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AMS ^{14}C STUDY OF TRANSIENT EVENTS AND OF THE VENTILATION RATE OF THE PACIFIC INTERMEDIATE WATER DURING THE LAST DEGLACIATION

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ABSTRACT. ^{14}C analysis of monospecific samples of planktonic and benthic foraminifera were performed in deep-sea sediment cores from the Atlantic and Pacific Oceans by Accelerator Mass Spectrometry (AMS). These measurements demonstrate that the Younger Dryas cold event, first described in the north Atlantic, is also present at the same time in the north Pacific Ocean. The comparison of the ^{14}C ages of planktonic and benthic foraminifera from the same sediment level in two Pacific cores shows that the ventilation time of the Pacific Ocean was greater than today during the last ice age, but significantly less than today during the deglaciation.

INTRODUCTION

During the last deglaciation, the earth's climatic system experienced tremendous variations. Between the last glacial maximum and now, the volume of the continental ice sheets decreased by more than 60%, most of the melting occurring in the Northern Hemisphere. The sea-surface temperature increased, noticeably in the high latitudes of both the Southern and Northern Hemispheres (Ruddiman & Mc Intyre, 1981; Pichon *et al,* 1988). Finally, the deep-water circulation changed from a glacial mode, characterized by ventilated intermediate waters strongly separated from poorly oxygenated deep and bottom waters, to the present mode where deep and bottom waters are well oxygenated, whereas intermediate waters are all characterized by a strong oxygen minimum (Duplessy *et al,* 1988; Kallel *et al*, 1988).

Details of the climatic evolution of the ocean during the last glacial to interglacial transition are recorded only in deep-sea sediment cores with a high sedimentation rate (≥10cm/1000 yr). In such cores, Duplessy *et al* (1981) recognized two major steps in the oxygen isotope record of benthic foraminifera; this has been interpreted as evidence that the ice caps, which covered northern Europe and northern America, melted in two phases separated by a pause which lasted 2 to 3 millennia. Ruddiman and Mc Intyre (1981) demonstrated that the deglacial retreat of polar waters from the northern Atlantic Ocean was a complicated time-transgressive process, which was not unidirectional. A polar water readvance, marked by a sea-surface-temperature (SST) drop in the north Atlantic and called the Younger Dryas event, occurred at ca 10,500 yr BP, interrupting the general southeast to northwest retreat.

In this paper, we first review Accelerator Mass Spectrometry (AMS) ^{14}C ages obtained on monospecific planktonic foraminiferal samples to compare the timing of major temperature changes in the north Atlantic and in the north Pacific. We then present new ^{14}C ages of benthic foraminifera from north Pacific core CH 84-14, estimate the age difference between planktonic and benthic foraminifera, and reconstruct the variations of the ventilation age of the intermediate water during the last 16,000 years. This record is compared to a recent one (Shackleton *et al,* 1988), which provides similar information for the Pacific deep waters. The experimental procedure followed at Gif was described by Arnold *et al* (1987).

DEGLACIAL SST CHANGES IN THE NORTH ATLANTIC OCEAN

Cores SU81–18 (37°46′N, 10°11′W, 3135m; Fig 1) and SU 81–14 (36°46′N, 9°51′W, 2795m; Fig 2) from the northeastern Atlantic show a sedimentation rate >20cm/kyr based on, respectively, 22 and 18 AMS ^{14}C dates obtained on *Globigerina bulloides.* Core SU 81–14 exhibits a strong age inversion between 140 and 100cm (Fig 2). This age inversion is too high to be interpreted in terms of global ^{14}C atmospheric change and is not present in the nearby core SU 81–18. Consequently, the four anomalous ^{14}C ages measured in core SU 81–14 are interpreted as due to reworking of sediment between 140 and 100cm depth. Ages of the same isotopic events are systematically 500 to 1000 yr older in core SU 81–14 than in core SU 81–18. As core SU 81–14 has been taken in the vicinity of a steep continental slope, we suspect that older sediments have been continuously incorporated with the more recent sedimentation and are responsible for the apparently "old" ^{14}C ages.

Both cores exhibit an abrupt temperature increase by >10°C in <400 yr at ca 12,500–13,000 yr BP, emphasizing the extreme rapidity of climatic changes during the last deglaciation.

