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Reconsidering Melt-water Pulses 1A and 1B: Global Impacts of Rapid Sea-level Rise

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Abstract Re-evaluation of the post-glacial sea level derived from the Barbados coral-reef borings suggests slightly revised depth ranges and timing of melt-water pulses MWP-1A (96–76 m, 14.3–14.0 ka cal BP) and 1B (58–45 m, 11.5–11.2 ka cal BP), respectively. Ages of non-reef sea-level indicators from the Sunda Shelf, the East China Sea and Yellow Sea for these two intervals are unreliable because of the well-documented radiocarbon (^{14}C) plateau, but their vertical clustering corresponds closely with MWP-1A and 1B depth ranges. Close correlation of the revised sea-level curve with Greenland ice-core data suggests that the ^{14}C plateau may be related to oceanographic-atmospheric changes due to rapid sea-level rise, fresh-water input, and impaired ocean circulation. MWP-1A appears to have occurred at the end of Bølling Warm Transition, suggesting that the rapid sea-level rise may have resulted from lateral heat transport from low to high-latitude regions and subsequent abrupt ice-sheet collapses in both North America-Europe and Antarctica. An around 70 mm a^{-1} transgression during MWP-1A may have increased freshwater discharge to the North Atlantic by as much as an order of magnitude, thereby disturbing thermohaline circulation and initiating the Older Dryas global cooling.

Key words melt-water pulse; MWP-1A; sea-level; ^{14}C plateau; coral reef; Bølling Transition

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1 Introduction

One of the most compelling concepts in understanding the ocean's recent history has been the recognition of a punctuated, non-steady post-glacial rise of sea level (Fairbanks, 1989). Based on AMS-^{14}C (Fairbanks, 1989) and U-Th (Bard *et al.*, 1990) dates from a series of borings on drowned reefs off Barbados, two major melt-water pulses were identified – MWP-1A (14.2–13.8 ka cal BP) and MWP-1B (11.5–11.1 ka cal BP)–during which sea level rose from −94 to −74 m and −58 to −43 m, respectively (unless otherwise specified, all ages reported in this paper are in calendar years), equating to an average sea-level rise of 35–40 mm a^{-1} (Fig.1).

Subsequent sea-level studies have had mixed results confirming the existence of MWP-1A and 1B. Coral-reef drilling on Tahiti (Bard *et al.*, 1996) and the elevated reefs of the Huon Peninsula of Papua New Guinea (Chappell and Polach, 1991; Edwards *et al.*, 1993) failed to reach MWP-1A, and neither boring showed conclusive evidence of MWP-1B. Guilderson *et al.* (2000) reported finding evidence for both MWP-1A and 1B from cores on the Argentine shelf, but these dates came from 'shell layers' or 'shell hash', which prevented definitive paleo-environmental delineation.

Despite the general lack of U/Th data from coral-reef borings and the untrustworthiness of ^{14}C dates preceding the Younger Dryas (Edwards *et al.*, 1993; Bard *et al.*, 1994; Bard *et al.*, 1998), MWP-1A nevertheless has been accepted by many as '... a proven feature of postglacial eustatic sea level history' (Peltier, 2002), although its chronology is subject to question. Bard *et al.* (1996), for instance, pointed out that the 14.2–13.8 ka BP time span for MWP-1A would mean it occurred during the Older Dryas cooling (Fig.2) – a rather unusual time to expect rapid ice melt.

A more recent re-evaluation of the timing of MWP-1A came from the Sunda shelf where Hanebuth *et al.* (2000) dated a series of mangrove peat deposits in five cores taken at depths between −96 and −80 m. AMS derived ^{14}C dates of these peat samples, calibrated using INTCAL98/CAL4.0 to redefine the timing of MWP-1A, were virtually identical between −96 m and −80 m (Figs.3a and b). While these closely spaced ^{14}C-derived dates may not only reflect incorporation of older and younger organic matter within the peat layers during a rapid transgression, they may also occur within the well-documented ^{14}C plateau (Fig.4c) (*e.g.* Kitagawa

