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Michael Sarnthein, Kyaw Winn, Jean-Claude Duplessy, Michael Fontugne. Global variations of surface ocean productivity in low and mid latitudes: influence on C0\_2 reservoirs of the deep. *Paleoceanography*, 1988, 3 (3), pp.361-399. 10.1029/PA003i003p00361 . hal-03543888

**HAL Id: hal-03543888**

**<https://hal.science/hal-03543888>**

Submitted on 26 Jan 2022

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GLOBAL VARIATIONS OF SURFACE OCEAN  
PRODUCTIVITY IN LOW AND MID LATITUDES:  
INFLUENCE ON CO<sub>2</sub> RESERVOIRS OF THE DEEP  
OCEAN AND ATMOSPHERE DURING THE LAST  
21,000 YEARS

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*Abstract.* Based on detailed reconstructions of global distribution patterns, both paleoproductivity and the benthic  $\delta^{13}\text{C}$  record of CO<sub>2</sub>, which is dissolved in the deep ocean, strongly differed between the Last Glacial Maximum and the Holocene. With the onset of Termination I about 15,000 years ago, the new (export) production of low- and mid-latitude upwelling cells started to decline by more than 2-4 Gt carbon/year. This reduction is regarded as a main factor leading to both the simultaneous rise in atmospheric CO<sub>2</sub> as recorded in ice cores and, with a slight delay of more than 1000 years, to a large-scale gradual CO<sub>2</sub> depletion of the deep ocean by about 650 Gt C. This estimate is based on an average increase in benthic  $\delta^{13}\text{C}$  by 0.4-0.5‰. The decrease in new production also matches a clear  $^{13}\text{C}$  depletion of organic matter, possibly recording an end of extreme nutrient utilization in upwelling cells. As shown by Sarnthein et al., [1987], the productivity reversal appears to be triggered by a rapid reduction in the strength of meridional trades, which in turn was linked via a shrinking extent of sea ice to a massive increase in high-

latitude insolation, i.e., to orbital forcing as primary cause.

#### INTRODUCTION

Measurements of gases trapped in polar ice cores [Delmas et al., 1980; Neftel et al., 1982; Oeschger et al., 1984; Barnola et al., 1987] convincingly demonstrated that the concentration of atmospheric carbon dioxide was subject to several dramatic natural changes which paralleled and possibly slightly preceded the major climatic fluctuations between and during glacial and interglacial stages of the last 160,000 years. Since the ocean contains about 60 atmospheric carbon units [e.g., Grassl et al., 1984; Sundquist, 1985], any such change of atmospheric pCO<sub>2</sub> must be tied to the ocean and requires a large-scale redistribution of the ocean chemical properties [e.g., Broecker and Takahashi, 1984]. First evidence for this change in the ocean was observed by Shackleton [1977] and Duplessy [1982] in the  $\delta^{13}\text{C}$  composition of benthic foraminifera. The evidence of Oeschger et al. [1984] and Barnola et al. [1987] even suggests that the carbon redistribution may have proceeded very rapidly, implying that most of the pCO<sub>2</sub> changes in the atmosphere possibly took place within a time span as short as a few centuries or less during early deglacial times. Also, much slower changes cannot be explained by the insufficient effect of an average temperature

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Paper number 8P0310.  
0883-8305/88/008P-0310\$10.00

increase of the surface ocean or by a sedimentation pulse of nutrients bound in organic matter on the continental shelves during the transgression at the end of glacial time [Broecker, 1982]. The storage of C, N, and P on the shelves slowly started during this transgression, while the atmospheric  $p\text{CO}_2$  was already high. Other mechanisms must therefore be invoked [Broecker, 1984; Dymond and Lyle, 1985].

A large number of ocean-atmosphere models have been used to explore the causes for these  $\text{CO}_2$  fluctuations [see Sundquist and Broecker, 1985]. The background reasoning and assumptions in many of these models have been summarized by Berger and Keir [1984], Broecker and Takahashi [1984], Broecker and Peng [1986], and Sundquist [1985]. Unfortunately, most of the models are backed up by little hard data.

Besides a minor but certain input from lowering the forest biomass [Shackleton, 1977], there remain, basically, two main options for decreasing the  $p\text{CO}_2$  in the atmosphere through increasing  $\text{CO}_2$  in the main reservoir of the deep ocean such as during the last glaciation. One choice is to reduce the production and turnover of deep water, in particular, that of North Atlantic Deep Water (NADW) in high latitudes. Such a change will result in a more sluggish deep-ocean circulation. Once the exchange rate of deep water diminishes, the oxygen supply from the high-latitude surface water is likely to become reduced. More particulate organic carbon and nutrients (in order to keep the Redfield ratio C:N:P = 106:16:1 constant, Takahashi et al., [1985]) will be stored in deep water over long time spans, and accordingly, more  $\text{CO}_2$  can be extracted from the surface ocean and the atmosphere [Duplessy, 1982; Duplessy and Shackleton, 1985; Oeschger et al., 1984; Broecker et al., 1985]. Broecker et al. [1984] and Broecker [1987] provided the first evidence from accelerator radiocarbon-dated foraminifera that indeed the glacial deep ocean, especially the Atlantic, was more sluggish than it is today.

A mechanism along this line still contains a number of basic problems. According to the model of Broecker and Takahashi [1984], it was not the deep water ventilation of the ocean only, but the ratio between it and the  $\text{CO}_2$  gas exchange rate between the air and the sea, that controls the different  $\text{CO}_2$  budgets (when

excluding, for simplification, the role of carbon and nutrient transfer with particulate organic matter in high latitudes). In this case, simply an increase of oceanic ventilation and a decrease of gas exchange would result in leading to the glacial lowering of atmospheric  $\text{CO}_2$  ("Redfield Ocean"). This model now appears less plausible in view of the recent results of Broecker [1987].

The second option for decreasing atmospheric  $\text{CO}_2$  is to assume a considerable increase in the flux rate of particulate carbon across the thermocline during glacial time, along with a decrease in the preformed nutrient content of the downwelled deep water that formed in the high-latitude oceans [Oeschger et al., 1984]. However, Mix and Fairbanks [1985] suggested that there was an increase of the preformed nutrient content of synglacial deep water because, in part, it possibly formed below sea-ice cover, an assumption we don't necessarily follow [Duplessy et al., 1988]. This second option implies that the synglacial new (or "export") primary production of the ocean was especially enhanced in the mid and low latitudes, whereas it was largely reduced in the higher latitudes as a result of expanded sea-ice cover. The high synglacial productivity in low latitudes, in turn, required a strongly enhanced lateral advection of nutrients to low-latitude upwelling regions, a transport which today takes place mainly in intermediate waters (upper 200-700 m). This turnover of intermediate waters has to be considered as decoupled from that of the deep water of the ocean because it originates from different downwelling zones. Hence it can cause a large-scale nutrient redistribution, which bypasses the deep ocean and fuels the little used nutrient reservoir of the high-latitude surface ocean to the warm low latitudes where the nutrients become almost completely fixed in organic tissues. Complementary to this mechanism, changes in the C:P (Redfield) ratio may be a possible cause for such a high-productivity scenario as theoretically considered by Broecker [1982] and demonstrated by M. Sarnthein and T. Takahashi [unpublished manuscript, 1988].

Based on modern oceanographic data, Newell et al. [1978], Newell and Hsiung [1984], and Flohn [1982] were the first to suggest that variations in low-latitude upwelling may be crucial in controlling

atmospheric  $p\text{CO}_2$ . They related this forcing to the combined effect of lowering the sea surface temperature (SST) and increasing productivity and carbon extraction from the surface water. Based on direct observations in the equatorial Atlantic, Garçon et al. [1986] regard the biological  $\text{CO}_2$  uptake as a more crucial constraint on the nutrient balance of the equatorial divergence than gas fluxes. Siegenthaler and Wenk [1984], unlike Wenk and Siegenthaler [1985], presented a glacial  $\text{CO}_2$  model, which includes this option of enhancing the particulate carbon transfer by biological activity in both high and low latitudes. To reach this target, they had to allow for an increased utilization of the surface water nutrient pool during the ice age. They assumed a simultaneous general reduction of preformed nutrients in the deep water as a result of biologically induced stronger nutrient depletion in the high-latitude downwelling regions. Like us, they considered this nutrient distribution to be the result of enhanced near-surface circulation and included upwelling in low latitudes as a major factor controlling the particulate carbon transfer.

Vincent and Berger [1985] specified the effects of low-latitude upwelling more explicitly in their "Monterey" hypothesis to explain the middle Miocene  $\text{CO}_2$  shift. Their approach includes a further important concept, the "Rain-Ratio" model of Berger and Keir [1984]. According to this model, for the particle flux crossing the thermocline the "rain" of carbonate carbon and organic carbon have an opposing effect on  $\text{CO}_2$  balance. With increasing fertility this Rain Ratio will shift substantially towards organic carbon and thereby strongly increase the total  $\text{CO}_2$  dissolved in the deep ocean. Indirect support for this concept comes from the findings of Eppley and Peterson [1979], who showed that the proportion of new production out of the total plankton production increases markedly from about 6 to 50% when going from low- to high-productivity regions. Based on this reasoning, Dymond and Lyle [1985] developed a three-box ocean model, which explicitly relates the required short-term changes in the extraction of atmospheric carbon to possible fluctuations of low- and mid-latitude primary production, which in turn is controlled by wind-driven upwelling. Hence high rates of new production may be triggered

rapidly, and synchronously, over wide parts of the ocean. Based on data from empirical paleoproductivity curves from the east Atlantic, Müller et al. [1983] and Sarnthein et al. [1987] arrived at a similar conclusion. Indeed, zonal sea surface temperature anomalies show that the average intensity of wind-driven coastal upwelling along the (north-) east Atlantic continental margin increased by at least 50% during the Last Glacial Maximum (LGM) [Sarnthein, 1982]. Recently, Boyle [1986a] presented a  $\text{CO}_2$  model of the ocean and the atmosphere, which relies on wind-driven low-latitude upwelling productivity. However, this model can only explain 1/3-1/4 (about 25 parts per million by volume) of the observed atmospheric  $p\text{CO}_2$  change during the last deglaciation.

In this paper we try to evaluate the contribution of the "second option" to the last glacial-to-interglacial change in  $p\text{CO}_2$  by two new, but still preliminary and small, global sets of empirical data. We compare the sedimentary record of surface ocean paleoproductivity with the benthic carbon isotope record of dissolved  $\text{CO}_2$  in the deep water from the various ocean basins during the LGM, glacial Termination I, and the Recent. For calculating paleoproductivity from sediments we utilize an empirical equation (improved version of Sarnthein et al. [1987], based on concepts of Müller and Suess [1979] and Suess [1980]). Since we cannot present a complementary set of global variations in  $\text{CaCO}_3$  production and dissolution, our conclusions on fluctuations of the atmospheric and oceanic  $\text{CO}_2$  budget have to rely strongly on the premises of the Berger and Keir [1984] Rain-Ratio model.

Furthermore, we discuss some possible signals of productivity stress on the nutrient and carbon reservoirs in the surface waters during times of extreme nutrient utilization, i.e., a possible environmental response to the proposed large-scale carbon extraction. Finally, we test the different options for a carbon enrichment of the deep ocean by a global survey of the leads and lags of the  $\delta^{18}\text{O}$  deglaciation signal versus changes of paleoproductivity and bottom water oxygenation during the special case of Termination I. From this we expect a better understanding of the cause and effect relationships and possible feedback loops during times of rapid climatic change.

## METHODS

Values of ancient new primary production of organic carbon ("new paleoproductivity" =  $P_{new}$ ) were derived from deep-sea sediments using equation (1)

$$P_{new} = 0.0238 * C^{0.6429} * S_B^{0.8575} * DBD^{0.5364} * z^{0.8292} * S_{B-C}^{-0.2392} \text{ (g m}^{-2} \text{ yr}^{-1}) \text{ (1)}$$

where C is the concentration of organic carbon, DBD is the dry bulk density,  $S_B$  the bulk sedimentation rate,  $S_{B-C}$  the (organic) carbon-free sedimentation rate, and z the water depth. The carbon concentrations in the sediment cores were measured at 1- to 2-cm-thick samples at 10 cm and smaller downcore intervals by means of both Leco<sup>R</sup> and Coulomat 702<sup>R</sup> instruments, and by mass spectrometry [Gif-sur-Yvette].

The principles underlying equation (1) were discussed in detail by Sarnthein et al. [1987]. The equation is based on the assumption that the carbon accumulation rate is mainly a function of primary production, water depth (according to equation (3)), and of the (carbon-free) sedimentation rates acting as "sealing factor," which comprises various processes of carbon degradation near the sediment surface (see below).

In the present paper the original equation of Sarnthein et al. [1987] was slightly modified and improved. First, we included the nonlinear positive relationship between total primary production ( $P_{tot}$ ) and new (=export) production ( $P_{new}$ ) as described by Eppley and Peterson [1979]:

$$P_{new} = P_{tot}^2 / 400 \quad (2)$$

$$(P_{new} = P_{tot} / 2 \text{ at } P_{tot} > 200 \text{ g m}^{-2} \text{ yr}^{-1})$$

This modification is important because  $P_{new}$ , not  $P_{tot}$ , is controlling the extraction of  $CO_2$  from the sea surface. Second, we nearly doubled the sediment trap data base (from 38 to 67 data points) for calculating the relationship between  $P_{new}$ , carbon flux near the seafloor  $F_C$ , and water depth (Table 1, Figure 1a) (equation (3)).

$$F_C = 20.5631 * P_{new}^{0.6648} * z^{-0.5537} \quad (3)$$

$$(r = 0.92)$$

Furthermore, the data matrix for the original paleoproductivity equation was

supplemented with data from 18 Pacific and Indian Ocean sediment samples in order to enlarge its calibration base (Table 2, Figure 1b). Finally, the complete data set derived from modern sediment samples and modern new productivity estimates (equation (4)) was subjected to a linear multiple regression analysis with total forcing resulting in equation (1).

$$P_{new} * z^{-0.8292} = f(C, S_B, DBD, S_{B-C}) \quad (4)$$

Measured (and calculated)  $P_{new}$  values and the  $P_{new}$  estimates from equation (1) agree with a correlation coefficient of  $r = 0.84$  ( $n = 57$ ) (Figure 1b).

We are aware that this empirical equation presents an attempt to deduce one of the most important variables of the ocean, paleoproductivity, from a deposit that constitutes, on the average, less than 0.5-2.0% of the carbon originally produced. Nevertheless, a test run of the equation employing modern sediment data [Sarnthein et al., 1987] provided satisfactory results and strongly encouraged its application to the fossil record. Furthermore, the paleoproductivity trends we find are corroborated by parallel fluctuations in the accumulation rates of biogenic silica, which are available in a few cases (e.g., from the south Indian Ocean, and the eastern equatorial Atlantic and Pacific; Pichon et al. [1987]; Thiede et al. [1982]; Lyle et al. [1988]).

The equation itself still contains a number of pitfalls and major generalizations, including the following:

1. Many of the values of modern primary productivity we used for equation (1) were derived from Koblenz-Mishke et al. [1970] (improved version from FAO [1981]) who measured them by the principle of C-14 assimilation, a method which has recently been criticized [Jenkins, 1982; Platt and Harrison, 1985]. Many authors claim that this method underestimates productivity; other authors rather see the conventional C-14 estimates confirmed (see review in the work of Brewer et al. [1986]).

2. The relationship between  $P_{tot}$  and  $P_{new}$  proposed by Eppley and Peterson [1979] may require further refinement and an enlarged data base. However, as shown by the careful studies of Betzer et al. [1984] and Bishop and Marra [1984], the  $F_C$  to  $P_{tot}$  ratio is, in principle, positively correlated to  $P_{tot}$ .

