Supplementary Material Submission for Paper

Peak glacial 14C ventilation ages suggest major drawdown into the abyssal ocean

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Introduction

The Auxiliary Texts no. 1 – 8 contain paragraphs that provide supplementary information about details of evidence, which contribute to a better understanding of the main text. Moreover, Fig. S1 shows the ^{14}C plateau-based derivation of planktic and benthic ^{14}C reservoir ages at six core sites for the interval 23-13 ka. Fig. S2 supplies supplementary evidence for a deglacial convection of deepwater in the Northeast Pacific.

Auxiliary Text #1:

By and large, we may equate the single data points in Fig. 2a with equal volumetric units below 2000 m w.d. (assuming a fairly homogenous global distribution of measuring points; compare Fig. 5). In contrast to (Key et al., 2004), we do not weight our $D^{14}C$ data by volumetric estimates that we might derive from the 'gridding' method. We regard this approach as problematic because of concerns about unrealistic spatial patterns that result from the gridding of GLODAP data (Section 2.1).

Auxiliary Text #2:

Different from the conjecture of Campin et al. (1999), the downwelling of deep waters from the Weddell Sea does not lead to DIC depletion of circumpolar and Pacific deep waters, rather to a slight and partly anthropogenic (Mikaloff-Fletcher et al., 2006) enrichment in DIC. Probably, this unexpected trend results from the low temperatures at which, and the short time during which the upwelled waters are exposed to atmospheric exchange prior to their renewed downwelling in the circum-Antarctic polynyas. This interval is too short for a major carbon release to the atmosphere. Per theory, an equilibrium between atmospheric and surface ocean pCO_2 requires an open contact over about six months (Sarmiento & Gruber, 2006). Seasonally open polynyas and unrestricted gas exchange in the Weddell Sea region last for six months and less. Thus the exchange of CO_2 with the atmosphere will rejuvenate only less than 50 % of carbon-enriched NADW waters upwelled over a whole year, which in turn leads to an initial age of <~1200 ^{14}C yr of Weddell Sea Deep Water. Probably, the exposure time would not rise, rather drop, with a much increased circum-Antarctic sea ice cover during peak glacial times (Gersonde et al., 2003).

Auxiliary Text #3:

Mol ratios of C_{org}/O_2 respiration vary from 0.48–1.43 for the different ocean basins and give a global average value of 0.95. These mol ratios agree reasonably well with averages of 1.13 and 1.23-1.7, published by Redfield et al. (1963) and Takahashi et al. (1985), respectively. However, C_{org} / PO_4 remineralization ratios estimated from the slopes of C_{org} and PO_4 versus $\Delta^{14}C$ (equivalent to ventilation age) reveal generally low values of 45-109 and a global average of 80, as compared to published values of 103-122 mol/mol. Yet, respective uncertainties are probably large due to low slope gradients of generally low concentrations in PO_4.

Auxiliary Text #4:

The separation of the organic and inorganic (calcite) contribution to the deep-ocean DIC increase is inferred from the regression of $\Delta^{14}C$ versus potential alkalinity (POTALK), which reflects the influence of

$CaCO_3$ dissolution. Different from Berner et al. (1975) we do not normalize POTALK by salinity which is almost constant in the deep ocean. Fig. 4 shows that a 1 ‰ decrease in $\Delta^{14}C$ parallels an increase by 1 (0.8–1.7) μmol/kg POTALK. Due to the 2:1 relationship of alkalinity versus DIC changes under $CaCO_3$ precipitation / dissolution (Zeebe & Wolf-Gladrow, 2001), a 1 μmol/kg rise in POTALK contributes 0.5 μmol/kg DIC to a total increase of 1.22 μmol/kg DIC per 1 ‰ decrease in $\Delta^{14}C$. The remainder of 0.72 μmol/kg represents the actual organic carbon contribution. Assuming an average aging of the water masses by 9.7 yr per 1‰ decrease in $\Delta^{14}C$ (Fig. 2a), the rate of total carbon remineralization in the deep ocean >2000 m amounts to 0.64 GtC/^{14}C yr stemming from particulate organic carbon (POC) and 0.45 GtC/^{14}C yr coming from calcite dissolution (particulate inorganic carbon = PIC).

Auxiliary Text # 5:

Projection age records are rarely employed in our study for three reasons. (1) Except for Skinner et al. (2010) and Thornalley et al. (2011) no robust projection-based ages were available for sites at >2000 m w.d. (2) Short-term changes in atmospheric ^{14}C introduce an uncertainty in the inherited-age calculation, that is larger than that of plateau tuning. (3) The varve-counted atmospheric ^{14}C record of Suigetsu (Bronk Ramsey et al., 2012) reveals for the LGM an older period of roughly constant $\Delta^{14}C$ around 24–21 ka, separated by a ~70-‰ drop (600 yr) near 21 ka from a younger one extending from ~20.5–17.5

ka. We neglect these shifts for our LGM average estimates of benthic $\Delta^{14}C$ in view of the overall magnitude of the benthic $\Delta^{14}C$ shifts under discussion and further uncertainties that apply to the derivation of deep-water $\Delta^{14}C$ (e.g., millennial-scale variability). For the subsequent HS-1, deep waters with apparent ^{14}C ages of 1000–5000 yr may contain a more significant $\Delta^{14}C$ 'heritage' of LGM waters reaching up to 120 ‰ (equal to ~1000 ^{14}yr) from an earlier ^{14}C-enriched atmosphere, making them artificially 'young'. In particular, this factor concerns the extremely old waters of the deep northeastern North Atlantic (Thornalley et al., 2011). However, the magnitude of the short-lasting ventilation pulse of 'young' northeast Pacific deep waters (Fig. S1h) far exceeds what could be expected from an inherited $D^{14}C$ signal during HS-1. The B/A provides a further example for a short-term ^{14}C heritage of 'fossil' deep waters, that may reach up to 100–220 ‰ (equal to 850–2000 ^{14}yr), when benthic ventilation age estimates are fairly low for all ocean basins, in part possibly an artifact of inherited high $\Delta^{14}C$, a factor so far neglected because of reconstruction uncertainties.

Auxiliary Text # 6:

Averaging techniques and uncertainties to calculate planktic reservoir ages from planktic ^{14}C plateaus.