The Younger Dryas cooling is well marked in core SU 81–18 and is dated between 11,010 ± 170 and 10,390 ± 130 yr BP. The polar front readvance corresponds approximately to a temperature drop of 0.5°C–1°C per century. The following warming was basically completed by 9360 ±130 yr BP. The Younger Dryas event is synchronous with that recorded in the more northern core CH 73–139C (Duplessy *et al,* 1986; Bard *et al,* 1987a,b). It cannot be studied in core SU 81–14, because it falls within the reworked levels. Nevertheless, the synchronism between the cold event in the north Atlantic surface-water temperature record and the cold event detected in pollen records of northern Europe is now well established.

EVIDENCE FOR A YOUNGER DRYAS COOLING IN THE NORTH PACIFIC OCEAN

The Younger Dryas was originally defined over the European continent and has been now amply observed in the north Atlantic Ocean. The development of models of the deglaciation dynamics requires a detailed description of temperature and circulation changes in different oceanic areas. Twelve AMS ^{14}C measurements were made on *G bulloides* and *Neogloboquadrina pachyderma* (left coiling) in core CH 84–14 (41°44′N,

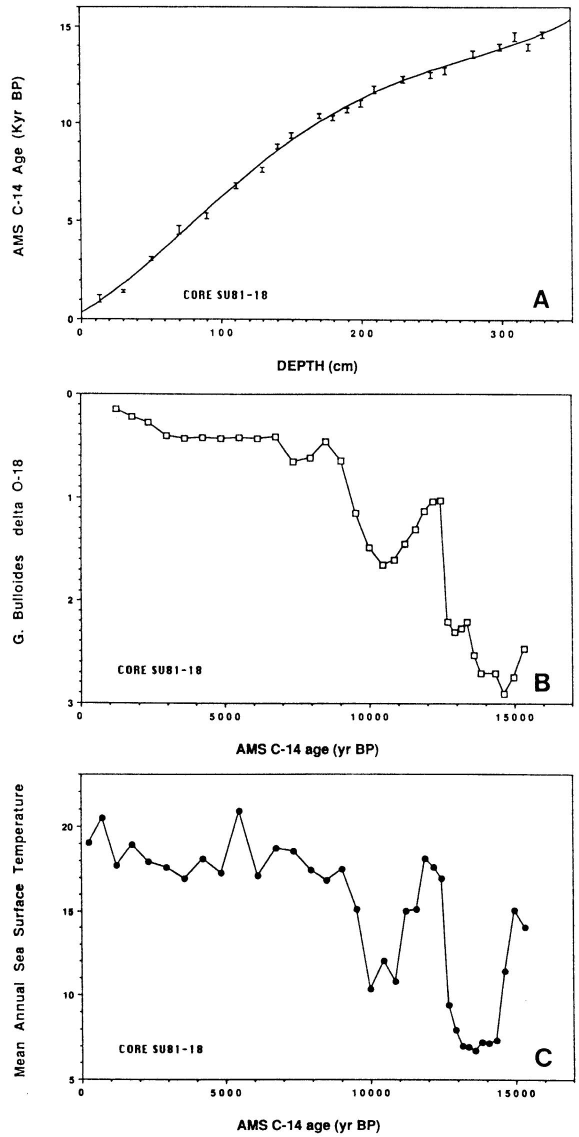

Fig 1. A. Sedimentation rate of core SU81–18; B. Variations of the oxygen isotope ratio of the planktonic foraminifer *G bulloides vs* ^{14}C age in core SU81–18; C. Variations of the sea surface temperature estimate *vs* ^{14}C age in core SU81–18

