555-550 Ma) is established mostly on a biostratigraphic basis. U-Pb dates from Russia indicate ages between 552.85 ± 0.3 Ma (Zimnie Gory Formation) to 550.2 ± 4.6 Ma (base of the Yorga Formation; Iglesia-Llanos et al., 2005), however Nilpena lacks any notable volcanic ash beds, and so accurate dating has been difficult. This correlation receives some moderate support from a single U-Pb detrital zircon date of 556 ± 24 Ma from the Bonney Sandstone (Preiss, 2000).

Mistaken Point (Newfoundland)

Palaeoenvironmental and stratigraphic setting – Fossiliferous horizons at Mistaken Point are dominated by relatively deepwater (> 500 m) turbiditic sandstones and mudstones (Wood et al., 2003; Ichasso et al., 2007; Mason et al., 2013; Liu et al., 2014). The fossil horizons analyzed here belong to the Drook (PC surface), Briscal (BC surface), Mistaken Point (E and D surfaces) and Trepassey (SH surfaces) Formations; for stratigraphic sectiosn see Wood et al. (2003) and Clapham et al. (2003). Previous studies infer a deepwater (toe of slope to lower slope) paleobathymetry well below storm wave base and the photic zone (Wood et al. 2003; Ichaso et al. 2007; Mason et al., 2013). Turbidite beds are typically overlain by a thin (1–2 cm) mudstone interpreted as pelagic fallout (Wood et al. 2003). This thin pelagic mudstone is characterized by thin, black, 'crinkly' and discontinuous silt laminae that may represent diagenetically altered microbial mats (e.g. Wood et al. 2003; Narbonne et al. 2005). Thin (1–2 cm) beds interpreted as deepwater contourite deposits (Wood et al. 2003) are found above terminal-stage turbidite beds and, when overlain by volcanic ash, typically contain Ediacaran fossils.

Taphonomic mode – Organisms at Mistaken Point were preserved in-situ after being smothered by volcanic ash ('Conception-style' preservation of Narbonne 2005). The local presence of seafloor microbial mats and rapid onset of anaerobic decay led to early lithification of the soles of overlying ash beds, effectively casting fine-scale morphology (Narbonne 2005; Laflamme et al. 2011; Liu et al. 2011).

Geochronology – Ash beds bracketing the fossiliferous horizons analysed in this study have been dated using U-Pb geochronology at 580 Ma, 578 Ma, and 565 Ma (see Benus, 1988; Bowring et al., 2003). See Darroch et al., 2013 (figure 1) for stratigraphic section with dated horizons in context.

White Sea (Russia)

Palaeoenvironmental and stratigraphic setting – Ediacaran deposits in the White Sea area of Russia are represented a thick (500 m) succession of sandstones, siltstones, and mudstones deposited in shallow basin at high palaeolatitudes; the studied assemblage comes from the Verkhovhka Formation, which underlies the Zimnie Gory Formation in the vicinity of the Solza River (Zakrevskaya, 2013). The analysed community comes from a single bed, and flourished in relatively shallow (at or within fair weather wave base) palaeonvironment, likely representing an alluvial fan or delta-front type setting disrupted by periodic mass sedimentation events which buried Ediacaran organisms (Zakrevskaya, 2013).