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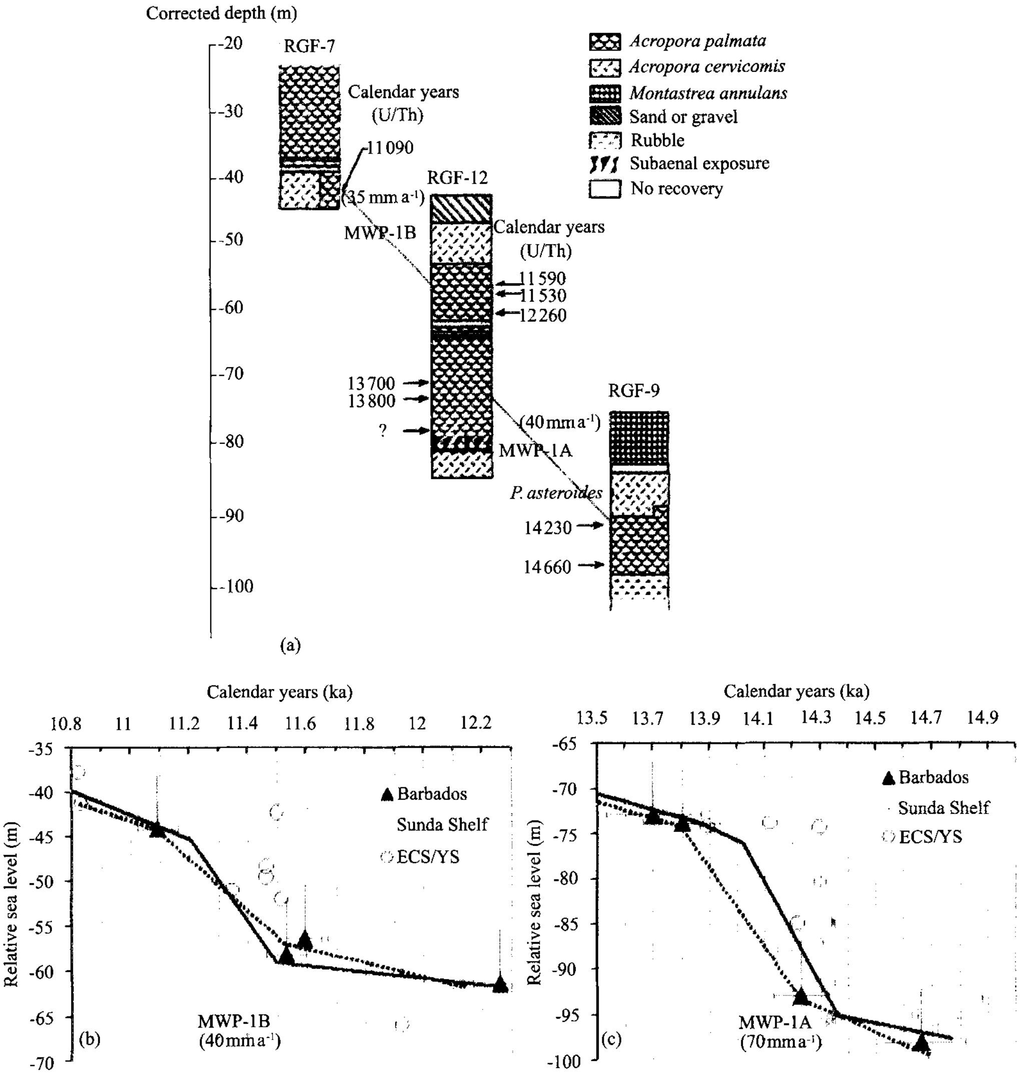

Fig.1 Core logs of borings RGF-9, 12 and 7 from three drowned coral reefs off Barbados (after Fairbanks, 1989), showing the facies sampled and U-Th-derived calendar ages (Bard *et al.*, 1990) used to date melt-water pulses 1A and 1B (a). The previous timing and rate of MWP-1A (c) and MWP-1B (b) were based on the intervals between the drowning of older coral reefs in RGF-9/12 and the establishment of newer, shallower reefs in RGF-12/7 (dash line); Solid line is the newly defined MWP-1A and 1B.