3. The relationship between the carbon fluxes near the seafloor and  $P_{new}$  has only

TABLE 1. Organic Flux Rates in the Water Column and Mean New Primary Production  $P_{new}$  Compiled From Various Sources

| Latitude, ° | Longitude, ° | Water<br>Depth, m | Carbon<br>Flux,<br>gC m <sup>-2</sup> yr <sup>-1</sup> | New Primary<br>Production<br>gC m <sup>-2</sup> yr <sup>-1</sup> | References |
|-------------|--------------|-------------------|--------------------------------------------------------|------------------------------------------------------------------|------------|
| 31.5 N      | 55.9 W       | 976               | 0.89                                                   | 4.0                                                              | (a)        |
| 31.5 N      | 55.9 W       | 3694              | 0.32                                                   | 4.0                                                              | (a)        |
| 31.5 N      | 55.9 W       | 5206              | 0.45                                                   | 5.0                                                              | (a)        |
| 13.5 N      | 54.0 W       | 389               | 2.46                                                   | 6.2                                                              | (a)        |
| 13.5 N      | 54.0 W       | 988               | 1.44                                                   | 6.2                                                              | (a)        |
| 13.5 N      | 54.0 W       | 3755              | 0.63                                                   | 6.2                                                              | (a)        |
| 13.5 N      | 54.0 W       | 5068              | 0.62                                                   | 6.2                                                              | (a)        |
| 15.3 N      | 151.5 W      | 378               | 1.30                                                   | 4.0                                                              | (a)        |
| 15.3 N      | 151.5 W      | 2778              | 0.40                                                   | 4.0                                                              | (a)        |
| 15.3 N      | 151.5 W      | 4280              | 0.32                                                   | 4.0                                                              | (a)        |
| 15.3 N      | 151.5 W      | 5582              | 0.24                                                   | 4.0                                                              | (a)        |
| 32nm SE     | Bermuda      | 3200              | 0.77                                                   | 4.0                                                              | (a)        |
| 0.6 N       | 86.1 W       | 2650              | 2.28                                                   | 25.0                                                             | (a)        |
| 27.7 N      | 78.9 W       | 675               | 2.60                                                   | 13.0                                                             | (a)        |
| 33.5 N      | 76.2 W       | 1345              | 5.40                                                   | 18.0                                                             | (a)        |
| 38.3 N      | 69.6 W       | 3650              | 4.20                                                   | 64.0                                                             | (a)        |
| 24.9 N      | 77.7 W       | 2000              | 2.10                                                   | 13.0                                                             | (a)        |
| 36.7 N      | 122.2 W      | 50                | 158.00                                                 | 250.0                                                            | (a)        |
| 36.7 N      | 122.2 W      | 250               | 92.00                                                  | 250.0                                                            | (a)        |
| 36.7 N      | 122.2 W      | 700               | 42.00                                                  | 250.0                                                            | (a)        |
| 36.7 N      | 122.2 W      | 50                | 33.00                                                  | 56.0                                                             | (a)        |
| 36.7 N      | 122.2 W      | 250               | 19.00                                                  | 56.0                                                             | (a)        |
| 36.7 N      | 122.2 W      | 700               | 17.00                                                  | 56.0                                                             | (a)        |
| 32.8 N      | 144.4 W      | 75                | 25.00                                                  | 25.0                                                             | (a)        |
| 32.8 N      | 144.4 W      | 575               | 5.30                                                   | 25.0                                                             | (a)        |
| 32.8 N      | 144.4 W      | 1050              | 4.40                                                   | 25.0                                                             | (a)        |
| 38.8 N      | 72.5 W       | 2200              | 6.30                                                   | 25.0                                                             | (a)        |
| 38.5 N      | 72.0 W       | 2750              | 2.30                                                   | 64.0                                                             | (a)        |
| 55.6 N      | 15.4 E       | 55                | 65.00                                                  | 150.0                                                            | (a)        |
| 15.1 S      | 75.4 W       | 50                | 240.00                                                 | 600.0                                                            | (a)        |
| 15.1 S      | 75.5 W       | 70                | 130.00                                                 | 300.0                                                            | (a)        |
| 15.1 S      | 75.5 W       | 100               | 110.00                                                 | 300.0                                                            | (a)        |
| 6.6 N       | 92.8 W       | 500               | 1.45                                                   | 21.3                                                             | (g)        |
| 6.6 N       | 92.8 W       | 1500              | 1.70                                                   | 21.3                                                             | (g)        |
| 6.6 N       | 92.8 W       | 3075              | 1.10                                                   | 21.3                                                             | (g)        |
| 8.8 N       | 104.0 W      | 2700              | 1.38                                                   | 14.1                                                             | (g)        |
| 34.0 N      | 65.8 W       | 5140              | 0.72                                                   | 13.0                                                             | (a)        |
| 32.5 N      | 117.8 W      | 1193              | 9.80                                                   | 136.0                                                            | (a)        |
| 32.3 N      | 117.5 W      | 1230              | 9.80                                                   | 136.0                                                            | (a)        |
| 32.5 N      | 120.6 W      | 3815              | 9.80                                                   | 153.0                                                            | (a)        |
| 5.3 N       | 81.8 W       | 667               | 4.56                                                   | 39.0                                                             | (b,f)      |
| 5.3 N       | 81.8 W       | 1268              | 3.28                                                   | 39.0                                                             | (b,f)      |
| 5.3 N       | 81.8 W       | 2265              | 3.28                                                   | 39.0                                                             | (b,f)      |
| 5.3 N       | 81.8 W       | 2869              | 3.94                                                   | 39.0                                                             | (b,f)      |
| 5.3 N       | 81.8 W       | 3769              | 4.15                                                   | 39.0                                                             | (b,f)      |
| 5.3 N       | 81.8 W       | 3791              | 3.84                                                   | 39.0                                                             | (b,f)      |
| 50.0 N      | 145.0 W      | 1000              | 3.40                                                   | 12.3                                                             | (g)        |
| 50.0 N      | 145.0 W      | 3800              | 2.25                                                   | 12.3                                                             | (g)        |
| 6.0 S       | 153.0 W      | 900               | 2.80                                                   | 107.0                                                            | (e)        |
| 0.0         | 153.0 W      | 900               | 3.00                                                   | 114.0                                                            | (e)        |
| 6.0 N       | 153.0 W      | 900               | 1.65                                                   | 36.5                                                             | (e)        |
| 12.0 N      | 153.0 W      | 900               | 0.90                                                   | 7.8                                                              | (e)        |
| 51.0 N      | 145.0 W      | 250               | 12.40                                                  | 81.0                                                             | (d)        |

TABLE 1. (continued)

| Latitude, ° | Longitude, ° | Water Depth, m | Carbon Flux, gC m <sup>-2</sup> yr <sup>-1</sup> | New Primary Production gC m <sup>-2</sup> yr <sup>-1</sup> | References |
|-------------|--------------|----------------|--------------------------------------------------|------------------------------------------------------------|------------|
| 51.0 N      | 145.0 W      | 600            | 11.50                                            | 81.0                                                       | (d)        |
| 51.0 N      | 145.0 W      | 900            | 9.10                                             | 81.0                                                       | (d)        |
| 51.0 N      | 145.0 W      | 1200           | 10.90                                            | 81.0                                                       | (d)        |
| 51.0 N      | 145.0 W      | 2000           | 8.20                                             | 81.0                                                       | (d)        |
| 51.0 N      | 145.0 W      | 2500           | 7.80                                             | 81.0                                                       | (d)        |
| 51.0 N      | 145.0 W      | 3000           | 6.75                                             | 81.0                                                       | (d)        |
| 60.9 N      | 57.0 W       | 965            | 5.41                                             | 3.3                                                        | (c)        |
| 60.9 N      | 57.0 W       | 2540           | 4.78                                             | 3.3                                                        | (c)        |
| 35.8 N      | 123.7 W      | 100            | 23.70                                            | 105.0                                                      | (h)        |
| 35.8 N      | 123.7 W      | 200            | 16.40                                            | 105.0                                                      | (h)        |
| 35.8 N      | 123.7 W      | 300            | 12.00                                            | 105.0                                                      | (h)        |
| 35.8 N      | 123.7 W      | 500            | 9.10                                             | 105.0                                                      | (h)        |
| 35.8 N      | 123.7 W      | 600            | 9.10                                             | 105.0                                                      | (h)        |
| 35.8 N      | 123.7 W      | 700            | 6.20                                             | 105.0                                                      | (h)        |

(a) See Table 1, Sarnthein et al. [1987]; (b) Honjo et al. [1982]; (c) Wefer et al. [1982]; (d) Lorenzen et al. [1983]; (e) Betzer et al. [1984]; (f) Bishop and Marra [1984]; (g) Honjo [1984]; (h) Karl and Knauer [1984].

been measured at few sediment trap locations in the world ocean running through a complete year or longer (Table 1). Recent data of Walsh et al. [1988] could no

longer be incorporated in our data set. The present variability of  $P_{new}$  and the particulate carbon fluxes ( $F_c$ ) may not be considered sufficiently. In general, we may assume that pulsating bloom populations dominate the export of particulate organic matter to the deep ocean.

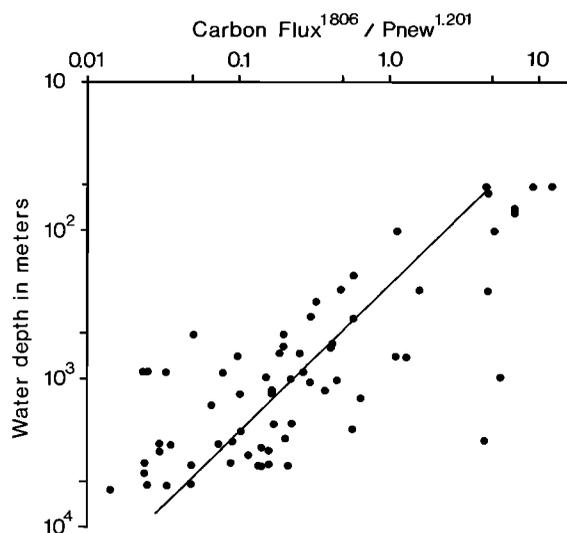


Fig. 1a. Organic carbon fluxes in water depths below 100 m at sites of sediment trap employment, normalized to annual means of new primary production. Data base in Table 1. Extremely high relative flux values are derived from Weddell Sea [Wefer et al., 1982].

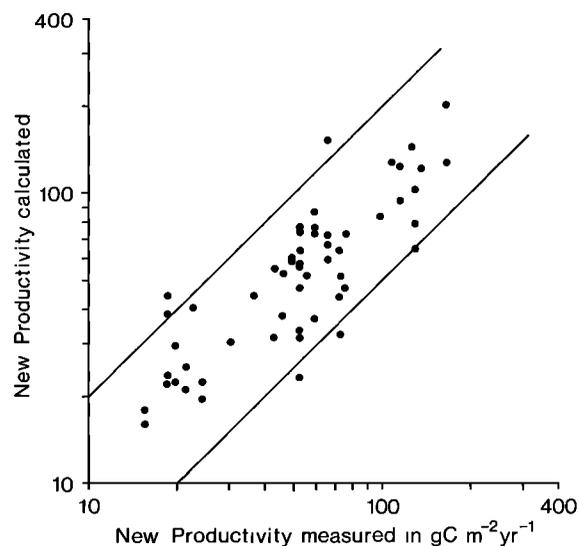


Fig. 1b. Measured values of new primary production versus estimates calculated from equation (1) based on Table 2. Bounding lines mark a deviation within a factor of 2.

TABLE 2. Core Data Used in the Derivation of Productivity Formula

| Core Number<br>or Station | Water<br>Depth, m | C, wt % | $\rho_s(1-\emptyset)$ , g/cc | $S_B$ , cm/ka | $S_{B-C}$ , cm/ka | New Production                    |                                    |
|---------------------------|-------------------|---------|------------------------------|---------------|-------------------|-----------------------------------|------------------------------------|
|                           |                   |         |                              |               |                   | Measured,<br>gC/m <sup>2</sup> yr | Estimated,<br>gC/m <sup>2</sup> yr |
| 23199-1                   | 1968              | 0.63    | 0.4190                       | 4.50          | 4.47              | 20.3                              | 15.2                               |
| 23055-2                   | 2308              | 0.55    | 0.5160                       | 2.00          | 1.99              | 25.0                              | 10.7                               |
| 12392-1                   | 2575              | 0.35    | 0.9780                       | 5.05          | 5.03              | 14.1                              | 22.0                               |
| 12310-3                   | 3076              | 0.34    | 0.6504                       | 3.80          | 3.79              | 20.3                              | 16.8                               |
| 12327-4                   | 2037              | 1.34    | 0.4065                       | 8.33          | 8.22              | 39.1                              | 36.6                               |
| 12328-4                   | 2798              | 1.66    | 0.5691                       | 15.08         | 14.83             | 115.0                             | 94.5                               |
| 12329-4                   | 3315              | 0.61    | 0.6233                       | 2.56          | 2.54              | 36.0                              | 20.0                               |
| 12336-1                   | 3645              | 0.44    | 0.6775                       | 2.20          | 2.19              | 39.1                              | 16.7                               |
| 12337-4                   | 3085              | 1.46    | 0.5691                       | 4.90          | 4.83              | 64.0                              | 47.1                               |
| 12344-3                   | 711               | 2.59    | 0.5691                       | 16.45         | 16.02             | 105.0                             | 42.7                               |
| 12345-4                   | 966               | 3.67    | 0.5691                       | 16.45         | 15.85             | 105.0                             | 69.1                               |
| 12347-1                   | 2710              | 2.34    | 0.5691                       | 12.48         | 12.19             | 76.6                              | 102.3                              |
| 13209-2                   | 4713              | 0.51    | 0.5691                       | 3.20          | 3.18              | 18.1                              | 26.1                               |
| 13521-1                   | 4504              | 0.37    | 0.6450                       | 3.50          | 3.49              | 20.3                              | 23.1                               |
| 16017-2                   | 812               | 1.81    | 0.9879                       | 6.80          | 6.68              | 105.0                             | 29.4                               |
| 16402-1                   | 4203              | 0.46    | 0.6037                       | 5.24          | 5.22              | 30.3                              | 31.1                               |
| 16403-2                   | 4234              | 0.45    | 0.6310                       | 3.66          | 3.64              | 30.3                              | 25.3                               |
| 16404-1                   | 4787              | 0.42    | 0.6460                       | 3.17          | 3.16              | 18.1                              | 24.8                               |
| 16405-1                   | 4870              | 0.43    | 0.7501                       | 3.40          | 3.39              | 20.3                              | 28.9                               |
| 16415-1                   | 3841              | 0.61    | 0.6500                       | 2.70          | 2.68              | 20.3                              | 23.9                               |
| 16432-2                   | 4515              | 0.52    | 0.6447                       | 5.40          | 5.37              | 20.3                              | 37.7                               |
| V15-141                   | 5934              | 0.72    | 0.6500                       | 2.90          | 2.88              | 25.0                              | 39.8                               |
| V15-142                   | 5885              | 0.92    | 0.6500                       | 3.30          | 3.27              | 25.0                              | 50.2                               |
| 10127-2                   | 5686              | 0.28    | 0.3710                       | 0.19          | 0.19              | 2.3                               | 2.9                                |
| 10132-1                   | 5004              | 0.22    | 0.5300                       | 0.58          | 0.58              | 4.0                               | 5.3                                |
| 10140-1                   | 5144              | 0.33    | 0.3735                       | 0.41          | 0.41              | 3.1                               | 4.7                                |
| 10141-1                   | 5189              | 0.31    | 0.3735                       | 0.36          | 0.36              | 3.1                               | 4.2                                |
| 10145-1                   | 4599              | 0.21    | 0.5300                       | 0.32          | 0.32              | 5.1                               | 3.3                                |
| 10147-1                   | 4619              | 0.23    | 0.5300                       | 0.43          | 0.43              | 5.1                               | 4.3                                |
| 10175-1                   | 5164              | 0.40    | 0.3968                       | 0.23          | 0.23              | 4.0                               | 3.9                                |
| 7706-37                   | 3700              | 13.20   | 0.2702                       | 50.00         | 43.40             | 85.6                              | 97.1                               |
| 7706-39                   | 186               | 13.20   | 0.2268                       | 160.00        | 138.88            | 165.0                             | 102.6                              |
| 7706-41                   | 411               | 19.60   | 0.1910                       | 160.00        | 128.64            | 165.0                             | 237.0                              |
| 7706-44                   | 580               | 7.83    | 0.4880                       | 13.00         | 11.98             | 85.6                              | 59.3                               |
| 7706-49                   | 3970              | 3.23    | 0.2300                       | 20.00         | 19.35             | 30.3                              | 142.5                              |
| 7706-50                   | 4902              | 0.78    | 0.3500                       | 6.00          | 5.95              | 20.3                              | 40.3                               |
| 7610-08                   | 2060              | 1.50    | 0.2904                       | 10.00         | 9.85              | 25.0                              | 37.1                               |
| MANOP H                   | 3500              | 0.90    | 0.1130                       | 0.66          | 0.65              | 20.3                              | 4.7                                |
| MANOP M                   | 3100              | 1.20    | 0.1700                       | 1.00          | 0.99              | 14.1                              | 8.2                                |
| MANOP C                   | 4450              | 0.36    | 0.3820                       | 1.80          | 1.79              | 16.0                              | 11.3                               |
| MANOP S                   | 4915              | 0.90    | 0.2240                       | 1.00          | 0.99              | 3.1                               | 11.5                               |
| P7                        | 3085              | 0.97    | 0.6000                       | 3.30          | 3.27              | 36.0                              | 29.1                               |
| S012-98                   | 3371              | 0.33    | 0.7540                       | 2.50          | 2.49              | 3.1                               | 14.9                               |
| S012229                   | 3327              | 0.11    | 0.6140                       | 3.20          | 3.20              | 7.6                               | 7.6                                |
| S026-12                   | 3105              | 1.49    | 0.2850                       | 1.36          | 1.34              | 10.6                              | 15.0                               |
| S026-58                   | 3200              | 0.50    | 0.6940                       | 3.20          | 3.18              | 16.0                              | 20.8                               |
| S026-90                   | 2211              | 0.18    | 0.5880                       | 3.90          | 3.89              | 20.3                              | 8.2                                |
| S026-96                   | 2706              | 0.79    | 0.4570                       | 2.05          | 2.04              | 36.0                              | 14.7                               |
| S026127                   | 2463              | 0.11    | 0.5930                       | 6.00          | 5.99              | 36.0                              | 8.6                                |
| S026131                   | 3381              | 0.98    | 0.6280                       | 3.81          | 3.77              | 30.3                              | 35.4                               |
| S035101                   | 3125              | 0.22    | 0.8220                       | 1.20          | 1.20              | 3.4                               | 7.2                                |
| S035102                   | 2910              | 0.13    | 0.6230                       | 1.28          | 1.27              | 3.4                               | 4.3                                |
| S035211                   | 2890              | 0.09    | 0.2750                       | 1.43          | 1.43              | 2.3                               | 2.3                                |
| MD77200                   | 2910              | 0.24    | 0.6200                       | 3.75          | 3.74              | 4.4                               | 12.4                               |
| MD77203                   | 2442              | 2.10    | 0.6200                       | 21.43         | 21.00             | 100.0                             | 127.9                              |
| KL 5                      | 3335              | 0.21    | 0.6800                       | 2.00          | 2.00              | 20.3                              | 9.1                                |
| KL 11                     | 3859              | 0.37    | 0.8400                       | 2.75          | 2.74              | 22.6                              | 20.2                               |