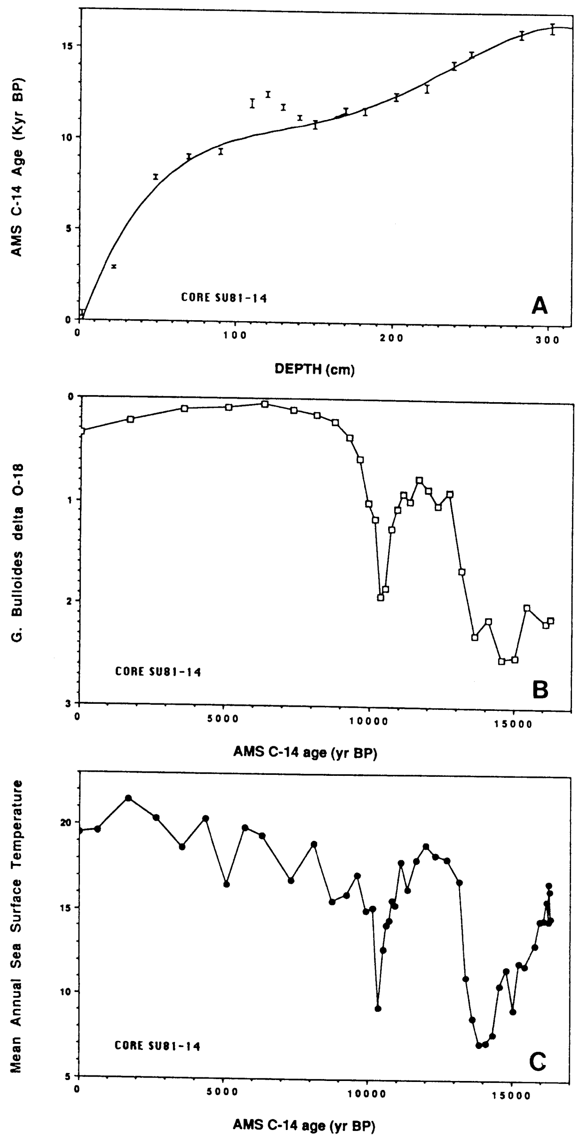

Fig 2. A. Sedimentation rate of core SU81–14; B. Variations of the oxygen isotope ratio of the planktonic foraminifer *G bulloides vs* ^{14}C age in core SU81–14; C. Variations of the sea surface temperature *vs* estimate ^{14}C age in core SU81–14.

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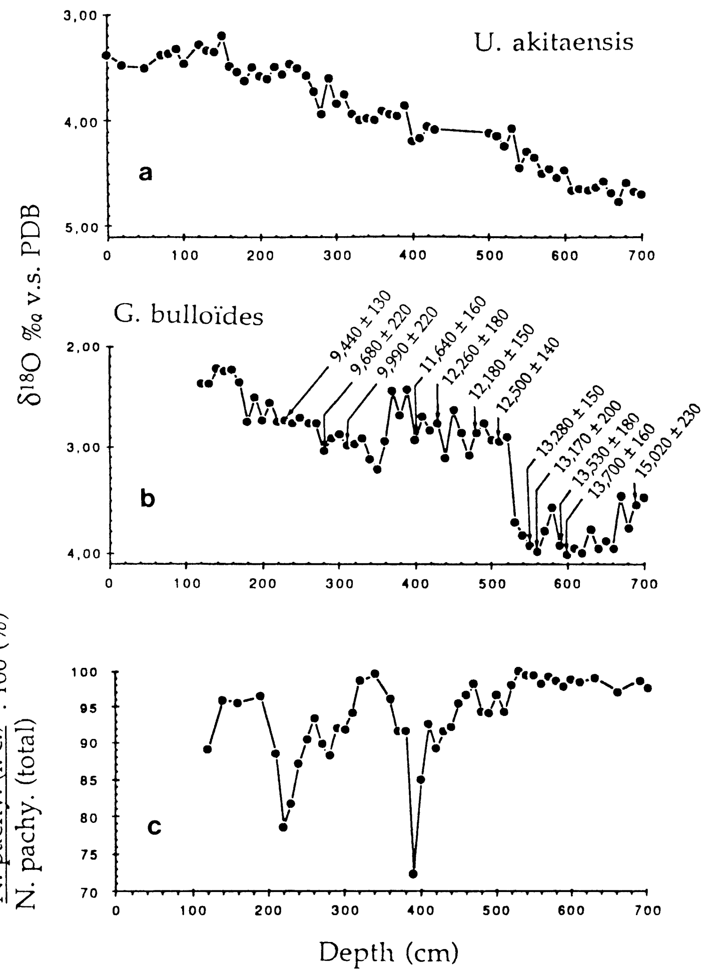