and van der Plicht, 1998), where the radiocarbon ages remain constant over hundreds of calendar years. Interestingly, brackish and intertidal sea-level indicators from the East China Sea and Yellow Sea show a similar trend as the Sunda data (Fig.3; Tables 1, 2) (Liu, 2001, Liu *et al.*, 2004). Given the ^{14}C age-calibration uncertainties and problems caused by the radiocarbon plateau, Hanebuth *et al.* (2000) correlated MWP-1A with the Greenland ice-core paleotemperatures proxy data (^{18}O), concluding that MWP-1A occurred synchronously with the Bølling warming event −14.6−14.3 ka cal BP (Fig.2), or 300−500 a earlier than the Barbados-derived age (Hanebuth, 2002, personal communication)①. This new age of MWP-1A already has been used to explain the rapid increase of the sea-surface temperature (SST) in the South China Sea (Kienast *et al.*, 2003). Moreover, instead of using those relatively accurate U/Th dates, Weaver *et al.* (2003) even modified the Barbados coral's reservoir correction from 400 a to 200 a, in order to match the timing of MWP-1A to this Sunda shelf-derived new age and the Bølling Warming Transition, and as an input to their paleoceanographic model. One obvious problem with using such a chronology, however, is that the date of the Bølling Transition itself varies from ice core to ice core (Southon, 2002). Moreover, as will be discussed in the following section, the chronology suggested by Hanebuth *et al.* (2000) would mean that the 14.23 ka BP Barbados coral reef at − 96 m

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① Hanebuth, T.J.J., 2002. Department of Geosciences, University of Bremen, Germany.

in RGF-9 would have accreted in water depths much greater than its accepted depth range.

Given the above uncertainties with MWP-1A and 1B, we re-analyze in this paper the existing Barbados coral-reef data and U/Th dates in an attempt to refine the depth ranges, timing, and rate of sea-level rise during both melt-water events. In doing so, we also touch upon correlations between sea-level rise and the paleoclimatic record. It should be emphasized that we refer to relative sea-level rise, and do not take into account possible hydro-isostatic corrections (*e.g.*, Peltier, 1998; Lambeck *et al.*, 2002), the magnitude of which are still unclear (Peltier and Drummond, 2002).

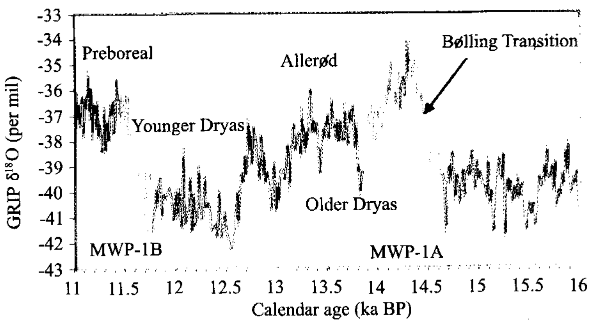

Fig.2 Proposed correlation of the chronology of MWP-1A with the Bølling Transition-Older Dryas paleo-air temperatures as indicated by $\delta^{18}O$ values derived from Greenland ice core. Time interval to the left reflects Fairbanks's chronology derived from the Barbados borings, and the right comes from Hanebuth *et al.*'s (2000) assumption that MWP-1A coincided with climatic warming during the Bølling Transition. Modified from Bard *et al.* (1996).

2 Melt-water Pulses and Coral Reef Records

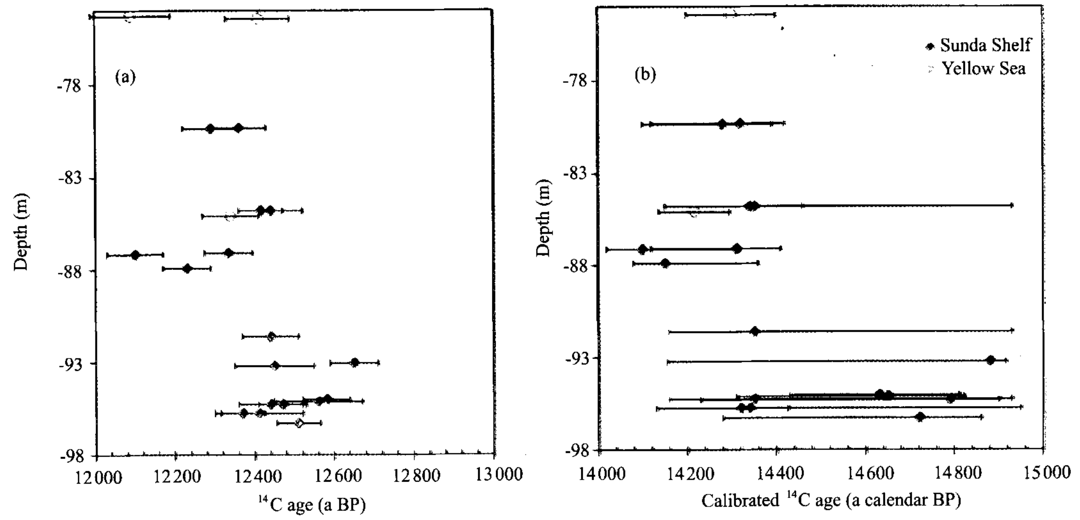

Fig.3 Depth-age relationship of sea-level indicators for defining the timing of MWP-1A derived from Sunda Shelf and Yellow Sea

(a) ^{14}C age versus depth; (b) Calibrated calendar age versus depth.