4. Equation (1) does not include the oxygen concentration of the deep ocean as a variable. This approach is based on the line of evidence presented by Suess [1980] and Sarnthein et al. [1987], who showed that the accumulation rate of organic carbon ( $C_A$ ) is not controlled by the oxygen content of the bottom water as long as it exceeds about 100  $\mu\text{mol}/\text{kg}$ . The variable oxygen concentration in the oxygen minimum layer near the oceanic thermocline may to some degree enter the equation by the exponent of  $z$ . We may assume that the  $F_C$  indeed influences the ocean chemistry and its  $O_2$  content seasonally [Walsh et al., 1988]. However, the ocean chemistry, especially that of the ocean at more than a few centimeters above the diffusive boundary layer at the seafloor, hardly influences  $F_C$  when more than 50–100  $\mu\text{mol } O_2/\text{kg}$  is available.

5. In most cases, fossil time slices and sedimentation rates were determined by identifying events in the oxygen isotope stratigraphy; only a few of the cores (mainly from the east Atlantic, east Pacific, and Indian oceans) have been C-14 dated. The end of Termination  $I_B$  has been dated at about 8000 years B.P., the onset of Termination  $I_A$  at 15,000 years B.P. The onset of stage 2 at 27,000 years B.P. (Figure 2) is different from Prell et al. [1986], the stage 2/3 boundary being placed at the top of the  $\sim 0.5\%$  slope marking the base of the  $\delta^{18}O$  trough of stage 2 [Duplessy et al., 1981; Vincent and Berger, 1985; Paterne et al., 1986; Bard et al., 1987; Sarnthein et al., 1982b, 1987]. Unfortunately, in many cases, the time slice "8000 years B.P. to Present" is incomplete because of the loss of the sediment surface during coring. In these cases, the interval only comprises the peak Holocene interval of 8000 to 6000/4000 years B.P. or less (Figure 2).

6. We did not systematically analyze the chemical composition of the organic carbon fraction in the sediments, which may partly originate from terrigenous organic matter and therefore may not be completely derived from marine productivity [e.g., Stein et al., 1986]. However, the stable isotopic composition of organic carbon was determined for some core profiles (Figure 5). The average  $\delta^{13}C$  values of  $-18$  to  $-21\%$  suggest that the bulk of the carbon deposited close to a continent in zones with modern and glacial high carbon accumulation rates is derived from marine production (see below). This conclusion is corroborated by C/N values of

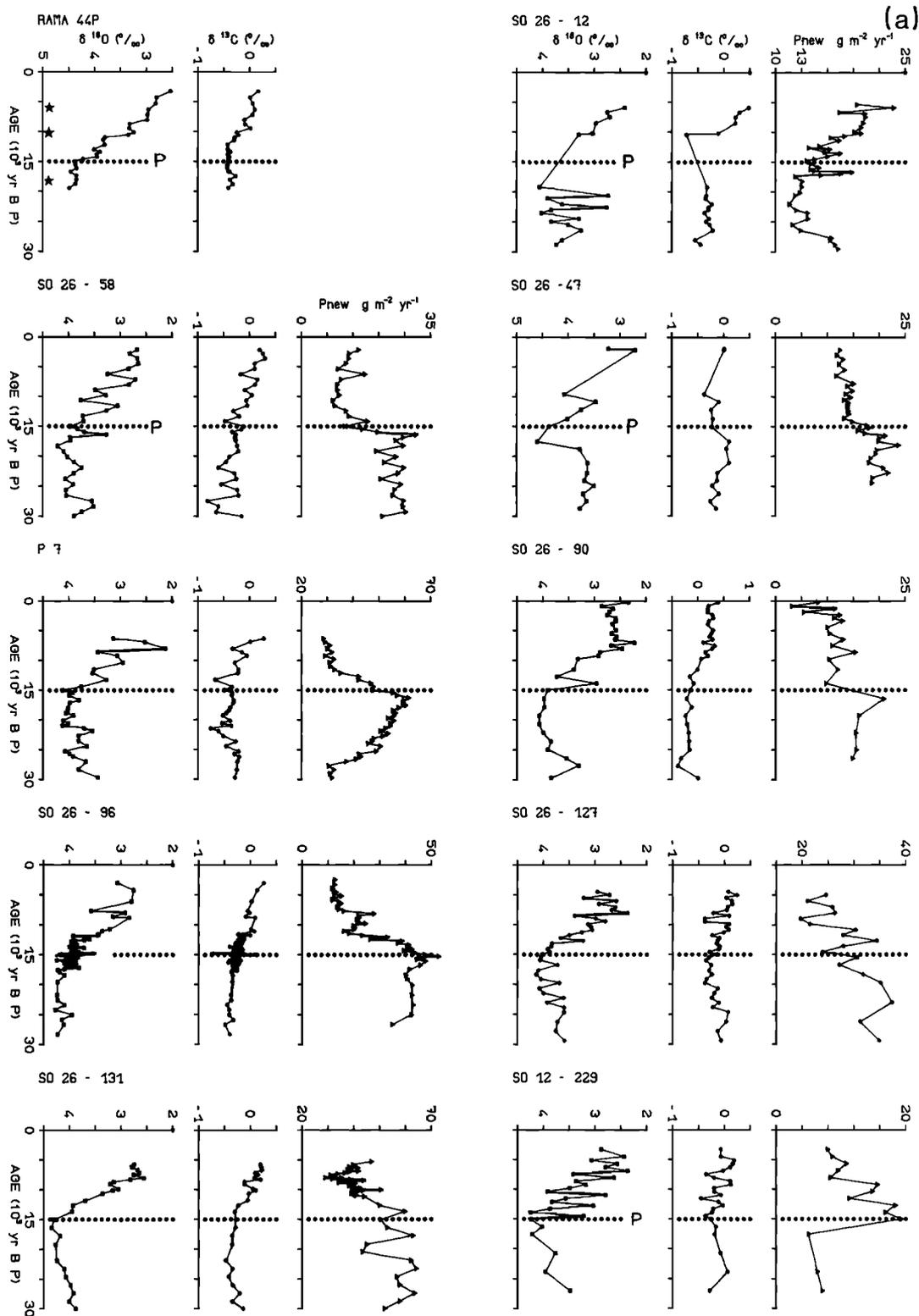
7–9 off northwest Africa [Hartmann et al., 1976].

7. In our calculations the long-term diagenetic loss of organic carbon was only considered for sediment sections with extremely low deposition rates of less than 0.5 cm/1000 years (applying formula (1) of Müller and Mangini [1980], for Pacific cores 10127–10175; Table 3). Occasionally, short-term losses may have also occurred due to long-term sediment storage in core repositories.

The  $CO_2$  content of the ocean bottom water was deduced from the  $\delta^{13}C$  composition of the elevated epifaunal foraminifer *Cibicides wuellerstorfi* [Lutze and Thiel, 1987]. As shown by Zahn et al. [1986] and postulated by Woodruff et al. [1980], Graham et al. [1981], Duplessy et al. [1984], and Berger and Vincent [1986], the carbon isotope composition of this species is fairly independent of the local carbon fluxes but depicts the general  $CO_2$  concentration of the deep water. However, as to be expected from data of Kroopnick [1971], the data of this paper and of Zahn-Knoll [1986] reveal that regional maxima of carbon fluxes to the seafloor can also modify the general carbon isotope level of near-bottom sea-water. This influence will be reflected in the  $\delta^{13}C$  content of *C. wuellerstorfi* by the same degree. Nevertheless, this factor appears to be much weaker than the pore water effect observed for the  $\delta^{13}C$  values of the infaunal genus *Uvigerina* [Zahn et al., 1986; Altenbach and Sarnthein, 1988].

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Fig. 2. (Opposite) (a–g) Stable isotopic records of *C. wuellerstorfi* (per mill versus PDB) and new paleoproductivity records ( $g\ m^{-2}\ yr^{-1}$ ) versus time in cores used for this study (order of cores: from north to south, following Table 3). Stars represent  $^{14}C$  dates. The  $\delta^{13}C$  values were omitted where  $\delta^{18}O$  values of *C. kullenbergi* replace those of *C. wuellerstorfi*. PL1, *Globigerinoides ruber*; PL2, *Neogloboquadrina pachyderma*; U. sp., *Uvigerina* sp. Further data from previously published records and from personal unpublished communications (1987) in Table 3. The onset age of Termination  $I_A$  is shown by dotted line normally based on benthic  $\delta^{18}O$  record. "C-14" marks onset ages derived from radiocarbon dates (stars); "P" marks onset ages obtained from planktonic  $\delta^{18}O$  curves (not shown because of format problems) where *C. wuellerstorfi* values were incomplete or based on too small specimen numbers.



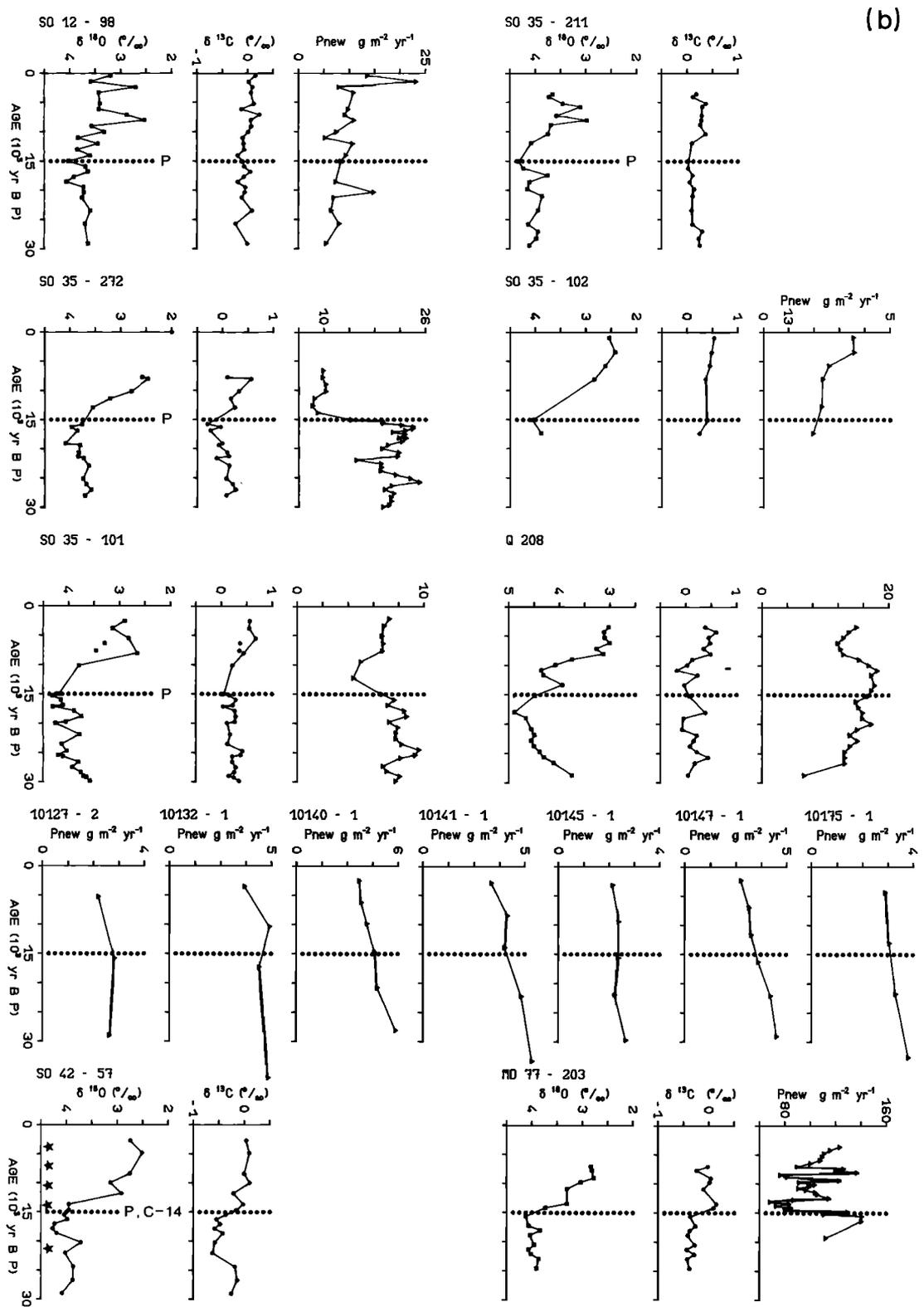


Fig. 2. (continued)