To calculate past planktic reservoir ages and associated $\Delta^{14}C$ we subtract the average ^{14}C ages of ^{14}C plateaus 1-7 in the Lake Suigetsu record of atmospheric ^{14}C (Bronk Ramsey et al., 2012) from the average ages of respective planktic ^{14}C plateaus measured in deep-sea cores, as shown in Fig. S1. Uncertainties of planktic ^{14}C age and $\Delta^{14}C$ are derived from the bandwiths of the respective plateaus enveloping the Suigetsu atmospheric and planktic ^{14}C ages each, assuming that half the plateau width includes the complete data scatter of ^{14}C ages, except for some extreme outliers (<10%), thus roughly corresponds to an uncertainty range of 2 sigma. ^{14}C analytical uncertainties are considerably smaller. Combining the 2-sigma uncertainties of the two ^{14}C plateau records by the square root of the sum of the squares gives an estimate of the uncertainty in the planktic $\Delta^{14}C$ estimate.

Auxiliary Text #7:

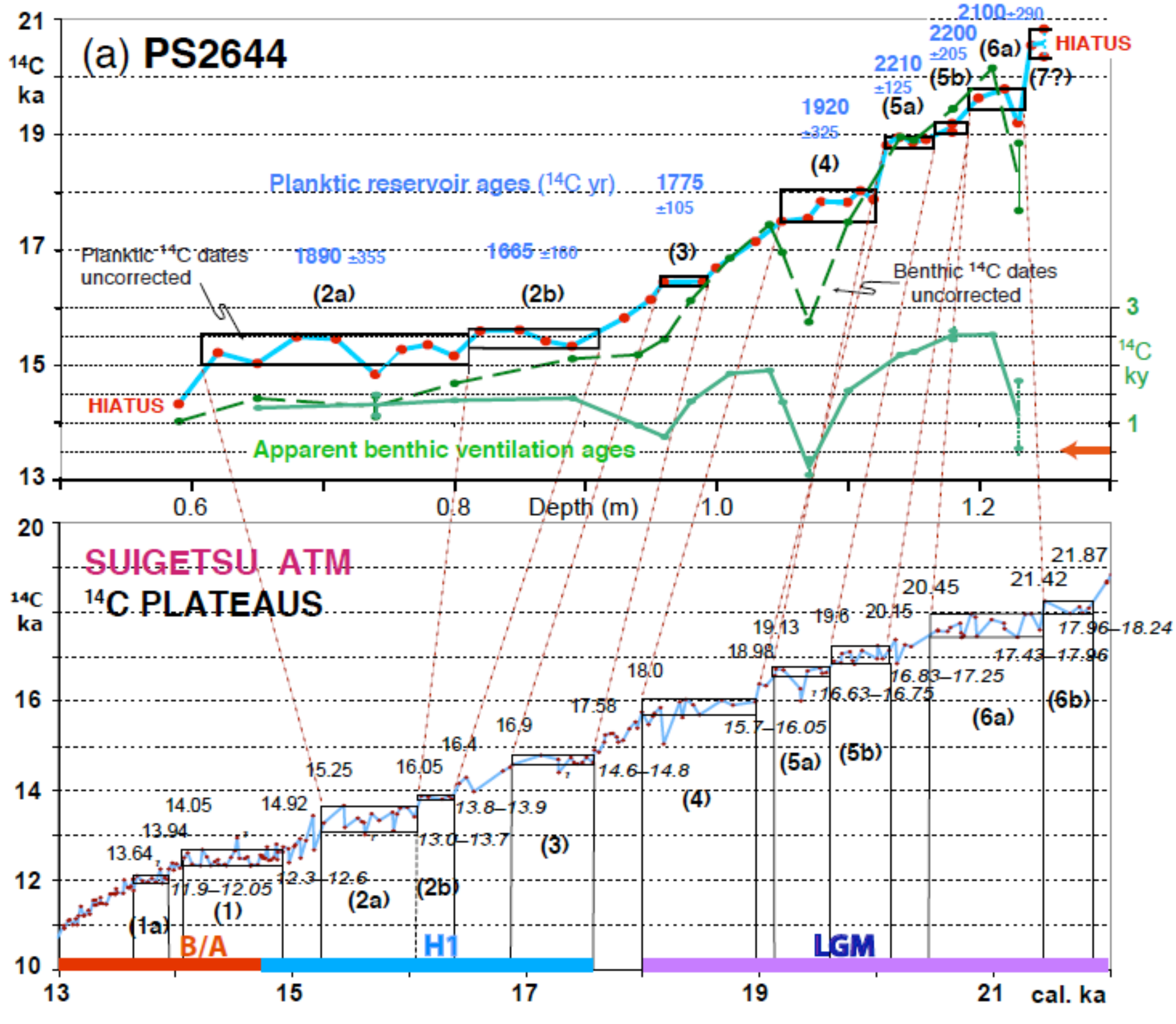
In contrast to conjectures suggesting errors in age control or reworking of old sediments as explanation for apparent high surface reservoir ages, we see robust arguments in favor of the very old planktic reservoir ages used in our study. First, similar age ranges result from independent lines of evidence based on 5 different techniques. Second, reworking of 'old' planktic foraminiferal sediments as cause for high planktic reservoir ages can be excluded for various reasons at the different core sites. (1) Over the last 12 years well dated tephra layers, such as the North Atlantic Vedde Ash, already served as stringent evidence at various sites. (2) Detailed inspection of sediment structures at the sites under discussion reveals an undisturbed hemipelagic sediment sequence free of turbidites, rarely interrupted by short-lasting stratigraphic gaps linked to stadial-to-interstadial changes in the sediment regime; (3) The selection of core sites on top of elevated submarine plateaus (e.g., the Detroit Seamount in the North Pacific; a promontory off northwestern Iceland; etc.) largely exclude a large-scale lateral input of reworked sediments. (4) Both surface and bottom water ages reached short-lasting maxima in the North Atlantic during HS-1. These extremes are just coeval with a minimum in NADW-linked bottom currents, that entails minimum particle transport at sediment drifts, as independently supported by a variety of other proxies ($\delta^{13}C_{be}$; Pa/Th; magnetic susceptibility records, silt modal grain sizes). (5) In many cases strongly oscillating benthic-planktic age differences show that high or low surface water ages do not necessarily covary with analogous changes in deep-water age (Thornalley et al., 2011). (6) To contaminate planktic ages by +1500/+2000 ^{14}C yr (equivalent to ~1/3 of a ^{14}C half-life) by reworked planktic foraminifera tests requires a significant lateral input of tests >60 ky to >20 ky older than the deposits used for reservoir age calculation. This input ranges from 17% - 22% of the total foraminifera number for an admixture that is 60 ky older, and from 19% - 24% for an admixture that is 20 ky older. These amounts are highly unlikely in view of foram census counts that suggest pronounced and abrupt millennial-scale SST changes (e.g., Weinelt et al., 2003). (7) High planktic reservoir age levels obtained for a particular time slice from different sites turn out to be consistent within a particular sea region. (8) At two sites (GIK 17940, PS2644), a major lowering of the very high planktic ^{14}C reservoir ages in conjunction with the large benthic-planktic age difference would result in negative benthic reservoir ages that are physically impossible. At other sites in the North Pacific and South China Sea, any lowering of planktic reservoir ages would imply benthic reservoir ages unreasonably low, i.e., indicating transient deepwater formation in the South China Sea during B/A and the Younger Dryas.