The melt-water pulses (1A and 1B) identified in the Barbados cores represent the intervals between the drowning of older coral reefs and the establishment of newer, shallower reefs. In most shallow-water coral reefs, maximum vertical accretion ($15\,\mathrm{mm\,a^{-1}}$) occurs in water depths less than 6 m. Where water depths are deeper than 6 m, the reef ultimately must 'give-up' (Lighty *et al.*, 1982; Neumann and Macintyre, 1985) and drown. It was on such drowned reefs that the Barbados borings were made. In effect, Fairbanks identified MWP-1A and 1B as the time when sea-level rose at rates sufficiently fast to drown the reefs. The dated samples selected from the Barbados cores, unfortunately, were based primarily on sample quality and not always on the shallowest or deepest coral in a particular core (Fairbanks, 2003, personal communication)①. As such, the given time-intervals of MWP-1A and 1B based on the original dating (^{14}C or U/Th) (Fairbanks, 1989; Bard *et al.*, 1990) may not represent the precise beginning or ending of the reef sequence, and should be used cautiously when trying to bracket the extent and timing of sea-level rise. Further mineralogical and geochemical analysis of the core logs and their facies are therefore critical. In the absence of such data, we must use the core logs presented by Fairbanks (1989) (Fig.1 a).

Although the accuracies of the Barbados core logs are probably + 1 m (Fairbanks, 2003, personal communication)②, as much as 1 m of *A. palmata* reef may extend above the 94 m, a sample depth with an age of 14.23 ka BP in RGF 9, above which there are 4 m of deeper-water *A. cervicornis* (Fig.1 a). This suggests that after 14.23 ka BP the *A. palmata* reef in

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① Fairbanks, R., 2003. Lamont-Doherty Earth Observatory, Columbia University, USA.

② Same as ①.

Table 1 Mangrove layers revealed from the Sunda Shelf

Cores	Depth BPSL (m)	^{14}C age†(ka)	Error (a)	Calibrated age (cal ka BP)††	1st ranges (cal ka BP)
18308	-80.31	12.36	70	14.32	14.42-14.12
	-80.34	12.29	70	14.28	14.39-14.10
18309	-84.78	12.42	55	14.34	14.46-14.15
	-84.78	12.44	80	14.35	14.93-14.15
18302	-87.10	12.34	60	14.31	14.41-14.12
	-87.15	12.10	70	14.10	14.32-14.02
	-87.90	12.23	60	14.15	14.36-14.08
18300	-91.61	12.44	70	14.35	14.93-14.16
	-93.06	12.65	60	15.29	15.52-15.19
	-93.23	12.45	100	14.92; 14.88; 14.36	14.915-14.155
	-95.04	12.58	60	15.21; 14.63; 14.43	14.81-14.32
	-95.15	12.56	110	15.18; 14.65; 14.42	14.82-14.31
	-95.28	12.44	80	14.35	14.93-14.16
	-95.31	12.47	60	15.02; 14.79; 14.37	14.90-14.23
	-95.77	12.41	110	14.34	14.95-14.13
18301	-95.77	12.37	55	14.32	14.425-14.13
	-96.31	12.51	55	15.10; 14.72; 14.39	14.86-14.28

Note: †AMS ^{14}C ages were calibrated using INTCAL98/CALIB4.0 (Hanebuth *et al.*, 2000).
††The calibrated calendar ages are not reliable because of the original problematic ^{14}C ages.