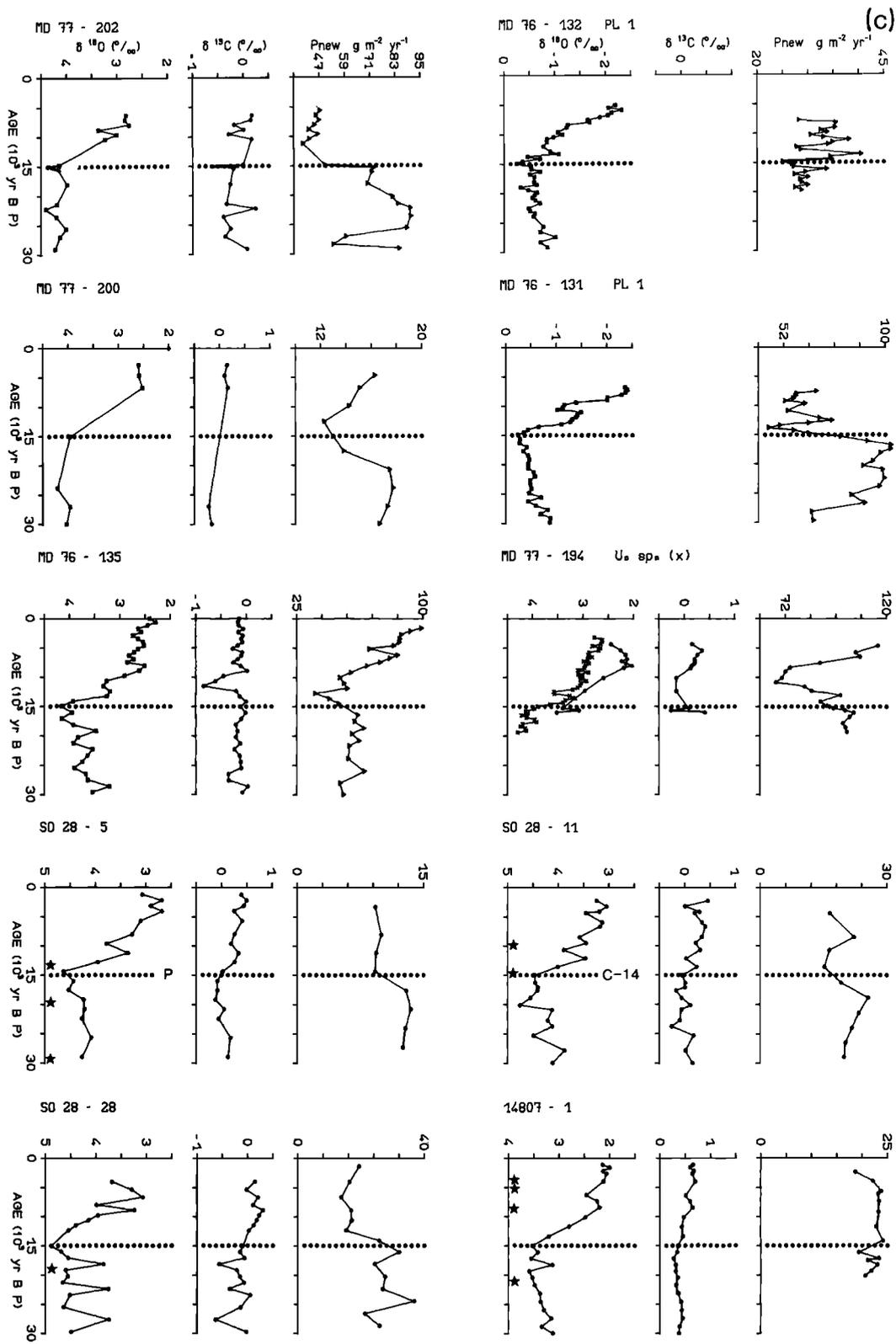


Fig. 2. (continued)

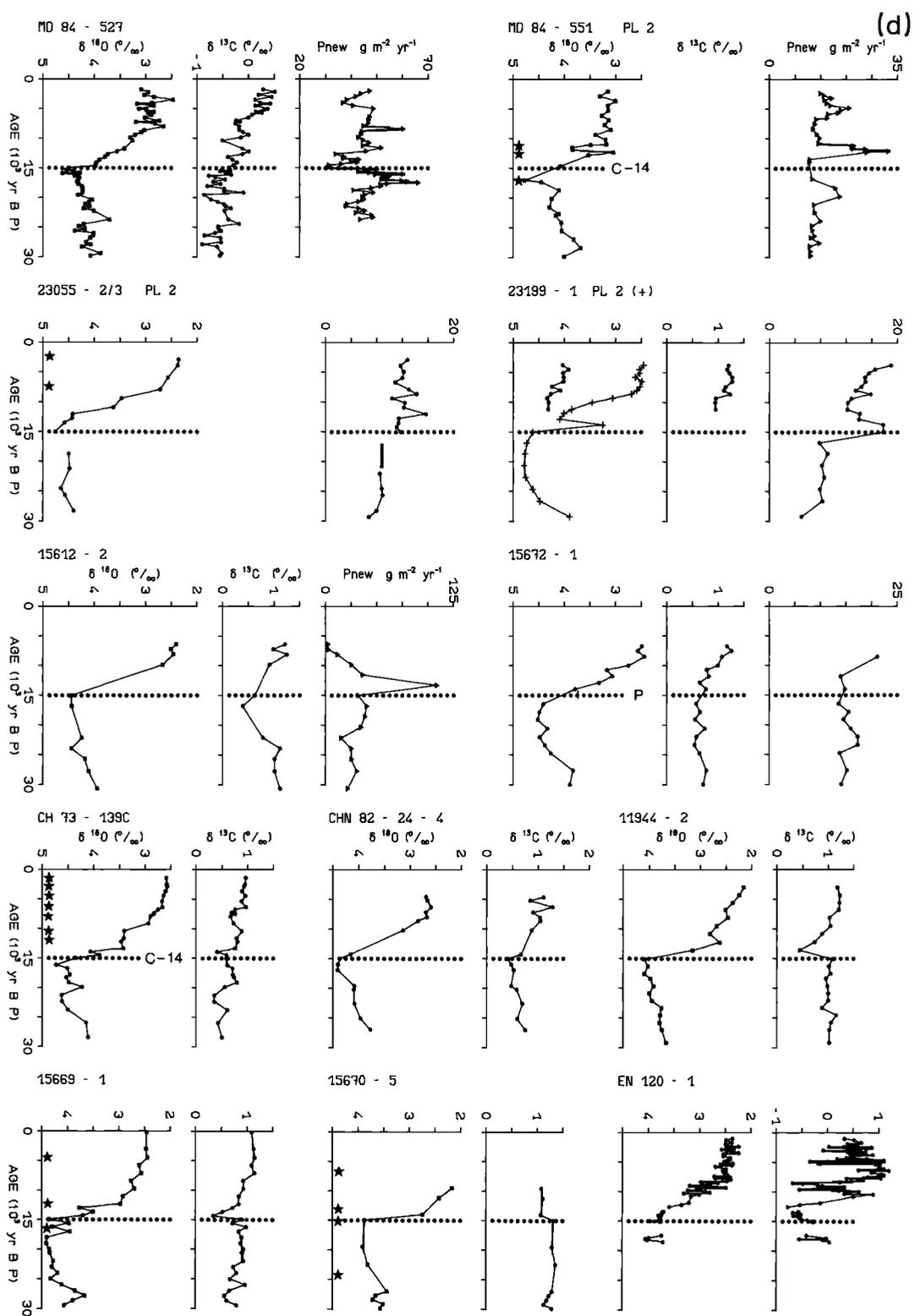


Fig. 2. (continued)

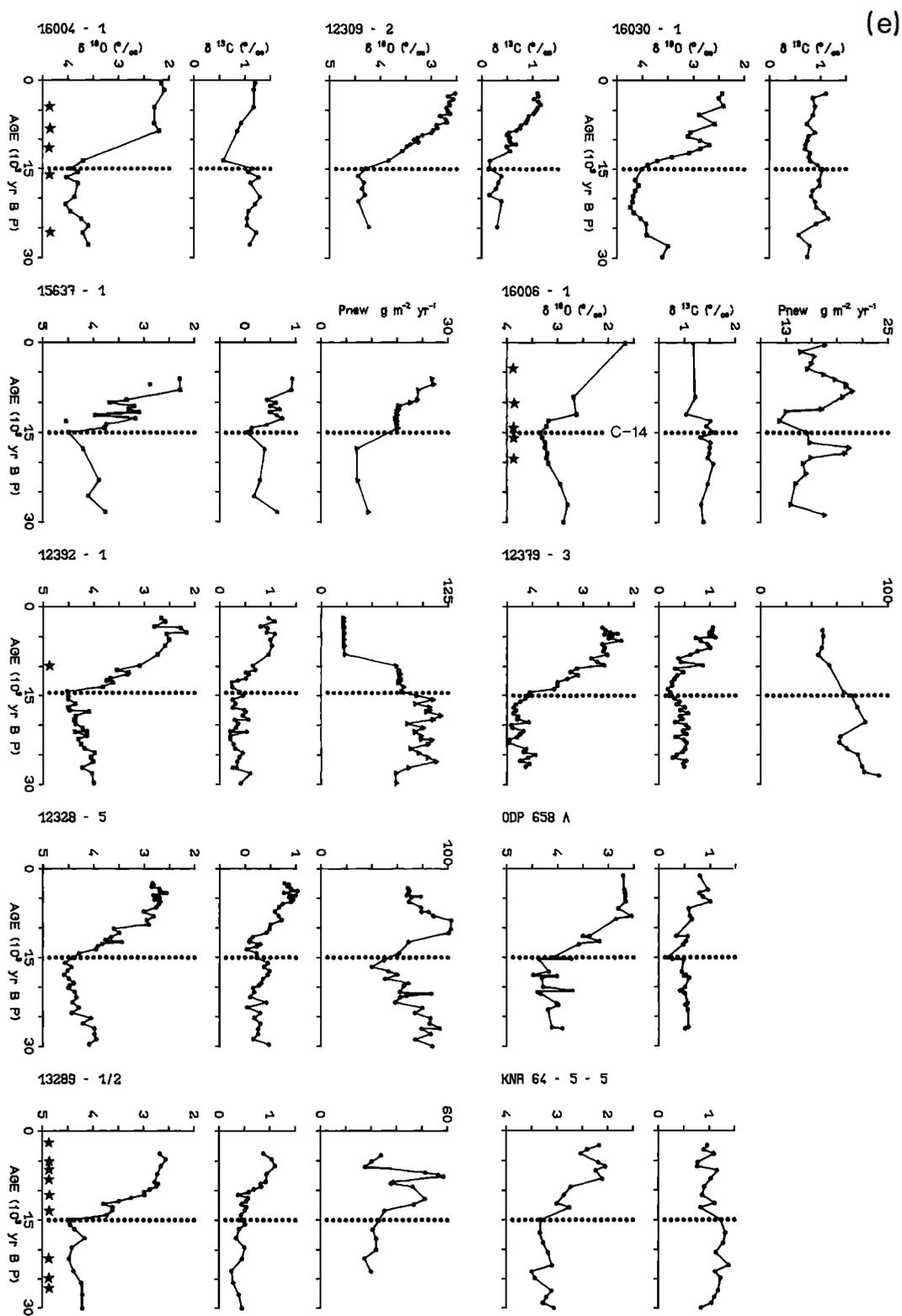


Fig. 2. (continued)

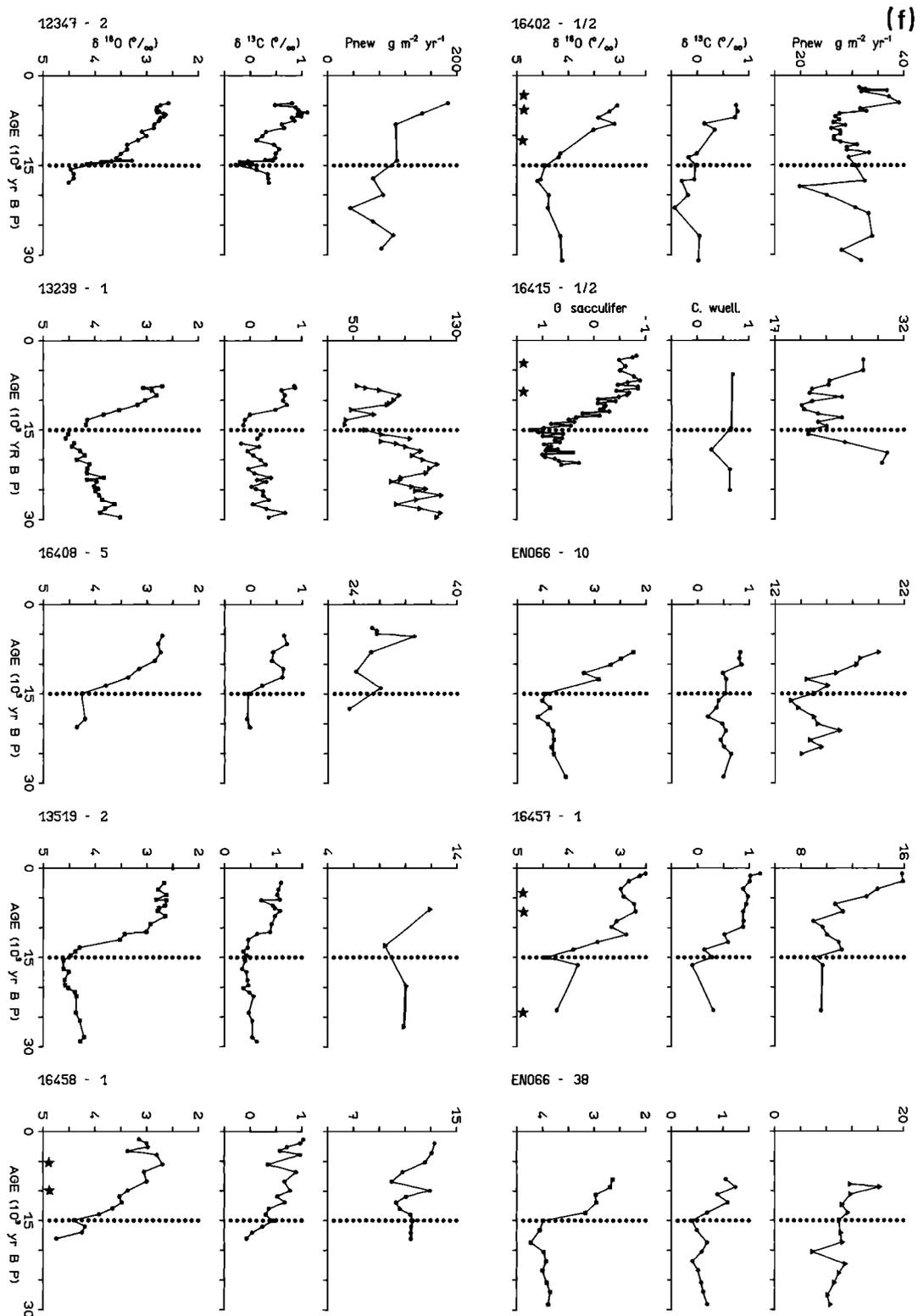


Fig. 2. (continued)