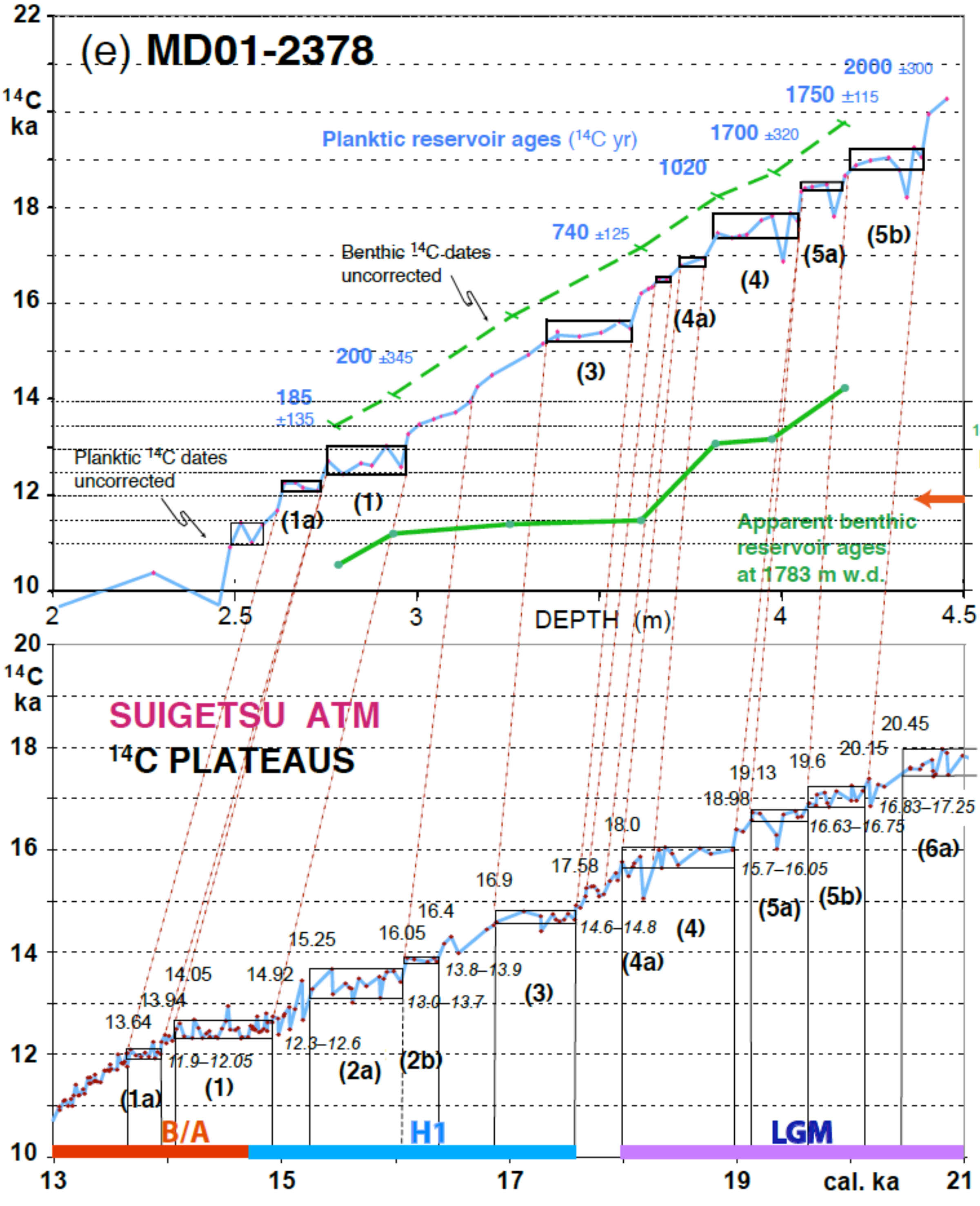
Unfortunately, a bias of presumed constant ^{14}C reservoir ages applies to great number of deglacial age estimates published for waters in the North Pacific (e.g., Jaccard et al., 2009; Okazaki et al., 2010) and the upwelling region off Chile (De Polz et al., 2010). Here allegedly constant planktic reservoir ages contrast sharply with short-term shifts in Holocene reservoir ages that almost reach 900 yr, as reported from the nearby upwelling region off Peru (Fontugne et al., 2004).