Table 2 Sea-level indicators from the shelf of Yellow Sea and East China Sea

Cores	BPSL (m)	Sample dated	Sed. facies	^{14}C dating	Δ^{13}C‰	Conventional	References	Cal. age
JS98	-48.36	*Euspira* sp.	Brackish	10250 ± 100	-9.2	10510 ± 100	Hori *et al.*, 2001	11462
HQ98	-42.41	*Corbicula* sp.	Brackish	10250 ± 80	-10.3	10490 ± 80	Hori *et al.*, 2001	11497
HQ98	-49.59	*Corbicula* sp.	Brackish	10250 ± 70	-9.2	10510 ± 70	Hori *et al.*, 2001	11462
HQ98	-51.00	*Corbicula* sp.	Brackish	10150 ± 70	-8.4	10420 ± 70	Hori *et al.*, 2001	11343
HQ98	-52.04	*Euspira* sp.	Brackish	10240 ± 40	-10.2	10480 ± 40	Hori *et al.*, 2001	11511
H80-11	-74.30	Shell and *Ammonia Beccarii*	Brackish	12090 ± 270	-1.0	12490 ± 270	Liu, *et al.*, 1987	13893
YSDP105	-74.45	Carbon particle	Intertidal	12410 ± 800	-0.2	12810 ± 800	Liu, *et al.*, 1997	14299
CC-04	-85.10	Shell fragments	Brackish		-3.0	12740 ± 70	Kim and Kucera, 2000	14217
KS-5	-103.00	Pitar sulfureum	Intertidal flat	12690 ± 120	0.0	13100 ± 120	Suk *et al.*, 1990	14606

RGF 9 may have grown for some period of time before it was effectively drowned. The time, $T_{(1)}$, of continued growth can be calculated as the thickness of the post-14.23 ka BP reef (L) divided by the growth rate of *A. palmata* reef ($R_{\mathrm{coralreef}}$):

$$T_{(1)} = L/R_{\mathrm{coralreef}}. \qquad (1)$$

Given a maximum thickness of post-14.23 ka BP reef (L) of 1 m and a maximum growth rate ($R_{\mathrm{coralreef}}$) of 15 mm a^{-1}, $T_{(1)}$ would be 70 a. Depending on the actual thickness of overlying *A. palmata*, the reef in RGF-9 therefore must have been drowned by 6 m of overlying sea level some time at around 14.16 ka BP. In contrast, the chronology given by Hanebuth *et al.* (2000) suggests that by 14.23 ka BP, the -94 m reef at RGF-9 would have been as much as 15 m below sea level; reef growth, according to their curve, should have ceased about 300 a earlier).

To obtain a better estimate of the initiation of MWP-1A, we can estimate the time, T, required for the accelerated MWP-1A sea-level rise to drown the uppermost *A. palmata* in RGF-9, which would be a function of the rate difference between sea-level rise ($R_{\mathrm{sea\text{-}level}}$) and the accretion of the reef coral ($R_{\mathrm{coralreef}}$):

$$T = 6\,m/(R_{\mathrm{sea\text{-}level}} - R_{\mathrm{coralreef}}). \qquad (2)$$

Assuming a sea-level rise of 50 mm a^{-1}, which is close to the values given by Fairbanks (1989) and Hanebuth *et al.* (2000), and assuming a maximum vertical reef accretion of 15 mm a^{-1}, for example, the topmost *A. palmata* reef in RGF 9 would have been 6 m below sea level–on the verge of 'giving up'–about 170 a after MWP-1A began. From the preceding analysis, the topmost shallow water reef 'gave-up' at about 14.16 ka BP, meaning that MWP-1A would have begun at about 14.33 ka BP. If the actual $R_{\mathrm{sea\text{-}level}}$ was somewhere between 40-100 mm a^{-1}, MWP-1A must have begun 70-240 a prior to 14.16 ka BP, meaning that MWP-1A could not have begun much earlier than 14.40 ka BP or later than 14.23 ka BP. This time frame is close to the timing originally proposed by Fairbanks (1989)–14.23 ka BP, but 200-400 a younger than that proposed by Hanebuth *et al.* (2000).