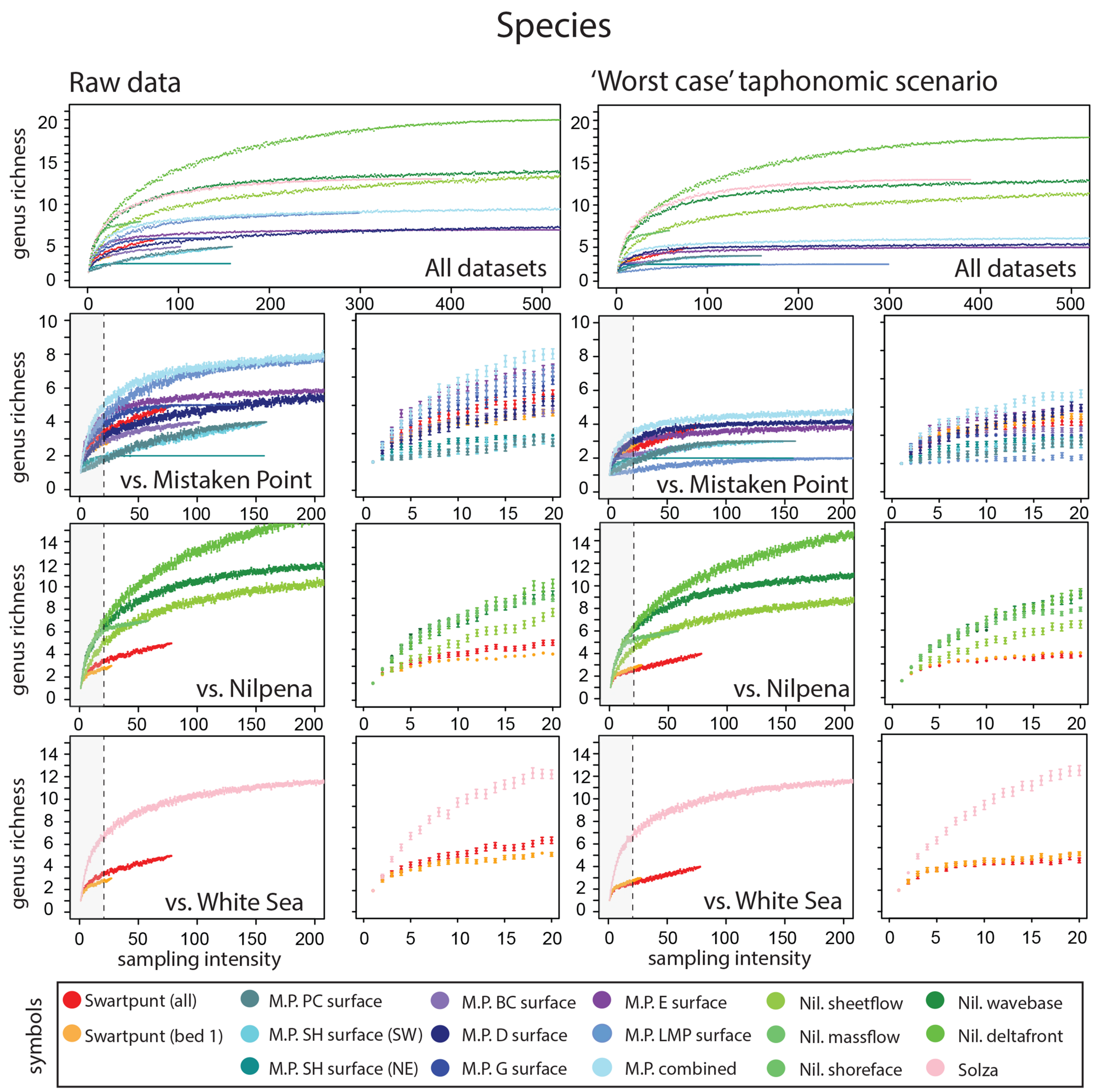
Taphonomic mode – White Sea fossils from the analysed horizon are preserved in 'Flinders-style' (of Narbonne, 2005), most likely as "death masks" after being smothered by transported sediment, similar to modes of preservation described for other Ediacaran localities worldwide (Zakrevskaya, 2013). This indicates that fossils are untransported, and most likely represent an in-situ accumulation largely in life-position (Narbonne, 2005; Zakrevskaya, 2013).

Geochronology – U-Pb dates from the White Sea area of Russia indicate ages between 552.85 ± 0.3 Ma (Zimnie Gory Formation) to 550.2 ± 4.6 Ma (base of the Yorga Formation; Llanos et al., 2005). The base of the Verhkovhka Formation has a U-Pb date of 558 ± 1 Ma (Grazhdankin, 2004).