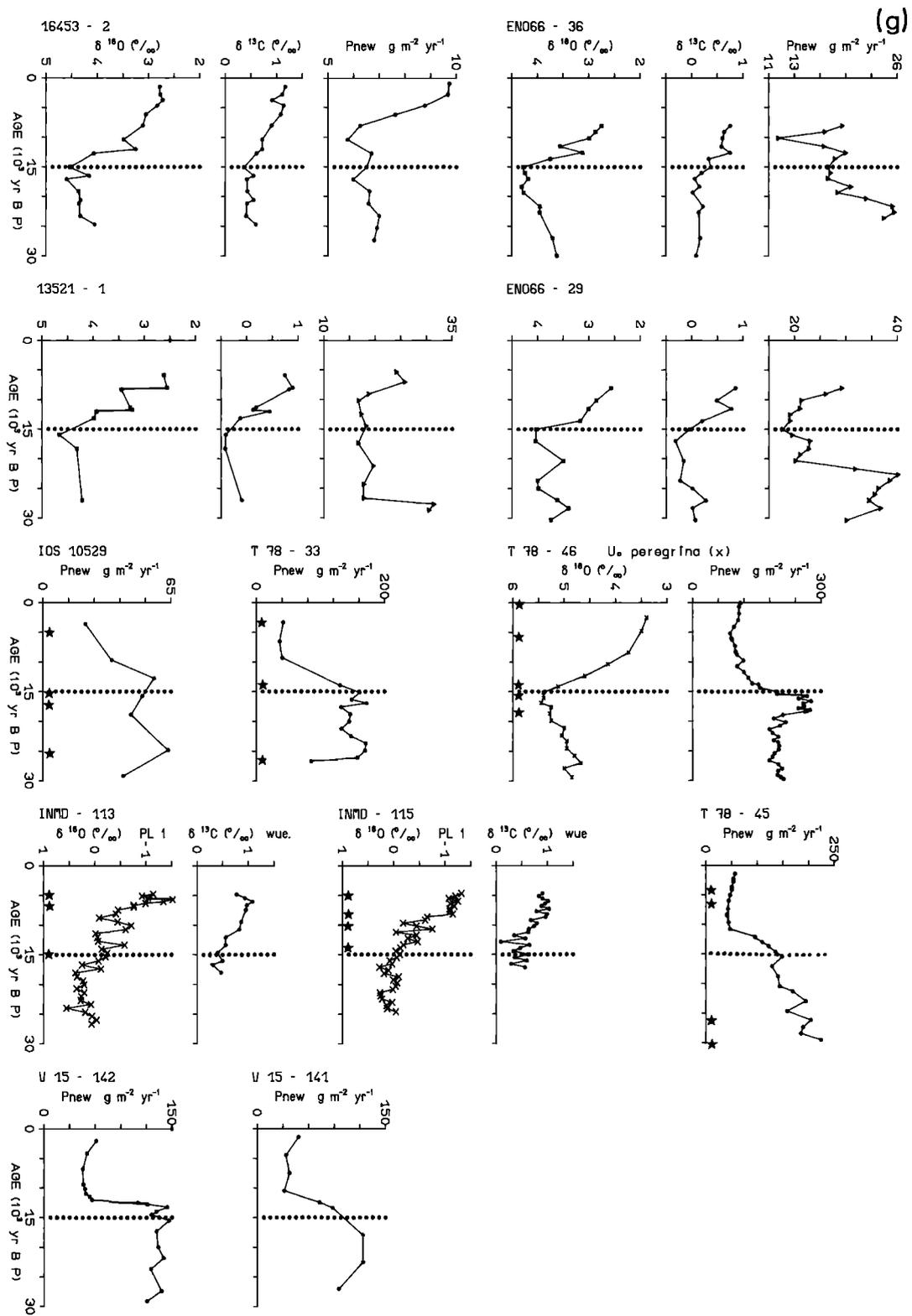


Fig. 2. (continued)

TABLE 3. Core Locations, Water Depths, Average  $\delta^{13}\text{C}$  Values and New Paleoproductivity Data From the LGM (17,000-21,000 Years B.P. and the Holocene (Last 8000 Years) Used in This Paper

| Core Number          | Latitude  | Longitude  | Depth, m | $\delta^{13}\text{C}$ ‰ |        |                             | Production, g/m <sup>2</sup> yr |        |                       | Reference |
|----------------------|-----------|------------|----------|-------------------------|--------|-----------------------------|---------------------------------|--------|-----------------------|-----------|
|                      |           |            |          | 0-8k                    | 17-21k | $\Delta\delta^{13}\text{C}$ | 0-8k                            | 17-21k | $\Delta\text{Pnew}$ % |           |
| <i>Pacific Ocean</i> |           |            |          |                         |        |                             |                                 |        |                       |           |
| ARAMA 44P            | 53°00.0'N | 164°39.2'W | 2980     | 0.05                    | -0.35  | 0.40                        | -                               | -      | -                     | c10       |
| *Y69-10-2            | 41°16.0'N | 126°24.0'W | 2743     | 0.01                    | -0.57  | 0.58                        | -                               | -      | -                     | c3        |
| *V32-128             | 36°28.0'N | 177°10.0'E | 3623     | 0.31                    | -0.17  | 0.48                        | -                               | -      | -                     | c3        |
| *S050-37             | 18°54.6'N | 115°45.8'W | 2695     | 0.16                    | -0.25  | 0.41                        | -                               | -      | -                     | a         |
| *S050-29             | 18°26.1'N | 115°39.2'W | 3766     | 0.22                    | -0.20  | 0.42                        | -                               | -      | -                     | a         |
| AS026-12             | 13°07.3'N | 103°00.5'W | 3105     | 0.33                    | -0.34  | 0.67                        | 20.2                            | 13.1   | 54.2                  | a         |
| *RC13-120            | 3°51.0'N  | 107°14.0'W | 3753     | 0.10                    | -0.40  | 0.50                        | -                               | -      | -                     | c3        |
| *V17-42              | 3°32.0'N  | 81°11.0'W  | 1814     | 0.01                    | -0.24  | 0.25                        | -                               | -      | -                     | c3        |
| AS026-58             | 2°43.7'N  | 95°11.3'W  | 3200     | 0.19                    | -0.32  | 0.51                        | 12.6                            | 24.2   | -48.0                 | a         |
| AS026-47             | 2°39.8'N  | 100°15.0'W | 4027     | -                       | -      | -                           | 12.8                            | 20.1   | -36.0                 | a         |
| AP 7                 | 2°36.3'N  | 83°59.2'W  | 3085     | 0.14                    | -0.42  | 0.56                        | 29.6                            | 56.2   | -47.4                 | a,c1      |
| AS026-90             | 2°15.0'N  | 92°20.9'W  | 2211     | 0.25                    | -0.19  | 0.43                        | 9.9                             | 16.1   | -38.6                 | a         |
| *W8402A-14           | 0°57.2'N  | 138°57.3'W | 4287     | -                       | -      | -                           | 9.7                             | 12.8   | -24.1                 | c12       |
| AS026-96             | 0°41.1'N  | 85°50.4'W  | 2706     | 0.10                    | -0.32  | 0.42                        | 13.4                            | 41.2   | -67.4                 | a         |
| *V24-109             | 0°26.0'N  | 158°48.0'E | 2367     | 0.31                    | 0.11   | 0.20                        | -                               | -      | -                     | c3        |
| *KN73-3              | 0°22.0'S  | 106°11.0'W | 3606     | 0.22                    | -0.22  | 0.44                        | -                               | -      | -                     | c4        |
| *V19-27              | 0°28.0'S  | 82°04.0'W  | 1373     | 0.32                    | -0.03  | 0.35                        | -                               | -      | -                     | c3        |
| AS026-127            | 1°32.8'S  | 85°23.1'W  | 2463     | 0.06                    | -0.28  | 0.34                        | 24.0                            | 33.5   | -28.5                 | a         |
| *V19-28              | 2°28.0'S  | 84°39.0'W  | 2670     | -                       | -      | -                           | 29.9                            | 60.4   | -50.5                 | c12       |
| *V19-30              | 3°23.0'S  | 83°21.0'W  | 3091     | 0.03                    | -0.43  | 0.46                        | -                               | -      | -                     | c3        |
| AS026-131            | 3°31.6'S  | 85°00.2'W  | 3381     | 0.16                    | -0.35  | 0.51                        | 37.3                            | 50.4   | -26.0                 | a         |
| *TR16-331            | 3°58.0'S  | 83°52.0'W  | 3209     | 0.02                    | -0.34  | 0.36                        | -                               | -      | -                     | c3        |
| AS012-229            | 4°14.4'S  | 103°54.3'W | 3327     | -0.03                   | -0.14  | 0.11                        | 9.1                             | 5.1    | 80.0                  | a         |
| BS012-98             | 10°32.1'S | 109°44.7'W | 3371     | 0.07                    | -0.10  | 0.17                        | 12.1                            | 11.0   | 10.1                  | a         |
| BS035-211            | 14°23.2'S | 177°08.7'E | 2890     | 0.26                    | 0.10   | 0.15                        | ??2.7                           | 3.0    | -11.5                 | a         |
| BS035-272            | 16°01.2'S | 177°41.4'E | 3410     | 0.37                    | 0.00   | 0.37                        | 9.8                             | 21.5   | -54.3                 | a         |
| BS035-102            | 22°24.3'S | 177°26.9'W | 2910     | 0.45                    | ?0.24  | ?0.21                       | 3.0                             | 2.0    | 54.0                  | a         |
| BS035-101            | 22°26.9'S | 177°19.8'W | 3125     | 0.56                    | 0.20   | 0.36                        | 6.8                             | 8.1    | -15.2                 | a         |
| BQ208                | 45°59.2'S | 177°59.3'W | 2830     | 0.46                    | 0.09   | 0.37                        | 13.1                            | 15.8   | -17.5                 | a         |
| B10127-2             | 13°41.7'N | 151°39.3'W | 5686     | -                       | -      | -                           | 2.2                             | 2.8    | -22.2                 | a10       |
| B10132-1             | 6°13.2'N  | 148°57.3'W | 5004     | -                       | -      | -                           | 3.7                             | 4.4    | -16.4                 | a10       |
| B10140-1             | 9°15.0'N  | 148°44.5'W | 5144     | -                       | -      | -                           | 3.7                             | 4.8    | -21.7                 | a10       |
| B10141-1             | 9° 6.2'N  | 148°46.7'W | 5189     | -                       | -      | -                           | 3.3                             | 4.8    | -31.2                 | a10       |
| B10145-1             | 3°59.5'N  | 148°49.3'W | 4599     | -                       | -      | -                           | 2.1                             | 2.5    | -13.0                 | a10       |
| B10147-1             | 3°50.2'N  | 145° 1.7'W | 4619     | -                       | -      | -                           | 3.0                             | 3.9    | -24.7                 | a10       |
| B10175-1             | 9°19.3'N  | 146° 1.1'W | 5164     | -                       | -      | -                           | 2.9                             | 3.3    | -13.0                 | a10       |
| <i>Indian Ocean</i>  |           |            |          |                         |        |                             |                                 |        |                       |           |
| BS042-57             | 20°54.5'N | 63°07.3'E  | 3422     | 0.07                    | -0.50  | 0.57                        | -                               | -      | -                     | a,a1      |
| BMD77-203            | 20°41.2'N | 59°34.0'E  | 2442     | -0.13                   | -0.33  | 0.20                        | 111.4                           | 112.0  | - 0.5                 | b,a       |
| CMD77-202            | 19°13.0'N | 60°40.2'E  | 2427     | 0.05                    | -0.26  | 0.31                        | 46.1                            | 75.8   | -39.2                 | b,a       |

TABLE 3. (continued)

| Core Number           | Latitude  | Longitude  | Depth, m | $\delta^{13}\text{C}$ ‰ |        |                             | Production, g/m <sup>2</sup> yr |        |                       | Reference |
|-----------------------|-----------|------------|----------|-------------------------|--------|-----------------------------|---------------------------------|--------|-----------------------|-----------|
|                       |           |            |          | 0-8k                    | 17-21k | $\Delta\delta^{13}\text{C}$ | 0-8k                            | 17-21k | $\Delta\text{Pnew}$ % |           |
| <i>Indian Ocean</i>   |           |            |          |                         |        |                             |                                 |        |                       |           |
| CMD76-132             | 16°59.0'N | 71°30.1'E  | 1430     | -                       | -      | -                           | 28.0                            | 28.7   | - 1.8                 | b,a       |
| CMD77-200             | 16°32.1'N | 67°53.1'E  | 2910     | 0.14                    | -      | -                           | 15.7                            | 15.6   | 0.6                   | b,a       |
| CMD76-131             | 15°31.1'N | 72°34.0'E  | 1230     | -                       | -      | -                           | 62.6                            | 96.6   | -35.2                 | b,a       |
| CMD76-135             | 14°26.0'N | 50°31.1'E  | 1895     | -0.14                   | -0.17  | -0.03                       | 82.4                            | 60.9   | 35.3                  | b,a       |
| *MD76-128             | 13°08.0'N | 73°19.0'E  | 1712     | 0.09                    | -0.13  | 0.22                        | -                               | -      | -                     | b         |
| *MD76-127             | 12°05.0'N | 75°54.0'E  | 1610     | 0.21                    | -0.37  | 0.58                        | -                               | -      | -                     | b         |
| CMD77-194             | 10°28.0'N | 75°14.0'E  | 1222     | 0.22                    | -      | -                           | 104.3                           | 100.3  | 4.0                   | b         |
| *MD76-125             | 8°35.0'N  | 75°20.0'E  | 1878     | 0.23                    | -0.08  | 0.31                        | -                               | -      | -                     | b         |
| CS028-5               | 6°39.8'N  | 61°08.0'E  | 3335     | 0.38                    | -0.05  | 0.43                        | 9.6                             | 13.3   | -27.5                 | a,a2      |
| CS028-11              | 5°23.4'N  | 60°15.1'E  | 3859     | 0.28                    | -0.03  | 0.31                        | 16.5                            | 24.4   | -32.4                 | a,a2      |
| CS028-28              | 1°24.3'N  | 67°21.9'E  | 4101     | 0.11                    | -0.25  | 0.36                        | 16.5                            | 25.9   | -36.4                 | a,a2      |
| *V34-55               | 6°02.4'S  | 88°57.4'E  | 2992     | -                       | -      | 0.20                        | -                               | -      | -                     | c2        |
| *V34-54               | 6°05.0'S  | 89°10.0'E  | 3254     | -                       | -      | 0.40                        | -                               | -      | -                     | c2        |
| *V34-51               | 6°11.5'S  | 89°58.0'E  | 4382     | -                       | -      | 0.60                        | -                               | -      | -                     | c2        |
| C14807-1              | 16°56.2'S | 118°50.5'E | 1186     | 0.62                    | 0.31   | 0.31                        | 22.2                            | 22.0   | 1.0                   | a,a3      |
| *MD79-254             | 17°53.0'S | 38°40.0'E  | 1934     | 0.65                    | 0.03   | 0.62                        | -                               | -      | -                     | b         |
| <i>Southern Ocean</i> |           |            |          |                         |        |                             |                                 |        |                       |           |
| *RC11-120             | 43°31.0'S | 79°52.0'E  | 3135     | 0.46                    | -0.37  | 0.83                        | -                               | -      | -                     | c3        |
| DMD84-527             | 43°49.3'S | 51°19.1'E  | 3262     | 0.15                    | -0.58  | 0.73                        | 43.8                            | 50.7   | -13.6                 | b         |
| DMD84-551             | 55°00.5'S | 73°16.9'E  | 2230     | -                       | -      | -                           | 16.1                            | 18.6   | -13.4                 | b1        |
| <i>Atlantic Ocean</i> |           |            |          |                         |        |                             |                                 |        |                       |           |
| D23055-2              | 68°24.4'N | 4°01.3'E   | 2308     | 1.32                    | -      | -                           | 12.1                            | 8.8    | 37.5                  | a4        |
| D23199-1              | 68°22.6'N | 5°13.5'E   | 1968     | 1.20                    | -      | -                           | 15.5                            | 8.6    | 80.3                  | a5        |
| *V28-14               | 64°47.0'N | 29°34.0'W  | 1855     | 0.62                    | 1.41   | -0.79                       | -                               | -      | -                     | c3        |
| *DSDP552              | 56°03.0'N | 23°13.0'W  | 2311     | 1.29                    | 0.94   | 0.35                        | -                               | -      | -                     | c3        |
| DCH73-139C            | 54°38.0'N | 16°21.0'W  | 2209     | 0.86                    | 0.71   | 0.15                        | -                               | -      | -                     | b         |
| *N075-08              | 45°42.0'N | 31°22.0'W  | 3454     | 1.07                    | 0.59   | 0.48                        | -                               | -      | -                     | b         |
| D15612-2              | 44°41.6'N | 26°32.6'W  | 3050     | 1.10                    | 0.55   | 0.55                        | 2.4                             | 36.5   | -93.4                 | a,a3      |
| *V29-179              | 44°00.0'N | 24°32.0'W  | 3331     | 1.10                    | 0.63   | 0.47                        | -                               | -      | -                     | c3        |
| *CH82-5020            | 43°29.9'N | 29°52.0'W  | 3020     | 1.25                    | 0.60   | 0.65                        | -                               | -      | -                     | c4        |
| *S58798               | 42°50.0'N | 23°04.0'W  | 3520     | 0.92                    | 0.60   | 0.32                        | -                               | -      | -                     | c3        |
| DCH82-24-4            | 41°43.0'N | 32°51.0'W  | 3427     | 1.04                    | 0.53   | 0.51                        | -                               | -      | -                     | c4        |
| *CH72-02              | 40°36.0'N | 21°42.0'W  | 3485     | 0.91                    | 0.77   | 0.14                        | -                               | -      | -                     | b         |
| *CH74-23-1            | 36°52.0'N | 26°37.0'W  | 2354     | 1.00                    | 0.56   | 0.44                        | -                               | -      | -                     | b         |
| D11944-2              | 35°39.1'N | 8° 3.7'W   | 1765     | 1.21                    | 1.00   | 0.21                        | -                               | -      | -                     | a3        |
| D15670-5              | 34°54.5'N | 7°34.6'W   | 1482     | 1.08                    | 1.29   | -0.20                       | -                               | -      | -                     | a3        |
| D15669-1              | 34°53.5'N | 7°48.9'W   | 2022     | 1.15                    | 0.90   | 0.25                        | -                               | -      | -                     | a3        |
| D15672-1              | 34°51.6'N | 8°07.6'W   | 2455     | 1.22                    | 0.65   | 0.57                        | -                               | 15.3   | -                     | a,a3      |
| DEN120-1              | 33°40.0'N | 57°37.0'W  | 4450     | 0.60                    | -0.20  | 0.80                        | -                               | -      | -                     | c4        |
| E16004-1              | 29°58.7'N | 10°38.8'W  | 1512     | 1.12                    | 1.20   | -0.08                       | -                               | -      | -                     | a3        |
| E16006-1              | 29°14.8'N | 11°29.8'W  | 796      | 1.17                    | 1.50   | -0.33                       | 17.3                            | 17.8   | - 2.4                 | a,a3      |