A more difficult task is to calculate the vertical rise and end of MWP-1A. Based on an age of 13.8 ka BP of *A. palmata* (at -74 m) in RGF-12, Fairbanks (1989) proposed an 18 m transgression over the 400 – an interval between the drowning of RGF-9 and the establishment of the shallower reef at RGF-12, equating to an average annual transgression of 45 mm a^{-1}. However, the U/Th dating of 13.8 ka BP at − 74 m may not represent the time and depth when the MWP-1A slowed down or stopped. The Barbados core log in fact indicates as much as 5 m of underlying *A. palmata* reef directly above a Pleistocene subaerial exposure (Fig.1). If some of this reef is post MWP-1A, then this would suggest that the MWP-1A slowed or ceased earlier than 13.8 ka BP. Onshore exposures at Barbados indicate that subaerial exposure features (such as root casts) are not always present in the sections of subaerially exposed reefs, and therefore some or most of the 5 m of *A. palmata* reef underlying the 13.8 ka BP horizon in RGF-12 may represent much older, subaerially exposed rock. Conversely, some of the reef may be post-MWP-1A reef; the lack of any dates prevents a more definitive chronology (see the core log in Fig.1). If we assume that half of the 5-m of underlying pre-13.8 ka BP *A. palamata* section – *i.e.* 2.5 m is post – MWP-1A, this would mean (assuming an accretion rate of 15 mm a^{-1}) that sea level would have reached or passed the − 76 m interval 165 a earlier. In other words, the rapid sea-level rise of MWP-1A would have ceased or slowed down at the time around 13.97 ka BP. Depending on the water depth when the *A. palmata* reef at RGF-12 initiated its growth, MWP-1A must have ceased when sea level reached between − 76 and − 79 m. Of course, if the whole 5 m reef was built in post-MWP-1A, MWP-1A would stop or slow down at − 79 m at around 14.1 ka BP, or about 330 a earlier than the 13.8 ka.

Given the age error range, it seems reasonable to conclude that MWP-1A represents a sea-level rise of about (20 + 3) m that began at 14.3 ka BP and ended at around 14.0 ka BP. This would translate to a rate of sea-level rise of around (65 + 10) mm a^{-1}. This means that the *A. palmata* dated at 14.23 ka BP would have been living in about − 5 m-or near its point of drowning (Fig.1 c).

The same calculation and calibration can be made for MWP-1B represented by the time interval between the drowning of reef RGF-12 and the establishment of reef RGF 7 (Fig. 1). The shallowest dated sample from RGF-12 (11.59 ka BP) is overlain by 3 m of younger, shallow-water *A. palmata* reef. Using a similar reasoning, we can presume that the shallow-water reef at RGF-12 was drowned about 200 a later, or at 11.39 ka BP. Given the lag time of 60 – 200 a between the sea-level acceleration and coral reef drowning, 11.5 ka BP may be a reasonable estimate for the initiation of MWP-1B. The oldest dated portion of RGF-7 (− 44 m, 11.09 ka BP) is underlain by 2 m of *A. palmata* and reef rubble, suggesting that the reefs may have been established about 100 a earlier, or around 11.2 ka BP. This would constrain the MWP-1B event to be between 11.5 and 11.2 ka BP, a 300 a interval during which sea level rose from − 58 m to − 45 m, giving a mean annual rate of around 40 mm a^{-1} (Fig.1b).

3 Paleoclimatic Implications

Our proposed timing and vertical extent of MWP-1A and 1B agree with those proposed originally by Fairbanks (1989) and Bard *et al.* (1990), although they are somewhat shorter in duration and the extent and rate of transgression somewhat higher. The timing of MWP-1A is 200 − 400 years younger than that proposed by Hanebuth *et al.* (2000).

It is interesting to note that MWP-1A appears to have occurred nearer the culmination of the Bølling Transition than during its early stages (compare Figs.4 a and b). Moreover, the ends of MWP-1A and 1B coincide closely with the ends of the ^{14}C plateaus (Fig.4 c) and the stabilization of ^{14}C activities (Fig.4 d). Such close coincidence, we suggest, infers a causal relationship between sea-level change and these paleoclimatic indicators.

Although we accept the relatively uncertain chronology of the ice-core record, the redefined timing of MWP-1A event (14.3 – 14.0 ka cal BP) suggests that rapid sea-level rise may not have occurred synchronously with the Bølling warming transition (14.7 – 14.3 ka). Rather, the onset of the MWP-1A may have resulted from heat accumulation at the end or maximum of the warming transition (Fig.4 a) and the subsequent collapse of both the Laurentide and Antarctic ice sheets (Clark *et al.*, 1996, 2002).

Although chronologies of the two melt-water pulses, the Greenland ice cores (Fig.4 a) and the ^{14}C plateaus (Fig.4 c), are clearly subject to reinterpretation, their close correlation with one another suggests possible causal relationships. The Δ^{14}C activity (past atmospheric ^{14}C activity normalized to the present value, per mil) between 15 and 10 ka BP showed that the normal decrease in activity was interrupted by two broad plateaus and two short-term rapid increases in ^{14}C activity (Fig.4 d), the latter occurrences presumably reflecting solar/cosmogenic activity (Lal and Peters, 1962; Kitagawa and Plicht, 1998) or abrupt shifts in deep-ocean ventilation (Keigwin *et al.*, 1991; Hughen *et al.*, 2000; Muscheler *et al.*, 2000).