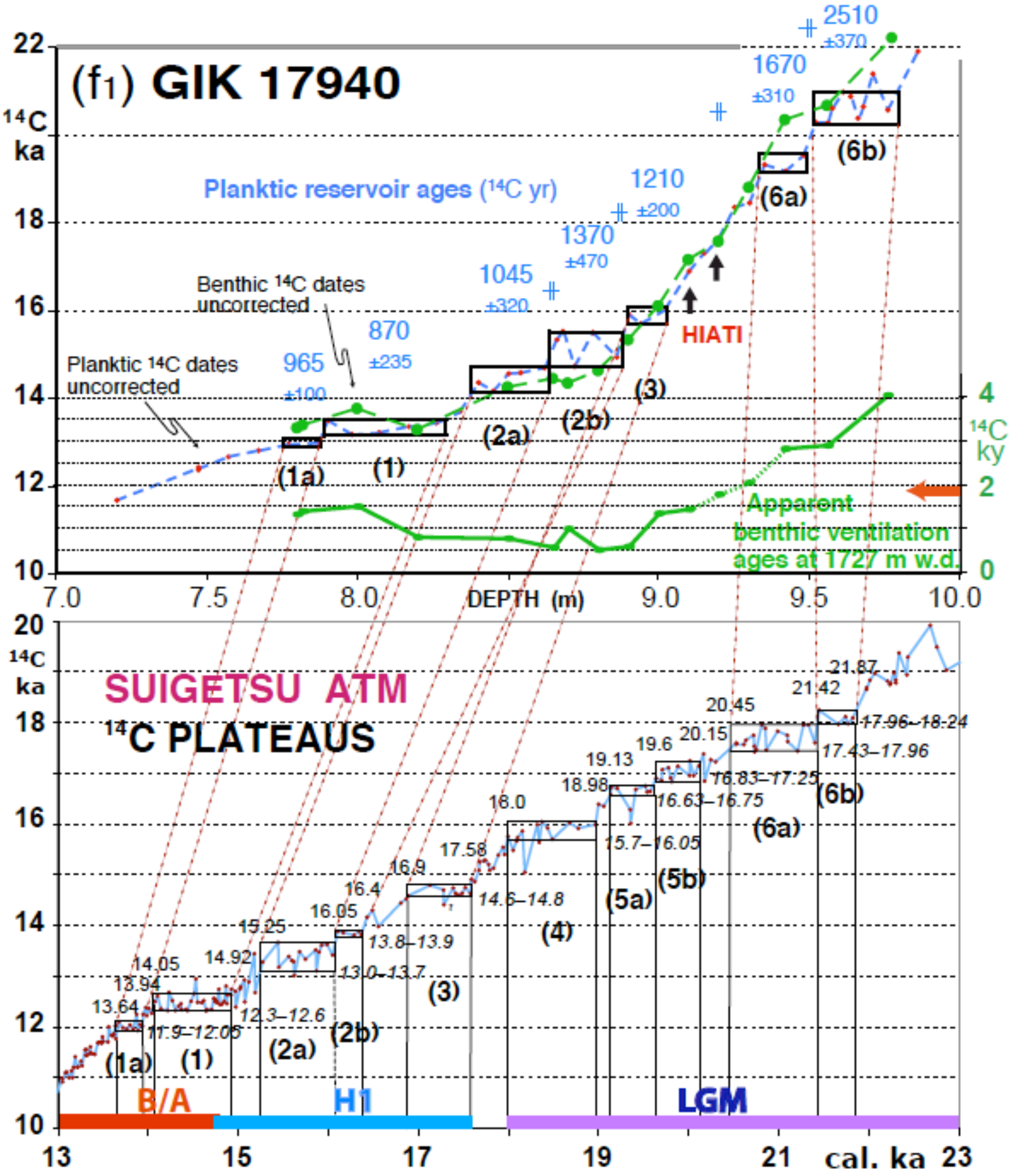
Auxiliary Text #8:
Skinner et al. (2010) also discuss (lower) deep-water ventilation ages from a second core TN057-21 retrieved in the Atlantic sector of the Southern Ocean near South Africa (Barker et al., 2010). However, age control at this site at ~5000 m w.d. appears problematic, since it is affected by the hardly defensible assumption of a constant planktic reservoir age of 600 yr and intervals of enhanced $CaCO_3$ dissolution (foraminiferal fragmentation rate of 40-60 % during LGM and 60-70 % during HS-1). Moreover, reservoir ages derived from the ^{14}C projection

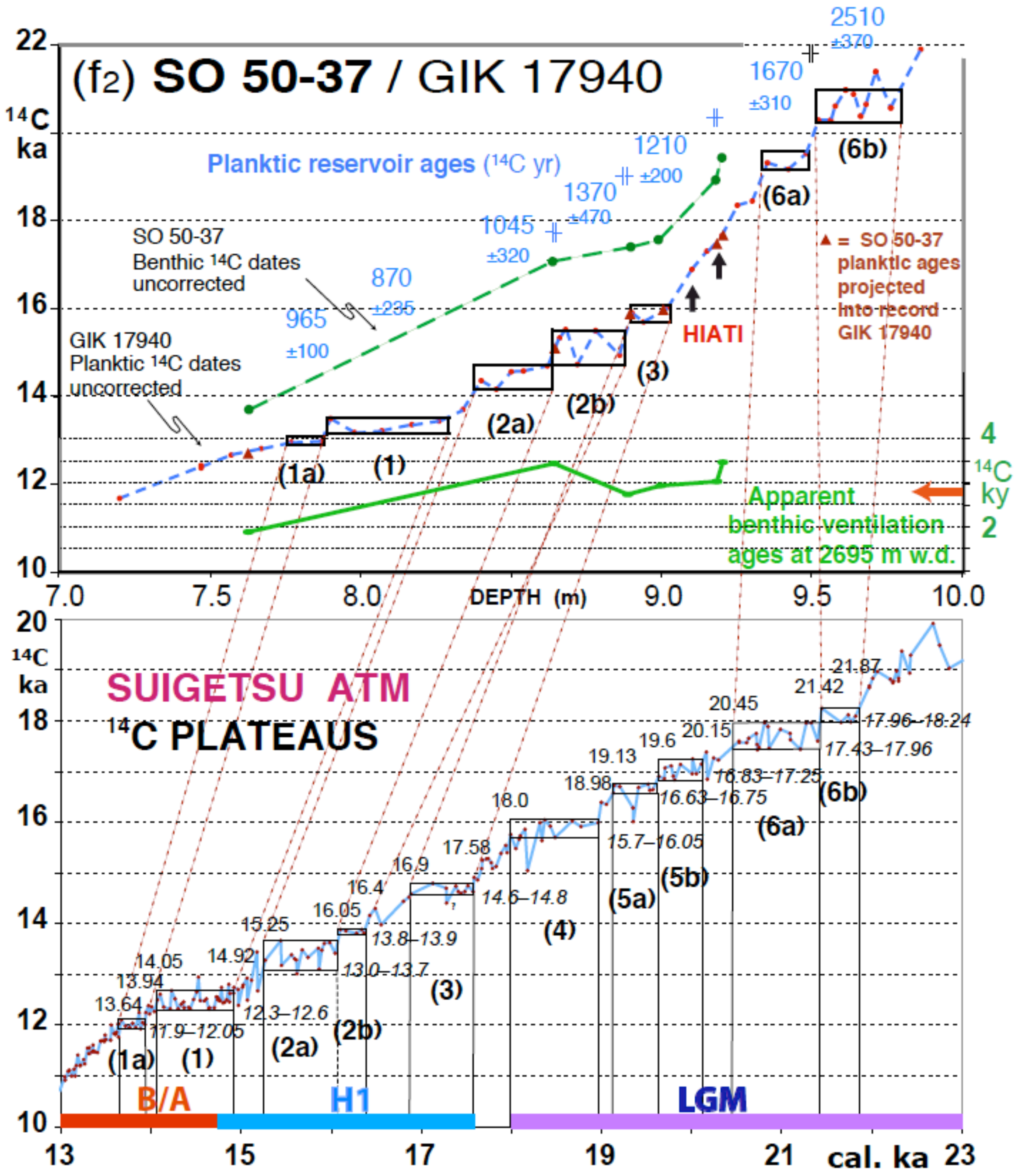
method suffer from a broad uncertainty range. Thus, the youngest end member of LGM benthic reservoir ages from this core was marked by a question mark in Fig. 3.