TABLE 3. (continued)

| Core Number           | Latitude  | Longitude | Depth, m | $\delta^{13}\text{C}$ ‰ |        |                             | Production, g/m <sup>2</sup> yr |        |                       | Reference |
|-----------------------|-----------|-----------|----------|-------------------------|--------|-----------------------------|---------------------------------|--------|-----------------------|-----------|
|                       |           |           |          | 0-8k                    | 17-21k | $\Delta\delta^{13}\text{C}$ | 0-8k                            | 17-21k | $\Delta\text{Pnew}$ % |           |
| <i>Atlantic Ocean</i> |           |           |          |                         |        |                             |                                 |        |                       |           |
| E15637-1              | 27°00.3'N | 18°59.2'W | 3849     | 0.92                    | 0.38   | 0.54                        | 25.2                            | 8.4    | 200.0                 | a         |
| E12309-2              | 26°50.3'N | 15°06.6'W | 2820     | 0.99                    | 0.29   | 0.70                        | -                               | -      | -                     | a3        |
| E12392-1              | 25°10.3'N | 16°50.7'W | 2575     | 0.97                    | 0.40   | 0.57                        | 22.3                            | 105.0  | -78.8                 | a,a6,c3   |
| E12379-3              | 23°08.1'N | 17°44.7'W | 2576     | 0.93                    | 0.47   | 0.46                        | 47.9                            | 79.3   | -39.6                 | a,a3,a7   |
| *V23-100              | 21°18.0'N | 22°41.0'W | 4579     | 0.59                    | 0.00   | 0.59                        | -                               | -      | -                     | c5        |
| E16030-1              | 21°14.1'N | 18°03.3'W | 1500     | 0.88                    | 0.89   | -0.01                       | -                               | -      | -                     | a3        |
| E12328-5              | 21°08.7'N | 18°34.4'W | 2778     | 0.82                    | 0.31   | 0.51                        | 73.5                            | 60.0   | 22.6                  | a,a3      |
| EODP658A              | 20°45.0'N | 18°34.9'W | 2263     | 0.80                    | 0.49   | 0.31                        | -                               | -      | -                     | a8        |
| E13289-2              | 18°04.4'N | 18°00.6'W | 2490     | 0.98                    | 0.42   | 0.56                        | 38.5                            | 26.3   | 50.0                  | a,a3,a7   |
| EKNR64-5-5            | 16°31.3'N | 74°48.4'W | 3047     | 0.95                    | 1.25   | 0.30                        | -                               | -      | -                     | c4        |
| F12347-2              | 15°49.5'N | 17°51.7'W | 2576     | 0.88                    | 0.35   | 0.53                        | 166.7                           | 78.2   | 113.0                 | a3,a7     |
| F16402-2              | 14°27.5'N | 20°32.5'W | 4234     | 0.60                    | -0.18  | 0.78                        | 31.8                            | 25.8   | 23.1                  | a         |
| *V22-197              | 14°10.0'N | 18°35.0'W | 3167     | 0.76                    | 0.17   | 0.59                        | -                               | -      | -                     | c3        |
| F13239-1              | 13°52.6'N | 18°18.8'W | 3156     | 0.86                    | 0.08   | 0.78                        | 55.9                            | 98.0   | -43.0                 | a         |
| *V22-196              | 13°50.0'N | 18°58.0'W | 3728     | 0.85                    | -0.20  | 1.05                        | -                               | -      | -                     | c3        |
| *CH75-03              | 10°03.0'N | 57°32.0'W | 3410     | 0.84                    | 0.13   | 0.71                        | -                               | -      | -                     | b         |
| *CH75-04              | 10°01.0'N | 56°01.0'W | 3820     | 0.94                    | -0.21  | 1.15                        | -                               | -      | -                     | b         |
| F16415-1/2            | 9°34.0'N  | 19°06.4'W | 3841     | 0.69                    | 0.27   | 0.42                        | 25.0                            | 29.8   | -15.0                 | a,a4      |
| F16408-5              | 9°00.3'N  | 21°21.9'W | 4336     | 0.59                    | -0.04  | 0.63                        | 28.4                            | 23.3   | 21.9                  | a,a4      |
| FENO66-10             | 6°20.0'N  | 21°53.9'W | 3527     | 0.82                    | 0.34   | 0.48                        | 20.0                            | 14.7   | 36.0                  | c6        |
| F13519-2              | 5°39.5'N  | 19°51.0'W | 2862     | 0.99                    | 0.43   | 0.56                        | 11.9                            | 10.1   | 18.0                  | a,a9      |
| *ENO66-16             | 5°27.3'N  | 21° 8.6'W | 3152     | 0.97                    | 0.43   | 0.54                        | -                               | -      | -                     | c6        |
| F16457-1              | 5°23.5'N  | 21°43.2'W | 3291     | 1.00                    | 0.11   | 0.89                        | 13.4                            | 9.6    | 39.7                  | a,a4      |
| F16458-2              | 5°20.1'N  | 22° 3.4'W | 3518     | 0.80                    | -0.02  | 0.82                        | 12.1                            | 11.5   | 5.7                   | a,a4      |
| *ENO66-44             | 5°15.8'N  | 21°42.7'W | 3428     | 1.05                    | 0.50   | 0.55                        | -                               | -      | -                     | c6        |
| FENO66-38             | 4°55.2'N  | 20°30.0'W | 2931     | 1.05                    | 0.64   | 0.41                        | -                               | 8.9    | -                     | c6        |
| G16453-2              | 4°44.1'N  | 20°56.8'W | 2675     | 1.01                    | 0.47   | 0.54                        | 8.4                             | 6.3    | 33.3                  | a,a4      |
| *CH71-07              | 4°23.0'N  | 20°52.0'W | 3083     | 1.08                    | 0.30   | 0.78                        | -                               | -      | -                     | b         |
| GENO66-36             | 4°18.4'N  | 20°12.7'W | 4270     | 0.75                    | 0.08   | 0.67                        | 19.5                            | 20.0   | - 2.5                 | c6        |
| *ENO66-21             | 4°14.0'N  | 20°37.3'W | 3995     | 0.84                    | 0.12   | 0.72                        | -                               | -      | -                     | c6        |
| *ENO66-26             | 3°05.1'N  | 20°01.0'W | 4745     | 0.68                    | -0.20  | 0.88                        | -                               | -      | -                     | c6        |
| G13521-1              | 3°01.2'N  | 22°01.9'W | 4504     | 0.82                    | -0.42  | 1.24                        | 25.0                            | 18.2   | 37.0                  | a,a7      |
| *ENO66-32             | 2°28.4'N  | 19°44.1'W | 5003     | 0.89                    | -0.12  | 1.01                        | -                               | -      | -                     | c6        |
| GENO66-29             | 2°27.6'N  | 19°45.7'W | 5104     | 0.85                    | -0.24  | 1.09                        | 29.2                            | 21.7   | 34.0                  | c6        |
| *V25-59               | 1°22.0'N  | 33°29.0'W | 3824     | 0.89                    | 0.07   | 0.82                        | -                               | -      | -                     | c5        |
| G10S-10529            | 4°56.8'S  | 0°27.7'E  | 4735     | -                       | -      | -                           | 21.5                            | 44.6   | -51.8                 | c7        |
| GT78- 33              | 5°11.0'S  | 7°58.0'E  | 4120     | -                       | -      | -                           | 38.7                            | 148.5  | -74.0                 | c11       |
| GT78- 46              | 6°50.1'S  | 10°45.3'E | 2100     | -                       | -      | -                           | 100.9                           | 239.0  | -57.8                 | c11       |
| GT78- 45              | 7°47.8'S  | 10°07.0'E | 4070     | -                       | -      | -                           | 49.7                            | 137.7  | -63.9                 | c11       |
| *V22-174              | 10°04.0'S | 12°49.0'W | 2630     | 0.80                    | 0.72   | 0.08                        | -                               | -      | -                     | c3        |
| G1NMD-113             | 15°15.0'S | 14°58.0'W | 3471     | 0.94                    | 0.47   | 0.47                        | -                               | -      | -                     | c8        |
| G1NMD-115             | 17°40.0'S | 16°13.0'W | 3427     | 0.92                    | 0.48   | 0.44                        | -                               | -      | -                     | c8        |
| *RC13-228             | 20°20.0'S | 11°12.0'E | 3204     | 0.50                    | -0.10  | 0.60                        | -                               | -      | -                     | c3        |

TABLE 3. (continued)

| Core Number           | Latitude  | Longitude | Depth, m | $\delta^{13}\text{C}$ ‰ |        |                             | Production, g/m <sup>2</sup> yr |        |                       | Reference |
|-----------------------|-----------|-----------|----------|-------------------------|--------|-----------------------------|---------------------------------|--------|-----------------------|-----------|
|                       |           |           |          | 0-8k                    | 17-21k | $\Delta\delta^{13}\text{C}$ | 0-8k                            | 17-21k | $\Delta\text{Pnew}$ ‰ |           |
| <i>Atlantic Ocean</i> |           |           |          |                         |        |                             |                                 |        |                       |           |
| *CHN115-70            | 29°55.2'S | 35°39.3'W | 2340     | 0.95                    | 0.71   | 0.24                        | -                               | -      | -                     | c6        |
| *CHN115-91            | 30°49.5'S | 38°25.8'W | 3576     | 0.62                    | 0.23   | 0.39                        | -                               | -      | -                     | c6        |
| *CHN115-92            | 30°50.3'S | 38°50.5'W | 3934     | 0.13                    | -0.43  | 0.56                        | -                               | -      | -                     | c6        |
| *CHN115-88            | 30°55.0'S | 36°04.8'W | 2941     | 0.68                    | 0.34   | 0.34                        | -                               | -      | -                     | c6        |
| *AII60-13A            | 31°59.1'S | 36°38.9'W | 2739     | 1.17                    | 0.43   | 0.71                        | -                               | -      | -                     | c6        |
| *RC12-294             | 37°16.0'S | 10°06.0'W | 3308     | 0.81                    | -0.23  | 1.04                        | -                               | -      | -                     | c3        |
| GV15-142              | 44°54.0'S | 51°32.0'W | 5885     | -                       | -      | -                           | 52.3                            | 132.7  | -60.6                 | c9        |
| GV15-141              | 45°44.0'S | 50°45.0'W | 5934     | -                       | -      | -                           | 39.8                            | 123.6  | -67.8                 | c9        |

References: a, this work (Kiel); a1, Kiel (F. Sirocko, unpublished, 1988); a2, Heidelberg [Scholten, 1987]; a3, Kiel [Zahn-Knoll, 1986]; a4, Kiel (E. Vogelsang and H. Kassens, unpublished, 1987); a5, Kiel (R. Zahn-Knoll, unpublished, 1986; Ramm, [1986]); a6, Kiel/Oregon [Thiede et al., 1982]; a7, Kiel [Hartmann et al., 1976]; a8, Kiel (R. Tiedemann, unpublished, 1988); a9, Kiel [Müller et al., 1983]; a10, Kiel/Heidelberg [Müller and Mangini, 1980; Cochran, 1985]; b, this work (Gif-sur-Yvette); b1, Gif-sur-Yvette [Pichon et al., 1987]; c1, Vancouver [Pedersen et al., 1988]; c2, Brown [Peterson, 1985]; c3, Cambridge [N. J. Shackleton, various sources, to 1987]; c4, Cambridge Mass. [Boyle and Keigwin, 1985, 1987]; c5, Lamont (R. G. Fairbanks, unpublished, 1987); c6, Woods Hole [Curry and Lohmann, 1984]; c7, Wormley [Morris et al., 1984]; c8, Scripps [Vincent and Berger, 1986]; c9, [Stevenson and Cheng, 1972]; c10, Woods Hole [Keigwin, 1987]; c11, Texel [Jansen et al., 1984; and unpublished data, 1987; Olausson, 1984]; c12, Lyle et al., 1988].

The  $^{13}\text{C}$  averages exclude values obviously affected by bioturbation. Data sources listed at end of table (above). Asterisks represent data not depicted in Figure 2. The prefix A-G on core numbers refers to Figures 2a-2g.

Most oxygen and carbon isotope data provided by the Kiel group were measured according to standard procedures [Duplessy, 1978; Ganssen, 1983] on a Finnigan MAT 251 mass spectrometer combined with a new, fully automated carbonate preparation line (CARBO-KIEL; C-14 Laboratory, Christian-Albrechts-Universität, Kiel, Dr. H. Erlenkeuser, and Finnigan Bremen, Dr. K. Habfast; for details see Zahn et al. [1986]). The stable isotope data provided by the Centre des Faibles Radioactivites, Gif-sur-Yvette, were analyzed on a VG 602D micromass spectrometer. The unpublished isotope values kindly provided by Peterson [1985] were measured at a Sira 903 at Brown University, Providence, Rhode Island (compare Table 3). The oxygen isotopic stratigraphy of many sediment cores from the Indian and Pacific oceans was corroborated by additional planktonic  $\delta^{18}\text{O}$  records.