Because the ocean dominates the global ^{14}C inventory, the sea-level curve suggests that the rapid sea-level rise may have resulted in the abrupt events of meltwater discharge (1A and 1B) to the surface ocean, and at same time the North Atlantic Deep Water (NADW) production declined or ceased entirely, as indicated by high-resolution paleoclimatic data from the North-Atlantic Ocean (Keigwin *et al.*, 1991; Keigwin and Schlegl, 2002). Prior to MWP-1A and 1B, the prevailing ocean thermohaline circulation (THC) resulted in polarward

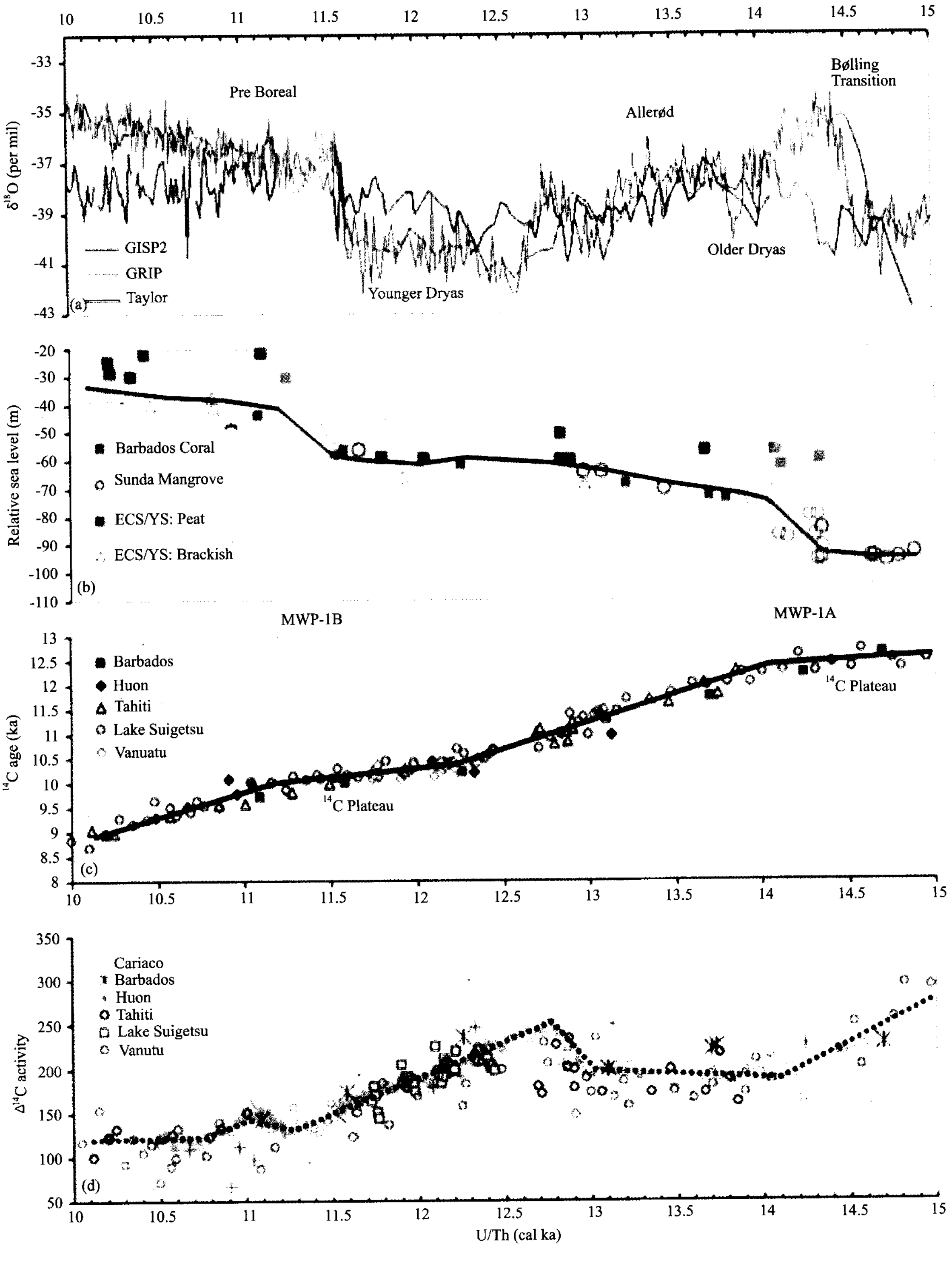

Fig.4 Comparisons of ice-core data, post-glacial sea-level rise, and variation of the Δ^{14}C activities
(a) GRIP, GISP2, and Taylor ice core paleotemperature (δ^{18}O) curve (Johnsen *et al.*, 1997; Dansgaard *et al.*, 1989; Steig *et al.*, 2000). The timing of MWP-1A, following the Bølling Transition, suggests lateral heat transport and subsequent collapse of the Antarctic and Greenland ice sheets. (b) Proposed relative sea-level rise between 15 and 10 ka cal BP. Barbados data from Fairbanks (1989) and Bard *et al.* (1990); Sunda Shelf data from Hanebuth *et al.* (2000); and East China Sea and Yellow Sea data from Liu (2001) and Liu *et al.* (2004). Peat samples from the East China and Yellow seas apparently were deposited subaerially, thus defining the upper limits of sea level. Note that the ^{14}C-derived calendar ages are relatively older at the end of MWP-1A and 1B. (c) and (d) The post-glacial ^{14}C plateau event and Δ^{14}C activity between 15–10 ka. Barbados coral reef dates from Bard *et al.* (1998); Huon Peninsula data from Edwards *et al.* (1993); Vanuatu data from Burr *et al.*, (1998), Cariaco data from Hughen *et al.* (1998); Lake Suigetsu data from Kitagawa and Plicht, (1998). There are at least two so-called ^{14}C plateaus, one between 14.5–14 ka, the other at around 11.5 cal ka, corresponding to MWP-1A and 1B, respectively. The atmospheric Δ^{14}C value (right y-axis) also decreased to the lowest point during each event.

heat advection, active North Atlantic Deep-Water (NADW) production, and active ocean ventilation, resulting in a gradual $\Delta^{14}C$ decrease (Fig.4 d), together with increasing atmospheric CO_2 (Monnin *et al.*, 2001; Smith *et al.