Fig. S1. Suite of raw-^{14}C plateaus (horizontal boxes) in six marine sediment cores (top panels), plotted vs core depth and tuned to the varve-counted atmospheric ^{14}C reference record of Lake Suigetsu (lower panel) (Bronk Ramsey et al., 2012). Core locations are for PS2644: 67°52'N, 21°46'W, 777 m w.d.; MD01-2378: 13°05'S, 123° 43.3'E, 1783 m w.d.; GIK 17940: 27°07'N, 117°23'E, 1727 m w.d.; SO50-37: 18°55'N, 115°45'E, 2695 m w.d.; MD01-2416: 51°27'N, 167°73'E, 2317 m w.d.; MD98-2181: 6°18'N, 125°49'E, 2114 m w.d.; and for MD02-2489: 54°39'N, 148°92'W, 3640 m w.d. (Sarnthein et al., in prep. for Radiocarbon, 2013). B/A = Bølling-Allerød; H1 = Heinrich 1; LGM = Last Glacial Maximum. Planktic reservoir ages result from the difference between the average uncorrected ^{14}C age of planktic ^{14}C plateaus measured in the cores and the ^{14}C age of equivalent atmospheric ^{14}C plateaus numbered 1 – 7. Green broken lines connect uncorrected ^{14}C age data of paired benthic foram samples. The light green record depicts temporal evolution of apparent benthic ventilation ages that sum up the planktic reservoir age and the coeval benthic-planktic age difference. Horizontal red arrows show apparent modern ventilation age. Planktic ^{14}C ages of Core SO50-37 (red triangles in Fig. S1f2) are projected onto the depth scale of the planktic ^{14}C record of neighbor core 17940 (Fig. S1f1), assuming that planktic reservoir ages do not change over small distances near the northern margin of the South China Sea. Fig. S1g$_2$ displays benthic (and planktic) $\Delta^{14}C$ ranges derived from two coeval atmospheric ^{14}C ages measured on paired wood fibres at 1270-1276 cm depth in Core MD98-2181 (average sedimentation rates are ~65 cm/ky). Gr = G. ruber, Gs = G. sacculifer measured in Kiel, Woods Hole, and Irvine. MiBe (= mixed benthics) and GsBr are ^{14}C ages of Broecker et al. (2004).