## RESULTS

### *The $\delta^{13}\text{C}$ Record of Global Shifts in the Concentration of Oceanic Bottom Water $\text{CO}_2$ During Termination I*

From about 105  $\delta^{18}\text{O}$ / $\delta^{13}\text{C}$  curves of *C. wuellerstorfi* (most of them depicted in Figure 2) two time slices were selected, which lie at 17,000-21,000 years B.P. (Last Glacial Maximum, LGM) and 0-8000 years B.P. (Holocene), and their respective  $\delta^{13}\text{C}$  values averaged. By these means we expect to exclude short-term local anomalies in the deep water  $\text{CO}_2$  concentration. The carbon isotopic difference (‰  $\Delta\delta^{13}\text{C}$ ) between the LGM and the Holocene and the source of data are presented in Table 3. The geographic distribution of

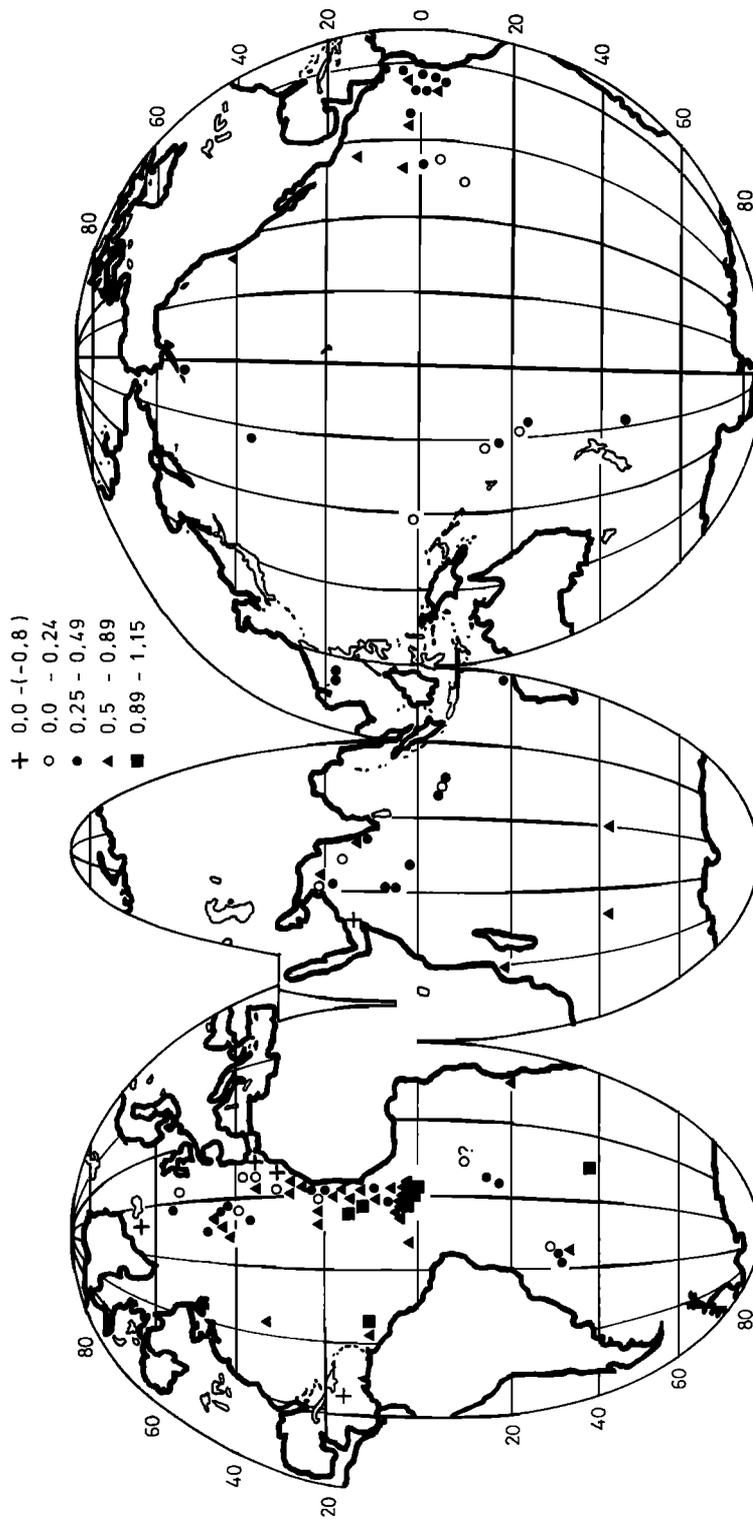


Fig. 3. Geographic distribution of  $\delta^{13}C$  differences between Last Glacial Maximum (17,000-21,000 years B.P.) and Holocene (last 8000 years). Data sources listed in Table 3. Positive values (plus signs) and negative values (minus signs) come from water depths between 1400 and 2000 m, except for Caribbean Sea datum.

the difference values is plotted in Figure 3. The deep water  $\delta^{13}\text{C}$  level has increased by about 0.15–0.9‰ on a global scale during glacial Termination I. This difference only applies to the depth range of NADW and deeper because most sediment cores under investigation were obtained from water depths of 2000–4000 m. A regional close-up reveals some fairly systematic variations in the  $\Delta \delta^{13}\text{C}$  distribution pattern. In large parts of the Pacific and northern Indian oceans the difference values lie between (0.15–) 0.2 and 0.5‰. This range may provide an idea of the changes in the carbon budget in the deep sea on a global scale as discussed below. On the other hand, most values from the Atlantic and the southern Indian oceans are somewhat higher, varying between 0.4 and 0.9‰.

Furthermore, Figure 3 (see plus signs) reveals three regions where at intermediate water depths (1000–2000 m) the  $\delta^{13}\text{C}$  values did not increase but decreased from peak glacial to Holocene times. The most important area with a  $\delta^{13}\text{C}$  reduction of –0.79‰ during Termination I lies south-east of Greenland at 60°N at 1855 m depth. Taking into account the local sharp  $\delta^{13}\text{C}$  rise within the last 8000 years from 0.25 to 0.91‰ at the sediment surface and to 1.1‰ in a neighboring GEOSECS profile, the negative LGM-to-Holocene  $\delta^{13}\text{C}$  difference is lowered to 0.5 and 0.3‰, respectively but still remains significant. The signal of  $^{13}\text{C}$  rich deep water during glacial times can be traced further down-slope to the southeast by means of unusually low positive  $\Delta \delta^{13}\text{C}$  numbers (0.14–0.35‰) through the deeper northeast Atlantic basins near Rockall Bank, up to 40°N, i.e., east of the Azores at about 3500 m water depth. Most probably, this anomaly in the northern Atlantic marks the main area of NADW formation and advection during the LGM [Duplessy et al., this issue; J. Sündermann et al., Atlantic circulation during the Last Glacial Maximum--A dynamic model, submitted to *Paleoceanography*, 1988 (hereinafter referred to as JS (1988))].

A second region where  $\delta^{13}\text{C}$  values have decreased by up to 0.3‰ from glacial to interglacial time, the area where the present (and past) Mediterranean Outflow Water (MOW) impinges upon the northwest African continental slope at 800–1700 m water depth, north of 22°N [Zahn-Knoll, 1986; Zahn et al., 1987]. This distribution pattern demonstrates that the outflow

of Mediterranean Water was less  $\text{CO}_2$  enriched during peak glacial times and had a stronger influence on the northeast Atlantic hydrography than today. It can be traced further south up to the equator by means of low carbon isotopic differences ranging near zero per mill along the depth range of 1000–1300 m [Zahn-Knoll, 1986]. A third small region with a slightly positive  $\Delta \delta^{13}\text{C}$  anomaly (–0.03‰) lies in the outer Gulf of Aden, also at intermediate water depths of about 1900 m. This  $\delta^{13}\text{C}$  decrease may be linked to an increase in local primary production and carbon flux to the seafloor since the LGM (Figure 4) as first reported by Prell and Curry [1980]. The large increases in  $\delta^{13}\text{C}$  are generally restricted to cores from the deep basins of the eastern equatorial south Atlantic, mostly below 3750 m (Figure 2). In this region the  $\delta^{13}\text{C}$  values of *C. wuellerstorfi* increased by more than +0.9–1.0‰ and below 5000 m water depth, even by 1.2‰ since the LGM. These high differences are caused by extremely low glacial  $\delta^{13}\text{C}$  values. In part, they may be the result of advection of  $^{13}\text{C}$  depleted Antarctic Bottom Water into the basins of the eastern south Atlantic [Curry and Lohmann, 1984]. Furthermore, we assume that enhanced fluxes of particulate carbon from local centers of high productivity in this equatorial region have added to this extreme glacial  $\delta^{13}\text{C}$  minimum (see below). However, in the southeastern Atlantic, bottom conditions never became completely anaerobic, as the benthic form *C. wuellerstorfi* is continuously present through this interval of the cores. This may also occur to core IOS-10529 (Table 3) where siliceous, carbonate-free sapropels indicate anoxic conditions in the southern Bay of Guinea at 4735 m water depth, between 19,000 and 14,000 years B.P. [Morris et al., 1984]. This oxygen-depleted regime in the eastern equatorial and south Atlantic basins is clearly distinguished from the general  $\text{CO}_2$  enrichment in the deep ocean during the LGM by the fact that it ended about 3000–5000 years earlier than the general  $\text{CO}_2$  depletion in the deep ocean during early Termination I (Figure 6).

Below regions with a marked glacial to interglacial productivity reduction of the surface ocean (Figure 4) the average glacial to interglacial differences in  $\delta^{13}\text{C}$  increase from about 0.2 to 0.5‰ to 0.4 to 0.8‰ in the open ocean. Such values occur below the divergence zone in the

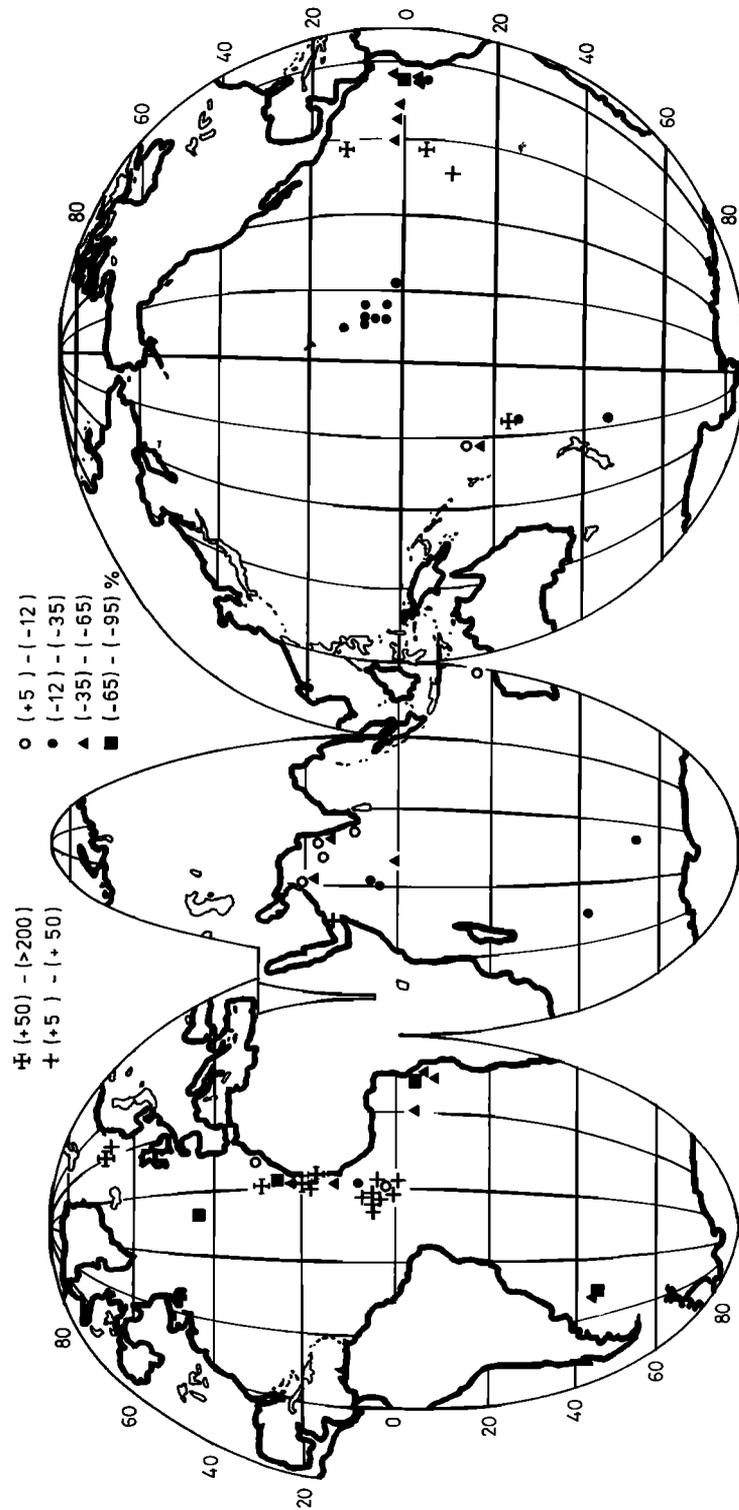


Fig. 4a. Geographic distribution of changes in new paleoproductivity from the Last Glacial Maximum (17,000-21,000 years B.P.) to the Holocene (last 8000 years). Relative changes in percent of glacial value.

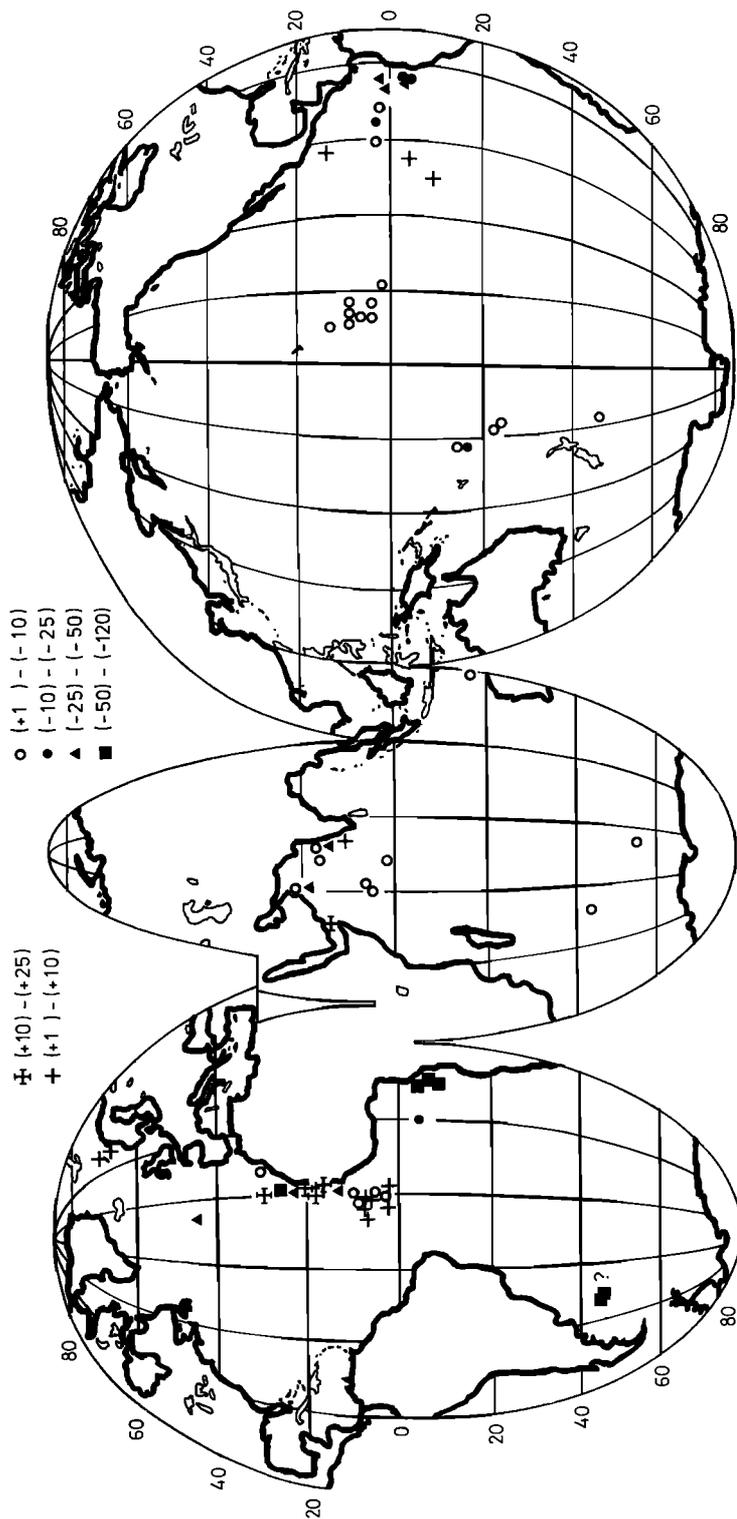


Fig. 4b. Geographic distribution of changes in new paleoproductivity from the Last Glacial Maximum (17,000-21,000 years B.P.) to the Holocene (last 8000 years). Absolute numbers (g m<sup>-2</sup> yr<sup>-1</sup>). Data sources listed in Table 3.

eastern equatorial Pacific, below the coastal upwelling region off Oregon, in the circum-Antarctic ocean, near coastal upwelling cells along the east Atlantic continental margin, and in a few cores from the Mid-Atlantic Ridge immediately north of the Azores (Table 3). These regional  $\Delta \delta^{13}\text{C}$  maxima are not linked to specific water depths or deep water masses. Hence we assume that the maxima and their underlying actual cause, the local carbon isotopic minima of *C. wuellerstorfi* during the LGM, were in part controlled by increased local fluxes and concentrations of particulate and dissolved organic carbon near the seafloor below the high-productivity zones of the ocean (compare distribution patterns of Figure 4). This influence from local carbon fluxes must be considered as additive to the one exerted by the general  $\text{CO}_2$  level of the deep water masses. A similar feature was observed by Kroopnick [1971] for modern  $\delta^{13}\text{C}$  values below the high-productivity belt of the equatorial Pacific. In this region the lowermost 40 m of the water column are marked by  $\delta^{13}\text{C}$  values, which are about 0.3‰ lower than those immediately above.