*, 1999). The subsequent sudden rise in sea level (MWP-1A) of about 70 mm a^{-1} meant that freshwater flux to the ocean would have increased by about $(20-25) \times 10^3$ km^3a^{-1}, compared to about 3.5×10^3 km^3a^{-1} at present. Because the LGM continental ice sheets were located primarily in NW Europe and NE North America, a considerable portion of the meltwater must have entered the North Atlantic Ocean, which presently receives only about 3.5×10^3 km^3a^{-1}①. Such a freshening of the North Atlantic's mixed layer could have slowed or shut down North Atlantic thermohaline circulation (Broecker *et al.*, 1989), curtailing deep-water production, reducing the overturn of the old carbon, and resulting in a changed release of ^{14}C to the atmosphere (Fig.4 d). At the same time, flooding of the worldwide shelves and huge alluvial inputs from the land, individually or collectively, could have altered carbon cycling between ocean and atmosphere. Such changes may explain why the ^{14}C plateaus and decreased $\Delta^{14}C$ activity appear to have ended abruptly near the ends of both melt-water pulse events, followed by a long term $\Delta^{14}C$ activity plateau (Figs.4 c, 4 d).

4 Concluding Statement

The speed with which climatic events occurred in the recent past has been well documented in the Greenland and Antarctic ice cores (Severinghaus and Brook, 1999; Ganopolski and Rahmstorf, 2001). We are equally impressed with the alacrity with which sea level seems to have responded to these climatic changes, inferring, for example, that as much as 30% of the glacial ice may have melted in no more than 600 years (combined duration of MWP-1A and 1B). A pattern of rapid transgression followed by a cold period during which little ice melted suggests a causal relationship between rapid discharge of glacial meltwater and subsequent cooling. This might explain the climate shifting from Bølling warming to the subsequent Older Dryas cooling event after MWP-1A and the Preboreal Oscillation after MWP-1B (Bard *et al.*, 1996). Rapid and stepwise sea-level rise is not only a result of climatic change, but also appears to play an important intermedial role in buffering and providing climatic feedback. Because the ^{14}C plateau problem effectively negates the use of ^{14}C dating for high-resolution chronology, gaining better and higher-resolution of the MWP-1A and 1B chronologies will require more U-Th dating of reef corals. At this point nothing else seems likely to refine the post-LGM sea-level curve.

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