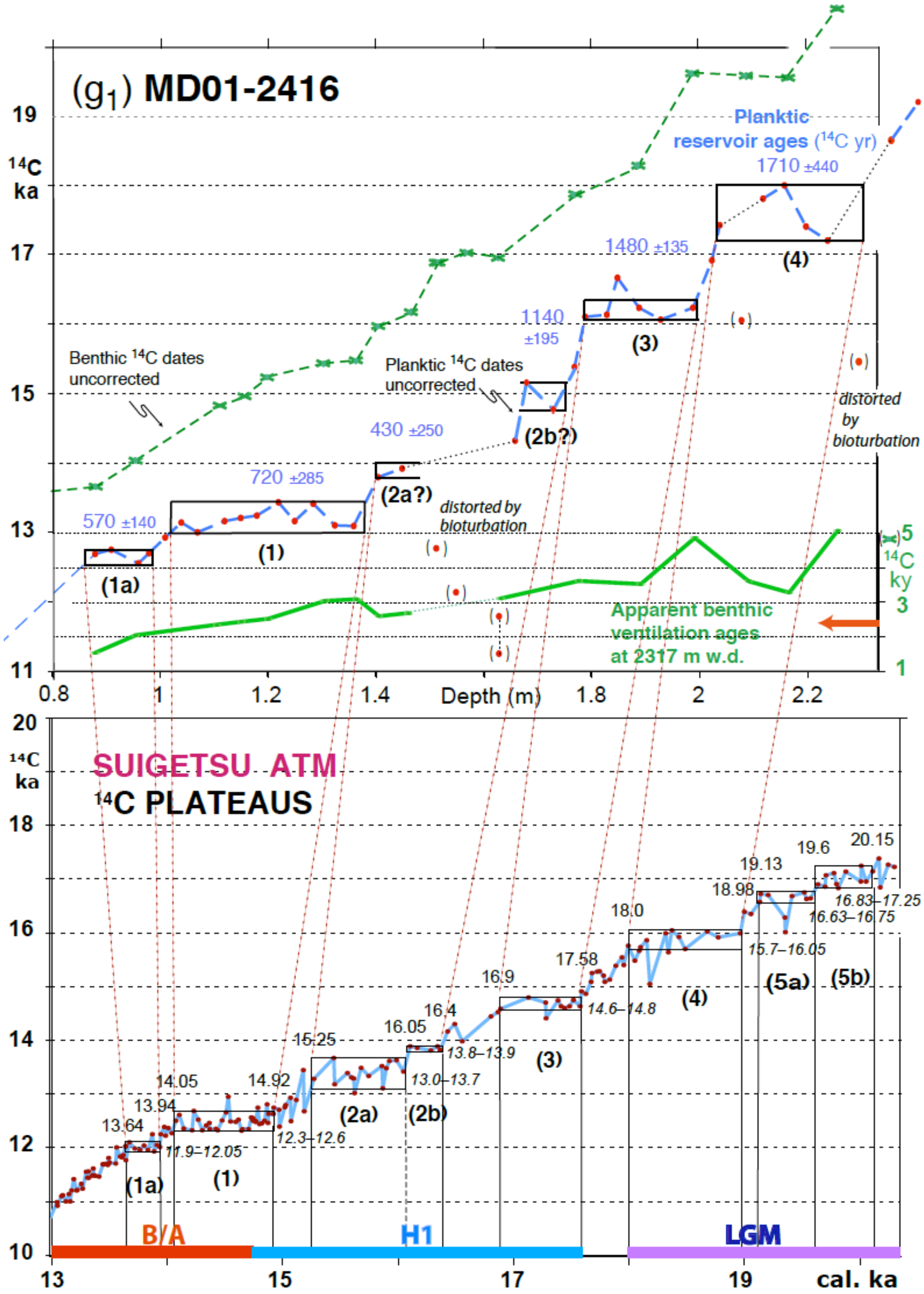


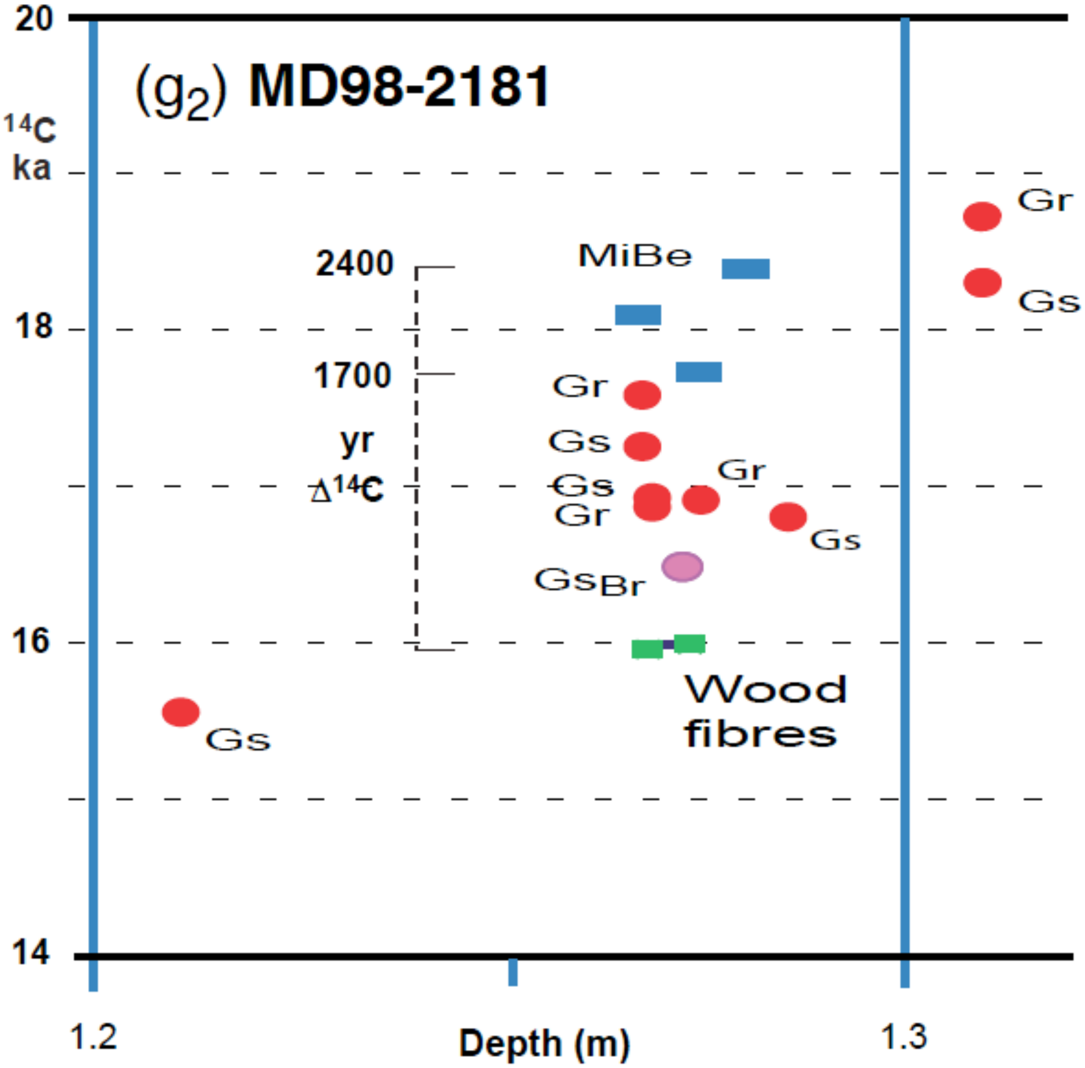

(e) MD01-2378
¹⁴C ka
22
18
16
14
12
10
Planktic reservoir ages (¹⁴C yr)
2000 ±300
1750 ±115
1700 ±320
1020
740 ±125
200 ±345
185 ±135
Benthic ¹⁴C dates uncorrected
Planktic ¹⁴C dates uncorrected
(1a)
(1)
(3)
(4a)
(4)
(5a)
(5b)
3
¹⁴C ky
2
1
Apparent benthic reservoir ages at 1783 m w.d.
2
2.5
3
DEPTH (m)
4
4.5
20
¹⁴C ka
SUIGETSU ATM
¹⁴C PLATEAUS
18
16
14
12
10
13.64
13.94
14.05
14.92
15.25
16.05
16.4
16.9
17.58
18.0
18.98
19.13
19.6
20.15
20.45
11.9–12.05
12.3–12.6
13.0–13.7
13.8–13.9
14.6–14.8
15.7–16.05
16.63–16.75
16.83–17.25
(1a)
(1)
(2a)
(2b)
(3)
(4a)
(4)
(5a)
(5b)
(6a)
B/A
H1
LGM
13
15
17
19
cal. ka
21


(f1) GIK 17940
14C ka
22
18
16
14
12
10
Planktic reservoir ages (14C yr)
Benthic 14C dates uncorrected
Planktic 14C dates uncorrected
965 ±100
870 ±235
1045 ±320
1370 ±470
1210 ±200
1670 ±310
2510 ±370
HIATI
(1a)
(1)
(2a)
(2b)
(3)
(6a)
(6b)
4
14C ky
2
0
Apparent benthic ventilation ages at 1727 m w.d.
7.0
7.5
8.0
DEPTH (m)
9.0
9.5
10.0
SUIGETSU ATM
14C PLATEAUS
20
14C ka
18
16
14
12
10
13.64
13.94
14.05
14.92
15.25
16.05
16.4
16.9
17.58
18.0
18.98
19.13
19.6
20.15
20.45
21.42
21.87
11.9–12.05
12.3–12.6
13.0–13.7
13.8–13.9
14.6–14.8
15.7–16.05
16.63–16.75
16.83–17.25
17.43–17.96
17.96–18.24
(1a)
(1)
(2a)
(2b)
(3)
(4)
(5a)
(5b)
(6a)
(6b)
B/A
H1
LGM
13
15
17
19
21
cal. ka
23