Fig 3A. a. Oxygen isotopic composition of the benthic foraminifer *Uvigerina akitaensis* in core CH84–14 from the North Pacific; b. Oxygen isotopic composition and ^{14}C ages of the planktonic foraminifer *G bulloides* in core CH84–14 from the North Pacific; c. Percent variations of *N pachyderma* (left coiling) within the total population of *N pachyderma* in core CH 84–14

142°33′E, 978m; Fig 3A) which provides an accurate time scale for this core, of which the sedimentation rate varies between 50 and 200cm/kyr (Kallel *et al,* 1988). The raw planktonic foraminifera ages of the recent (pre-bomb) surface water were corrected to 560 years and we assume that this correction has remained constant in the past, which is an oversimplification (Shackleton *et al,* 1988).

The core CH 84–14 is presently located in the cold, low-salinity Oyashio current, which flows southward along the Pacific coast of the northern Japanese islands. It is close to the front between the Oyashio current and the warm Kuroshio current, which itself flows northward from the Philippines Pacific coast, and then eastward at ca 36°N, off Japan.

Both water masses are characterized by different coiling types of the foraminiferal species *N pachyderma*, the cold left-coiling type being characteristic of the Oyashio current, whereas the temperate right-coiling type is dominant in the Kuroshio (Thompson & Shackleton, 1980). Core CH 84–14 presents a continuous record of the end of the last glaciation and of the deglaciation between 8500 and 15,500 ^{14}C yr BP.

Downcore variations of the left-coiling to total *N pachyderma* ratio (Fig 3A) indicate that the location of core CH 84–14 was always dominated by the cold water mass. However significant variations are observed. Prior to 12,800 yr BP, the coiling ratio of *N pachyderma* (close to 100% of left-coiling type) indicates a maximum influence of the cold water mass. This ratio then decreases with a sharp peak close to 11,500 yr BP, indicating a progressive northward migration of the Pacific polar front.

A dramatic climatic deterioration is well marked in the climatic record, culminating at ca 10,550 yr BP, exactly at the same time as the Younger Dryas event in Europe and in the north Atlantic Ocean. A sharp southward shift of the polar front is indicated by both an increase to almost 100% of the abundance of left-coiling *N pachyderma* and an increase in the oxygen isotope record of *G bulloides*. By 9400 yr BP, the polar front had retreated to its northern position. This retreat was followed by a new readvance at ca 9250–9000 yr BP, but the cooling was less pronounced than that associated with the Younger Dryas.

These results indicate that the evolution of the north Pacific Ocean was synchronous with that of the north Atlantic. The major retreat of the polar front began between 12,500 and 13,000 yr BP as in the Atlantic (Bard *et al,* 1987a; Broecker *et al*, 1988b). Similar hydrologic changes have been reported for the China Sea (Broecker *et al,* 1988a). The polar front reached its northernmost position during the period of climatic amelioration at ca 11,500 yr BP (as in north Atlantic core CH 73-139C). The establishment of the conditions associated with the Younger Dryas type cooling was extremely rapid and synchronous in the Pacific and Atlantic Oceans, suggesting that this cooling affected the whole of the high latitudes of the Northern Hemisphere.

AGE OF LAST GLACIAL PACIFIC DEEP AND INTERMEDIATE WATERS

Since the recent discovery that the global circulation of deep and intermediate waters was strongly dependent on the earth's climate (Duplessy & Shackleton, 1985; Duplessy *et al,* 1988; Kallel *et al,* 1988), one of the most attractive projects of AMS ^{14}C determination has been measuring changes in the radiocarbon age of the deep ocean.

Initial attempts to achieve this by Broecker *et al* (1984) were thwarted by the difficulties imposed by bioturbation, which permanently mixes the upper 10cm of sediment or more. The implications of this mixing for an

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accurate dating of the deep-sea record have been extensively discussed since ^{14}C AMS analysis provided a new method to explore the effects of bioturbation in marine sediment (Duplessy *et al,* 1986; Bard *et al,* 1987).