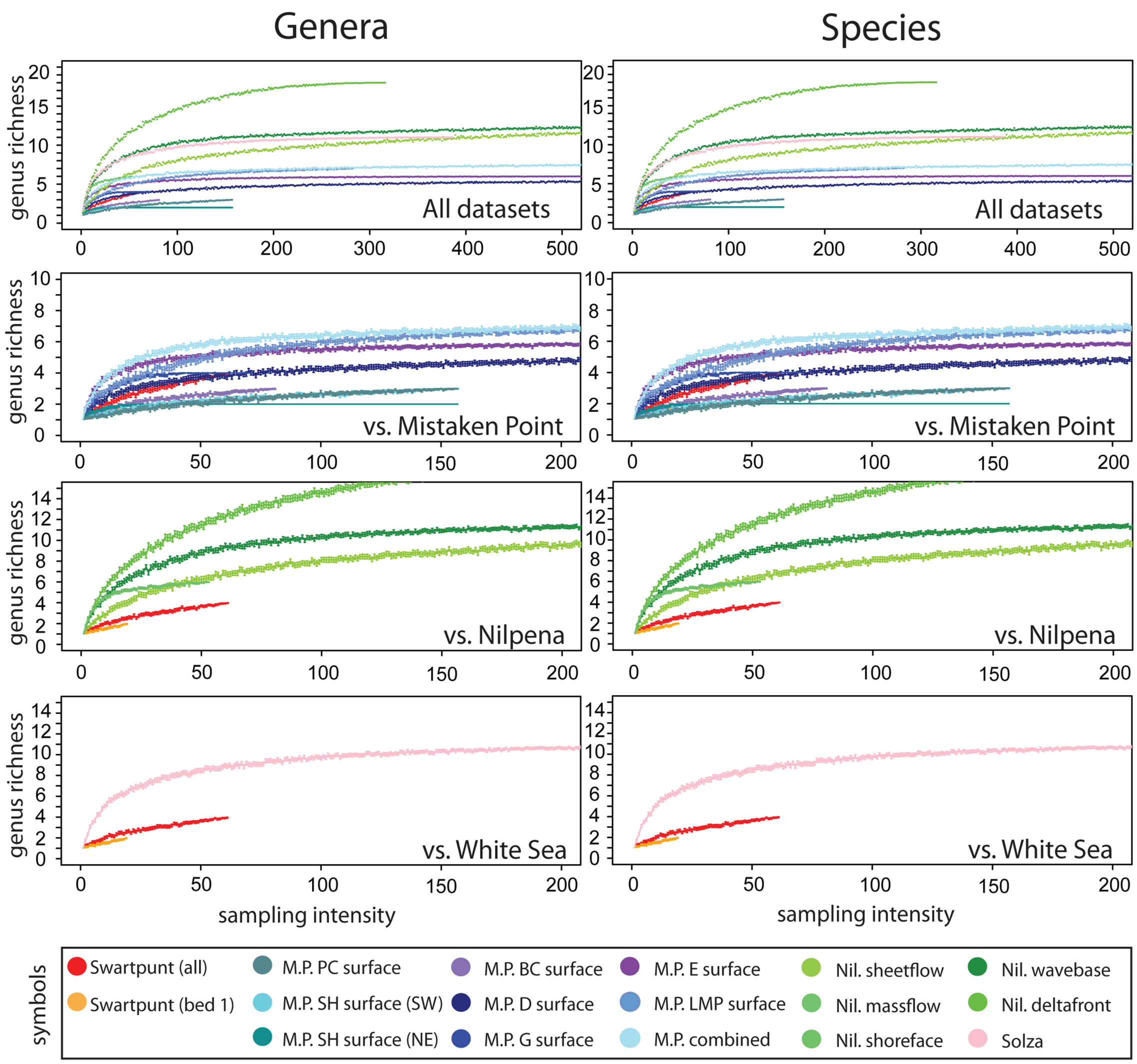
S7 – Palaeoecological indices for all studied (raw) datasets; 'SR' = Species Richness, 'Dom.' = Dominance (1 – Simpson's Index), 'M-Div' = Margalef's Diversity, 'S-W' = Shannon-Weiner Index, 'B&G Even.' = Buzas and Gibson's Evenness. Note that no surveyed-area estimates have been published for Nilpena datasets (Gehling and Droser, 2013), raising the possibility (however unlikely) that some of the elevated diversity seen in these sites may be due to richness-area effects. Also note that given the incomplete outcrop and geometry of our 'Bed 1' at Swartpunt, no reliable estimates of surveyed area could be obtained. For Mistaken Point datasets, '*Charnia*' on the Mistaken Point BC, D, E, and SH surfaces is now assigned to *Beothukis* (Brasier and Antcliffe, 2009). 'Networks' on the D surface are now assigned to *Hapsidophyllas* (Bamforth and Narbonne, 2009). 'Charnia I' on the LMP surface is now assigned to *Trepassia* (Narbonne and Gehling, 2003), while 'Charnia II' and 'ostrich feathers' on the same surface are both assigned to *Culmofrons* (Laflamme et al., 2012). *Hiemalora* on the LMP surface is now assigned to *Primocandelabrum*, on the basis of observations by Hoffmann et al. (2008). Similar to Darroch et al. (2013) we exclude Ivesheadiomorphs from analyses, as these may not represent body fossils (see for example Liu et al., 2012). For Nilpena datasets, numbers of *Aspidella* and *Funisia* are listed as '>999' in some facies. In these cases we have standardized the number of these taxa at 1000 individuals. All indices were calculated using the open-access statistical software R.