(f2) SO 50-37 / GIK 17940
14C ka
22
18
16
14
12
10
Planktic reservoir ages (14C yr)
2510 ±370
1670 ±310
1210 ±200
1370 ±470
1045 ±320
870 ±235
965 ±100
SO 50-37 Benthic 14C dates uncorrected
GIK 17940 Planktic 14C dates uncorrected
(1a)
(1)
(2a)
(2b)
(3)
(6a)
(6b)
HIATI
▲ = SO 50-37 planktic ages projected into record GIK 17940
4
14C ky
2
Apparent benthic ventilation ages at 2695 m w.d.
7.0
7.5
8.0
DEPTH (m)
9.0
9.5
10.0
20
14C ka
SUIGETSU ATM
14C PLATEAUS
18
16
14
12
10
13.64
13.94
14.05
14.92
15.25
16.05
16.4
16.9
17.58
18.0
18.98
19.13
19.6
20.15
20.45
21.42
21.87
11.9–12.05
12.3–12.6
13.0–13.7
13.8–13.9
14.6–14.8
15.7–16.05
16.63–16.75
16.83–17.25
17.43–17.96
17.96–18.24
(1a)
(1)
(2a)
(2b)
(3)
(4)
(5a)
(5b)
(6a)
(6b)
B/A
H1
LGM
13
15
17
19
21
cal. ka
23


(g1) MD01-2416
19
14C ka
17
15
13
11
Planktic reservoir ages (14C yr)
1710 ±440
(4)
1480 ±135
(3)
1140 ±195
Benthic 14C dates uncorrected
Planktic 14C dates uncorrected
(2b?)
430 ±250
distorted by bioturbation
720 ±285
(2a?)
570 ±140
(1)
(1a)
distorted by bioturbation
5
14C ky
3
1
Apparent benthic ventilation ages at 2317 m w.d.
0.8
1
1.2
1.4
Depth (m)
1.8
2
2.2
20
14C ka
SUIGETSU ATM
14C PLATEAUS
18
16
14
12
10
20.15
19.6
19.13
18.98
16.83–17.25
16.63–16.75
18.0
15.7–16.05
(5a)
(5b)
17.58
16.9
(4)
14.6–14.8
16.4
16.05
15.25
13.8–13.9
(3)
14.05
14.92
13.0–13.7
13.94
(2a)
(2b)
13.64
12.3–12.6
11.9–12.05
(1a)
(1)
B/A
H1
LGM
13
15
17
19
cal. ka


(g2) MD98-2181
20
14C ka
18
16
14
2400
1700
yr
Δ14C
MiBe
Gr
Gs
Gr
Gs
Gs
Gr
Gr
Gs
GsBr
Wood fibres
Gs
1.2
Depth (m)
1.3

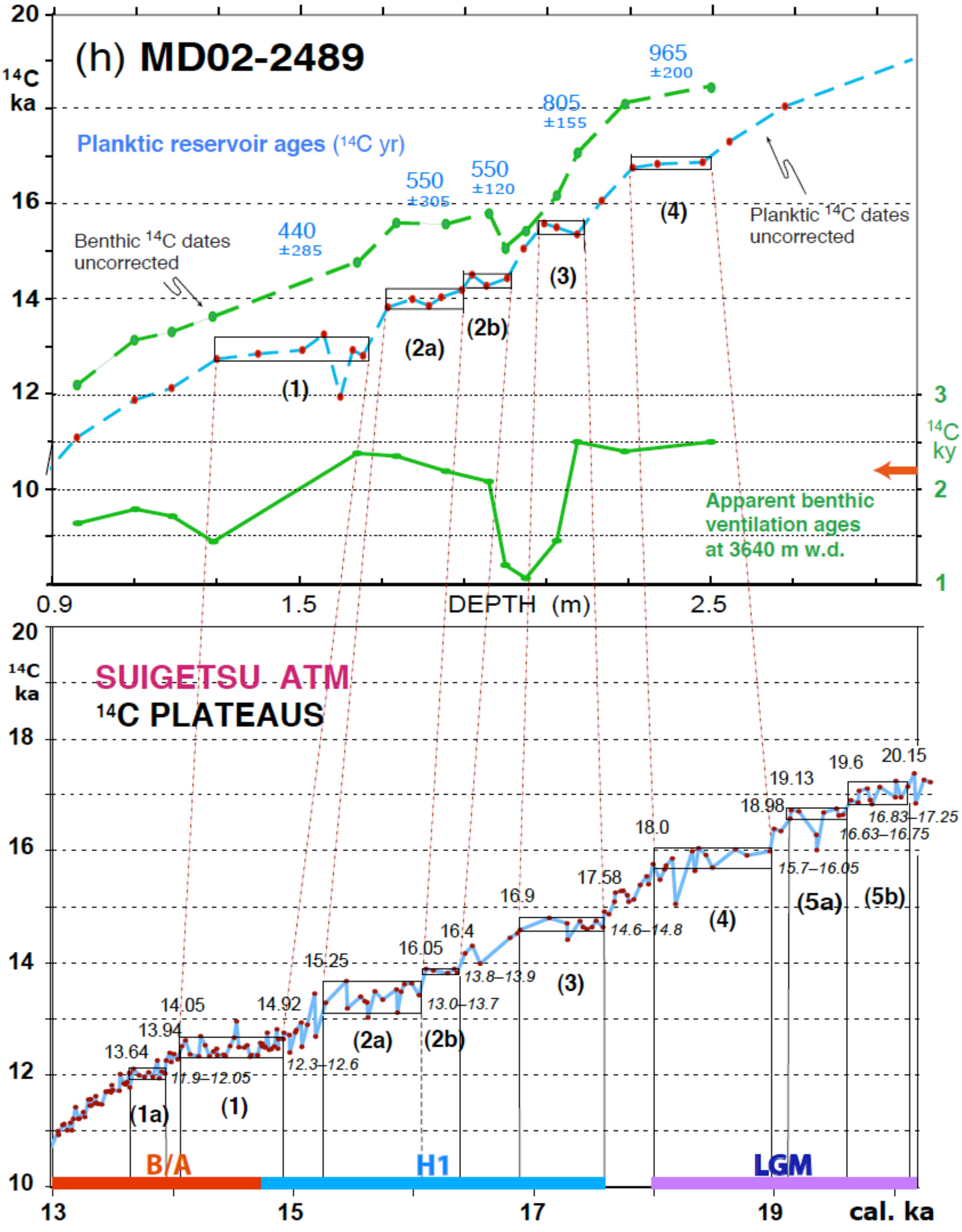
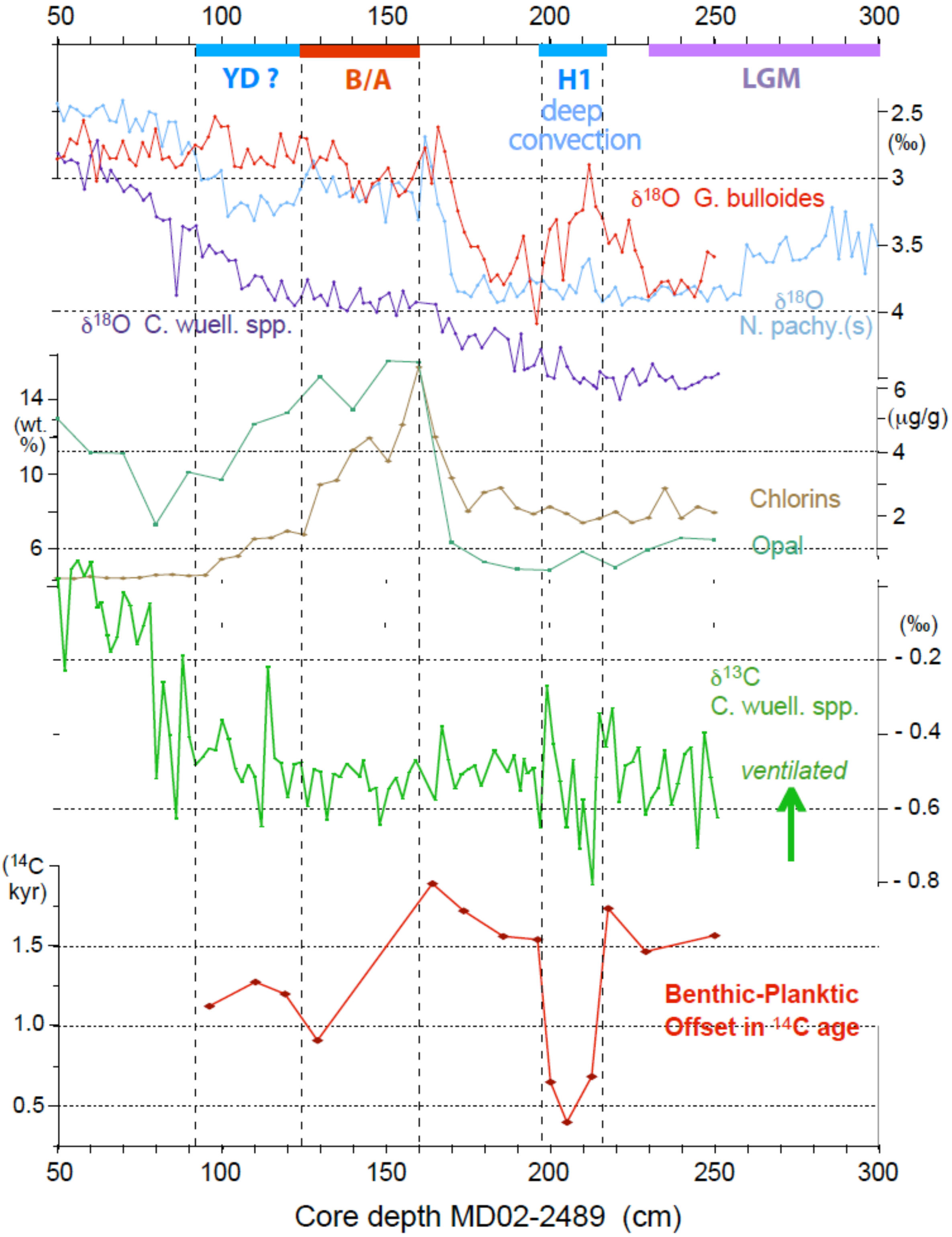