Shackleton *et al* (1988) have overcome this difficulty by making measurements in a core with a sufficiently high accumulation rate (≥10cm/kyr) that bioturbation becomes negligible. These authors demonstrated that the raw age difference between the planktonic foraminifera, *N dutertrei*, and the benthic foraminifera, *Uvigerina,* has changed during the last 30,000 yr. During the last glaciation, it was close to 2100 yr, indicating that the ventilation age of the deep Pacific was ca 500 yr greater than it is today.

We followed the same strategy to determine the ventilation age of the Pacific Intermediate waters and compared the raw ^{14}C ages of planktonic

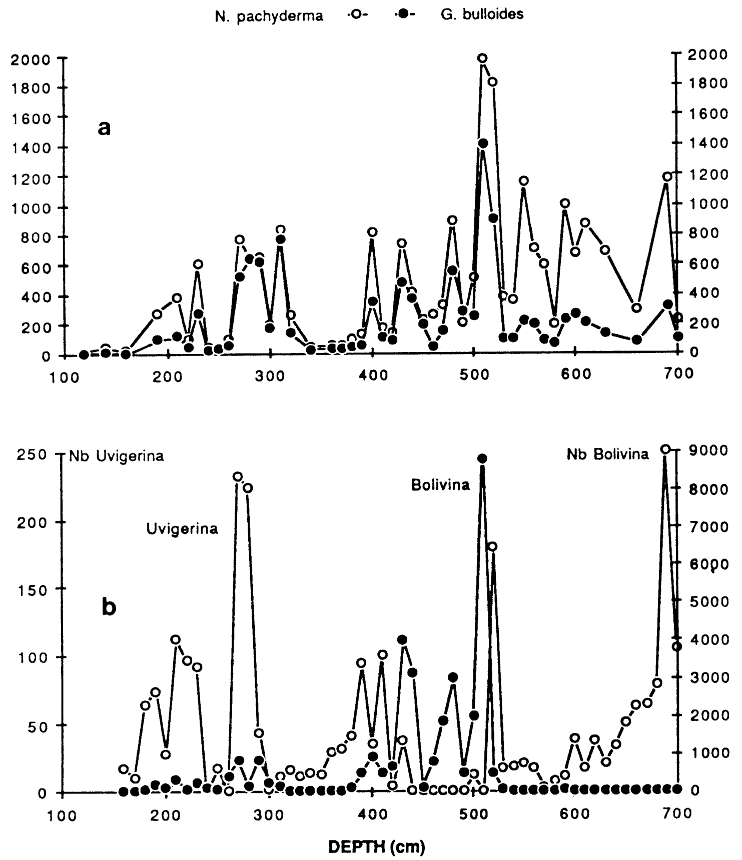

Fig 3B. a. Abundance variations of the planktonic foraminifer *N pachyderma* and *G bulloides* in core CH84–14 from the North Pacific; b. Abundance variations of the benthic foraminifer *Uvigerina* and *Bolivina* in core CH84–14 from the North Pacific

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and benthic foraminifera in core CH 84–14. We also dated only the peaks of abundance of planktonic and benthic foraminifera in order to minimize the effects of bioturbation, because the abundance of foraminifera vary by 1–2 orders of magnitude in response to local climatic variations. As food is brought to the abyss by sinking particulate matter formed in the surface water, the development of benthic organisms is directly related to the surficial productivity. Consequently, the peaks of abundance of planktonic and benthic foraminifera are generally found in the same sediment levels (Fig 3B). Foraminiferal counts have been made every 10cm. A better coincidence would probably have been found if counting had been made at closer intervals, smaller than the bioturbation depth. However, as the sedimentation rate is close to 80cm/10^3 yr during the deglaciation, the error introduced by the sampling on the age/depth relationship is smaller than 1 century.

TABLE 1

^{14}C ages of planktonic and benthic foraminifera in core CH84–14 from the North Pacific Ocean. Ventilation ages are calculated as the age difference between benthic and planktonic foraminifera from the same levels.