Dataset	n	Area (m^2)	SR	Dom.	M-Div.	S-W	B&G Even.	Ref.
Farm_Swartpunt	79	20358.68	5	0.52	0.92	0.90	0.49	NA
Swartpunt_Bed1	28	NA	3	0.54	0.60	0.74	0.7	NA
MP_E_surface	3020	104.75	6	0.34	0.62	1.29	0.61	[31]
MP_BC_surface	103	0.71	4	0.59	0.65	0.74	0.52	[31]
MP_D_surface	1455	63.4	7	0.66	0.82	0.70	0.29	[31]
MP_G_surface	135	7.05	5	0.39	0.82	1.12	0.61	[31]
MP_LMP_surface	300	14.0	8	0.38	1.23	1.22	0.42	[31]
MP_PC_surface	158	16.7	2	0.80	0.20	0.35	0.71	[31]
MP_SH_surface (NE)	159	NA	4	0.90	0.59	0.24	0.32	[31]
MP_SH_surface (SW)	160	NA	4	0.92	0.59	0.22	0.31	[31]
Nilpena_shoreface	11	NA	5	0.22	1.67	1.55	0.94	[32]
Nilpena_wavebase	3069	NA	15	0.23	1.74	1.79	0.40	[32]
Nilpena_deltafront	554	NA	19	0.25	2.85	1.88	0.34	[32]
Nilpena_sheetflow	1455	NA	14	0.49	1.79	1.21	0.24	[32]
Nilpena_massflow	59	NA	7	0.19	1.47	1.75	0.82	[32]
MP_combined	4610	175.2	10	0.79	1.41	1.3	0.38	NA
White Sea (Solza)	390	14.4	12	0.19	1.84	1.9	0.56	XXX

S8 – Results of rarefaction analyses at species (rather than genus) level; note that patterns are virtually identical between analyses at both taxonomic resolutions.



S9 – Results of rarefaction analyses excluding *Aspidella* for both genus- and species-level analyses; results are identical to those of raw data, illustrating that patterns are not controlled by frondose taxa. Top panels illustrate all datasets. Middle panels illustrate contrasts between Swartpunt and Mistaken Point datasets, and lower panels illustrate contrasts between Swartpunt and Nilpena datasets; error bars have been added to these panels as 95% confidence intervals around mean diversity values. Areas of low sampling intensity (shaded in grey) have been expanded in adjacent panels to better illustrate differences in richness at low sample numbers.



S10 – Supp. Geochemical data Table 1 (as .xls file)

S11 – Supp. Geochemical data Table 2 (as .xls file)

S12 – Although these geochemical tests provide no evidence for a stressed environment, caveats do exist. First, current geochemical proxies can fingerprint anoxic conditions with certainty, but have difficulty unambiguously distinguishing oxic from ferruginous conditions under certain conditions (Sperling et al., 2014). The sum of multi-proxy data from the Spitskopf Member, however, makes a ferruginous Palaeoenvironment unlikely. More pertinently, available geochemical proxies distinguish oxic from anoxic conditions in an essentially binary fashion, and cannot inform us about degrees of dysoxia that are biologically relevant (Poulton and Canfield, 2011). Along these lines, it is also possible that the Nama Group Ediacarans were living in close proximity to a chemocline, and were periodically flooded by low-O_2 waters. The biological relevance of this is mitigated by the observation that in modern environments where metazoans are subjected to periodic upwelling of anoxic and even euxinic waters, such as off the coast of Namibia, a well-established and moderate diversity (albeit lower diversity than in very nearshore waters) community continues to exist (Zettler et al., 2009; 2013). This illustrates that in the modern ocean, relatively diverse communities of aerobic multicellular heterotrophs can exist in the face of periodic dysoxic to anoxic waters (although many Ediacaran organisms may not actually have been animals – see Erwin et al., 2011; Laflamme et al., 2013). Finally, it is noted that organic carbon contents of the fossiliferous strata are not just low, but essentially nonexistent. In conjunction with a complete absence of pyrite, it suggests that these rocks have been subject to oxidative weathering processes. While this will not unduly affect the ability of the iron speciation proxy to distinguish an oxic from anoxic water column, as pyrite will weather into iron oxides and remain in the highly reactive pool, it does indicate that the original organic carbon values were likely higher than measured.

Supplementary references

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