(h) MD02-2489
14C ka
20
16
14
12
10
Planktic reservoir ages (14C yr)
440 ±285
550 ±305
550 ±120
805 ±155
965 ±200
Benthic 14C dates uncorrected
Planktic 14C dates uncorrected
(1)
(2a)
(2b)
(3)
(4)
3
14C ky
2
1
Apparent benthic ventilation ages at 3640 m w.d.
0.9
1.5
DEPTH (m)
2.5
SUIGETSU ATM
14C PLATEAUS
14C ka
20
18
16
14
12
10
13.64
13.94
14.05
14.92
15.25
16.05
16.4
16.9
17.58
18.0
18.98
19.13
19.6
20.15
11.9–12.05
12.3–12.6
13.0–13.7
13.8–13.9
14.6–14.8
15.7–16.05
16.63–16.75
16.83–17.25
(1a)
(1)
(2a)
(2b)
(3)
(4)
(5a)
(5b)
B/A
H1
LGM
13
15
17
19
cal. ka

Fig. S2. $\delta^{18}O$ of planktic and benthic foramininiferal species, contents of biogenic opal and chlorophyll pigment (chlorins), benthic $\delta^{13}C$ of *C. wuellerstorfi*, and $\Delta^{14}C$ age difference between benthic and planktic foraminifera in ^{14}C kyr from core MD02-2489 plotted versus core depth (data from Gebhardt et al., 2008, suppl). Age control deduced by means of ^{14}C plateau tuning (Fig. S1h) and the $\delta^{18}O$ record of *N. pachyderma* s. During the marked HS-1 minimum in the benthic-planktic $\Delta^{14}C$ offset benthic $\delta^{13}C$ shows an abrupt major drop, in our opinion linked to an initial down mixing of intermediate waters. The subsequent gradual rise up to a narrow maximum suggests a short-lasting ventilation pulse (at a sampling resolution of 65 yr), when down-welled intermediate waters were replaced by a convection of surface waters. During early B/A peak concentrations of opal and chlorin suggest maximum productivity and sedimentation rates, in harmony with an extended length of ^{14}C plateau 1 in Fig. S1h.

Fig. S2


50
100
150
200
250
300
YD ?
B/A
H1
deep convection
LGM
2.5
(‰)
3
3.5
4
δ18O G. bulloides
δ18O N. pachy.(s)
δ18O C. wuell. spp.
14
(wt. %)
10
6
6
(μg/g)
4
2
Chlorins
Opal
(‰)
- 0.2
- 0.4
- 0.6
- 0.8
δ13C C. wuell. spp.
ventilated
(14C kyr)
1.5
1.0
0.5
Benthic-Planktic Offset in 14C age
50
100
150
200
250
300
Core depth MD02-2489 (cm)

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