Level (cm)	Planktonic foraminifer	Age (yr)	SD* (yr)	Benthic foraminifer	Age (yr)	SD* (yr)	Atmospheric "^{14}C age," *G bulloides* –560 (yr)	Ventilation age (yr)
70				*Uvigerina akitaensis*	4200	90		
180				*Uvigerina akitaensis*	9380	130		
230	*G bulloides*	10,000	140	*Uvigerina akitaensis*	10,850	140	9440	850
280	*G bulloides*	10,230	140	*Uvigerina akitaensis*	11,060	150	9670	830
310	*G bulloides*	10,640	150	*Uvigerina / Bolivina*	11,370	130	10,080	730
340	*G bulloides*	10,870	150	*Uvigerina akitaensis*	11,630	180	10,310	760
400	*G bulloides*	12,180	160	*Bolivina seminuda*	13,200	150	11,260	1020
430	*G bulloides*	12,820	180	*Bolivina seminuda*	13,010	170	12,260	190
480	*G bulloides*	12,750	150	*Bolivina seminuda*	13,930	220	12,190	1180
510	*G bulloides*	13,060	140	*Bolivina abreviata*	13,500	200	12,500	440
520				*Uvigerina akitaensis*	13,520	180		
550	*N pachyderma*	13,830	150	*Uvigerina akitaensis*	14,140	200	13,270	310
560	*G bulloides*	13,720	160					
590	*N pachyderma*	14,100	190					
600	*G bulloides*	14,350	170					
690	*G bulloides*	15,570	210	*Uvigerina akitaensis*	15,940	190	15,010	370

*SD = Standard deviation

^{14}C determinations are reported in Table 1, expressed in ^{14}C yr (5568 yr half-life), with no adjustment for the "age" of sea water. If the ventilation of the Intermediate Pacific did not change, the raw ages for planktonic and benthic foraminifera should present a constant offset of ca 1300 yr, as measured during the GEOSECS program. In fact, the mean difference is

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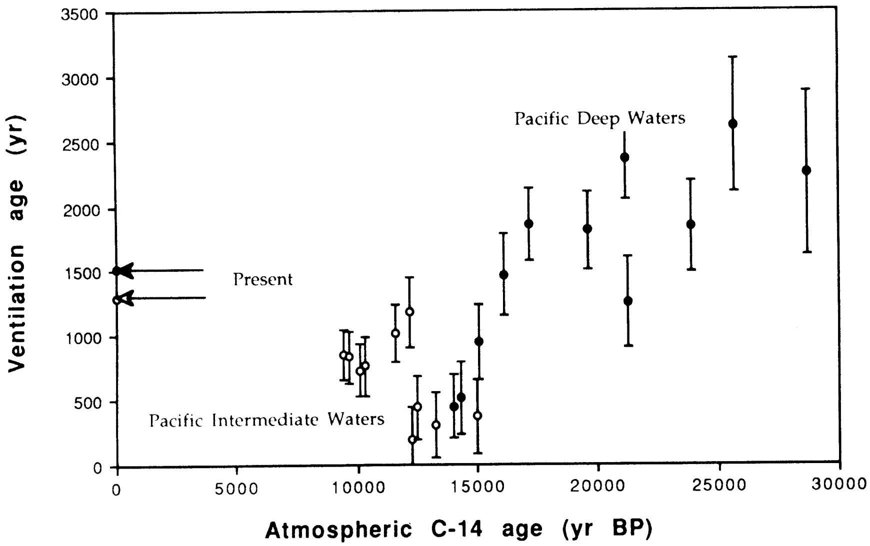

Fig 4. Variations of the ventilation age of the Pacific deep waters (core TR163–31B) and of the Pacific intermediate waters (core CH84–14) *vs* atmospheric ^{14}C age

always lower than 1000 yr in this core before 10,000 BP, indicating that the ventilation of the intermediate water was much more important than today during the deglaciation. During the Holocene, dissolution is high in this core, as in most north Pacific sediment cores and planktonic foraminifera are not abundant enough to pursue this study.

To compare the variations of the ventilation time of the intermediate and deep waters of the Pacific Ocean, we plotted in Figure 4 the age difference between benthic and planktonic foraminifera in cores CH 84–14 and TR 163–31B (3°37′S, 83°58′W, 3210m) analyzed by Shackleton *et al* (1988). The ventilation rate of intermediate and deep Pacific waters shows a similar pattern of variation and was smaller than under modern conditions. Active deep and intermediate water circulation efficiently diluted the water resulting from melting ice sheets in the ocean water, which was salty and therefore denser than the meltwater.

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