On a global scale the LGM-to-Holocene  $\delta^{13}\text{C}$  increase below 1500–2000 m water depth averages 0.4–0.5‰, if we disregard the regionally higher values associated with local high fluxes of organic carbon. This corresponds to a total release of about 580–720 Gt C from the deep ocean below 1500–2000 m to the surface ocean and the atmosphere (applying a simple calculation scheme proposed by Duplessy [1982]).

One might expect the stable isotope composition of planktonic foraminifera to record a corresponding decrease in  $\delta^{13}\text{C}$  from the LGM to the Holocene in order to compensate for the  $\delta^{13}\text{C}$  enrichment in the deep sea. However, in most cases, such a simple inverse relationship is not observed. The mechanism for paleoproductivity changes discussed below may provide an explanation for the parallel  $\delta^{13}\text{C}$  variations found in both surface and bottom water near upwelling regions [Sarnthein and Tiedemann, 1988]. Moreover, a parallel shift in planktonic and benthic  $\delta^{13}\text{C}$  records is observed for downwelling regions of the ocean where fresh, oxygenated deep water has continuously formed through glacial and interglacial times [Duplessy et al., this issue]. The only examples of a reversed  $\delta^{13}\text{C}$  shift in oceanic deep and surface waters were found in the nutrient depleted, stratified

waters of subtropical gyres such as the Sargasso Sea, where the average glacial  $\delta^{13}\text{C}$  values of planktonic foraminifera from the surface water increased by 0.2‰ [Curry and Crowley, 1987]. Therefore the  $\delta^{13}\text{C}$  trends of the surface water parallels that in the underlying intermediate water (Figure 3) [Zahn et al., 1987; Duplessy et al., this issue].

#### *Paleoproductivity Changes Since the LGM*

Figures 4a and 4b present the changes in new (export) paleoproductivity ( $P_{\text{new}}$ ) from the LGM (average of 17,000–21,000 years B.P.) to the Holocene interglacial (average of the last 8000 years). Difference values were calculated using equation (1) for about 65 deep-sea cores obtained from various key oceanographic regions in the low- and mid-latitude ocean, representing both high and low primary productivity areas. From these few regions we extrapolate to much larger parts of the ocean, for which data is lacking.

Basically, three modes of change since the LGM can be distinguished:

(1) In most regions where modern new production is high,  $P_{\text{new}}$  was even higher during the LGM. Since the LGM,  $P_{\text{new}}$  has decreased by 25–80%, which is a factor of up to 5. This reduction occurred along the eastern continental margins of the Atlantic, Pacific, and northwest Indian oceans, off India, and below the equatorial divergence zones of the eastern Pacific, eastern Atlantic, and western Indian oceans. The central equatorial Atlantic forms a slight exception to this rule in that maximum productivity was reached during early stage 2 and started to decrease prior to 20,000 years B.P. (Figure 2g; cores 13521, ENO66–29, and –36). Thus the central equatorial Atlantic data deviate from the average  $P_{\text{new}}$  numbers in Figure 4 and Table 3.

A post-glacial productivity decrease is also observed at the few sites from the southern mid-latitude Indian and Atlantic oceans along the glacial position of the Antarctic divergence zone [CLIMAP, 1981]. Likewise, we assume a synglacial divergence zone immediately north of the Azores near 45° N, which led to a local productivity high vanishing during early stage 1 (Figure 2d, core 15612).

(2) In modern low-productivity zones, glacial  $P_{\text{new}}$  varied in a non systematic way. In wide areas, such as south of

Hawaii, it decreased by 0-50%, similar to the trend found in the high-productivity zones. In many other areas, however,  $P_{new}$  increased by up to 200%. This is the case for the unfertile subtropical gyres of both the Pacific and Atlantic oceans (Table 3 and Figures 4a and 4b).

(3) Few regions show a clear reversed trend with a Holocene increase in  $P_{new}$ . For example, the increase in  $P_{new}$  paralleled the deglacial retreat of perennial sea ice in the Norwegian Sea [Kellogg, 1980] by 35-65%. Furthermore, a productivity increase during Termination I marked the areas immediately offshore from the mouths of the Indus and Senegal rivers, which then started to discharge enormous quantities of nutrients (Figures 2c and 2f, cores 12347 and MD 76-132; Sarnthein et al. [1982b], and Fontugne and Duplessy, [1986]). Finally, offshore from southern Arabia and especially from Yemen, the postglacial increase in  $P_{new}$  (Figures 2 and 4) matches the well-known mid-Holocene onset of monsoon-driven coastal upwelling [e.g., Prell and Curry, 1980; Duplessy, 1982].

In most core profiles from the northernmost Arabian Sea, however, the pattern of productivity history appears more complex. Here the distinct mid-Holocene increase in  $P_{new}$  was preceded by a short-term decrease of 30-60% near the onset of Termination IA. This productivity low lasted until about 8000 years B.P., the end of Termination IB.

In summary, our data indicate that the small but crucial high-production zones acted in phase with a massive decrease in new production in almost all parts of the low- and mid-latitude ocean during Termination I. A reversed trend is only found in parts of the low-production zones in both the subtropical gyres and the high latitudinal ocean covered by sea ice during the LGM, some narrow prodeltaic areas, and the narrowly confined coastal upwelling zone off southern Arabia. In spite of their wide areal distribution, most of these regions with a reversed trend are not quantitatively important for the global productivity budget as shown on Figure 4b and Tables 3 and 4. The absolute range of production and productivity changes in this regions is much lower or even negligible as compared to the values of the high-productivity belts. Thus we conclude that an overall decrease occurred in the amount of carbon extracted by  $P_{new}$  from the low- and mid-latitudinal sea surface

to the deep ocean at the end of the last glaciation. Hence low-latitude upwelling and its associated pulsating export productivity must be considered as a strong additional factor, if not the major agent, in changing ocean and atmospheric chemistry during Terminations I and II.

#### *Changes in $\delta^{13}C$ of Organic Matter Parallel to Changes in Ocean Productivity*

The  $\delta^{13}C$  values of organic matter were reported from a number of sediment cores from coastal upwelling zones off northwest Africa [Müller et al., 1983], India, and south Arabia [Fontugne and Duplessy, 1986] (examples in Figure 5). The values varied between -18‰ and -22‰ from Glacial to Interglacial times. With minor exceptions (e.g., core MD 76-131) the  $\delta^{13}C_{org}$  records closely parallel the local fluctuations in new productivity ( $r=0.84$ ; Figure 5d) and apparently form a little understood isotopic response. Prior to an attempt of interpreting it, we shall discuss what the records may not mean.

The  $\delta^{13}C$  range of our limited data set testifies that the organic matter and its downcore variations mainly originate from the marine plankton production and not from the terrigenous input of land plants, the mean isotopic values of which are much lighter ranging near -26‰  $\delta^{13}C$  [Cachier et al., 1986; Fontugne and Duplessy, 1981, 1986]. Furthermore, the  $\delta^{13}C_{org}$  values get heavier as the carbon concentrations in the sediment and  $P_{new}$  values increase. This is the opposite of what one would expect if the sediments were receiving an increased input of terrestrial organic matter. Also, the exceptionally heavy carbon isotope ratios of some  $C_4$  land plants such as grasses (-13‰) can be ruled out as a possible source for the heavier  $\delta^{13}C$  values in our records: typical C:N ratios for grasses range from 20 to 50, whereas those found in the organic matter from sediments below the upwelling region off northwest Africa amount to 8-9, a value characteristic of marine plankton [Suess and Müller, 1980; Müller et al., 1983].

Accordingly, the downcore variations in  $\delta^{13}C$  of organic carbon must be related to changes in marine plankton production. Varying sea surface temperatures [Sackett et al., 1965] can also be ruled out as a cause. For example, we must assume an average decrease in sea surface temperatures from 20° to 15°C during the LGM,

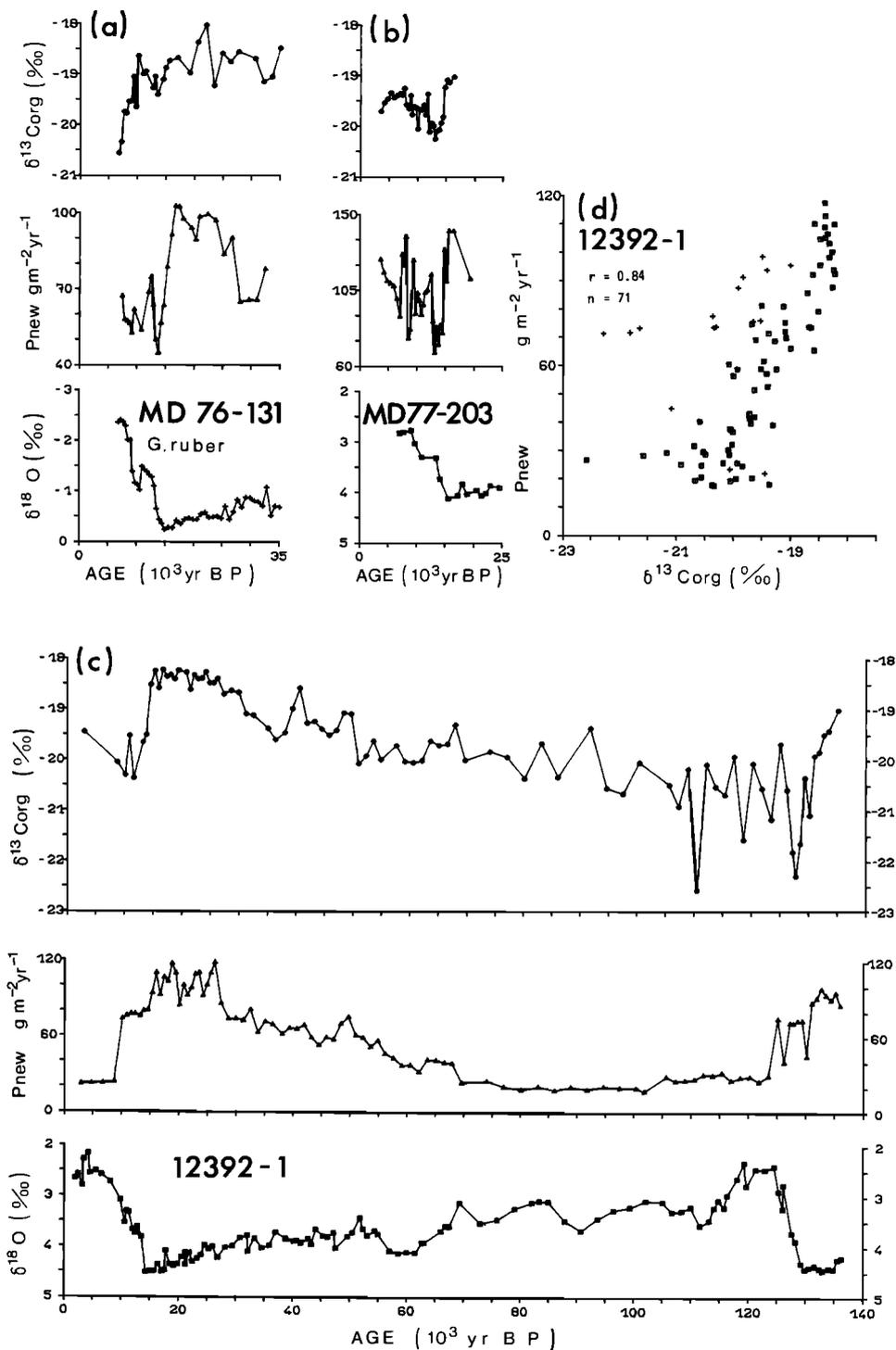


Fig. 5. (a-c) Variations in the carbon isotopic composition (per mill versus PDB) of organic matter versus new paleoproductivity and  $\delta^{18}\text{O}$  stratigraphy (*C. wuellerstorfi* unless otherwise mentioned) of sediment cores from the east Atlantic and northwest Indian Ocean ( $\delta^{13}\text{C}_{\text{Org}}$  data from Müller et al. [1983] and Fontugne and Duplessy [1986]). (d) Correlation between new productivity and  $\delta^{13}\text{C}$  values of organic matter in Meteor core 12392 (plus signs represent samples from sediment surface and stage 6 subject to diagenetic bias).

when the upwelling intensity and productivity along the east Atlantic continental margin was much enhanced [Sarnthein et al., 1982a]. According to Degens et al. [1968b] and Fontugne and Duplessy [1981], this cooling led to a lowering of the mean  $\delta^{13}\text{C}$  values of organic matter from about -20 to -22‰. However, our data just exhibit the reversed trend for the LGM, i.e., a rise from -20 to -18‰ (Figure 5, core 12392).

The only modern analogue of the enriched  $\delta^{13}\text{C}$  values that characterize the organic carbon in sediments from Glacial and Holocene upwelling maxima are data from plankton collected inside (-18.7‰) and outside (20.0‰) of the highly productive Peru upwelling region [Degens et al., 1968a; Reimers and Suess, 1983]. This parallel between high  $\delta^{13}\text{C}_{\text{org}}$  values of marine plankton and high productivity suggests a direct causal link. It might be caused by continued, extensive fractionation of light organic carbon from the  $\text{CO}_2$  reservoir near the sea surface. This process might gradually deplete the  $^{12}\text{C}$  dissolved in the surface water and result in an increased incorporation of  $^{13}\text{C}$  into the organic tissues of marine plankton. Moreover, plankton production might increasingly utilize the isotopically heavier bicarbonate [Degens et al., 1968b; Deuser, 1970]. However, recent experiments on marine phytoplankton cultures [Descolas-Gros and Fontugne, 1985] do not corroborate this model. They suggest that the  $\delta^{13}\text{C}$  composition of marine algae is independent of the isotopic equilibrium and concentration of total dissolved  $\text{CO}_2$  in ambient water. Moreover, Boyle [1986a] reports of a general excess of  $\text{CO}_2$  in the surface ocean.

On the other hand, the experiments of Descolas-Gros and Fontugne [1985] provide essential new insights that may help to unravel the puzzling  $\delta^{13}\text{C}$  response of marine plankton to productivity changes. Their findings suggest two different ways for raising the  $\delta^{13}\text{C}_{\text{org}}$  values, which may overlap. First, they clearly distinguish two phases of monospecific cell growth in the carbon isotopic composition of diatoms. The initial phase of exponential growth produced isotopically light plankton (-23 to -17‰), whereas the second, stationary growth phase of the cell culture (after 2 days) induced a massive  $\delta^{13}\text{C}_{\text{org}}$  rise up to values indicative of  $\text{C}_4$  metabolism (-9 to -13‰). Descolas-Gros and Fontugne [1985] surmised that this shift may result from deteriorating growth

conditions such as lowered light intensity. However, experiments of Degens et al. [1968b] and measurements of Wefer and Killingley [1986] on algae from the natural environment revealed just the contrary, a decreasing  $\delta^{13}\text{C}$  trend in algae along with decreasing light intensity. We propose as an alternative explanation that both the shift from exponential to stationary growth and the increase in the  $\delta^{13}\text{C}$  ratio are due to a drastic depletion of (some portions of) nutrients in the monospecific cell culture after 2 days.

Second, Descolas-Gros and Fontugne [1985] found the increased carbon isotopic ratios clearly linked to the special carbon fixation mechanism [ $\beta$  carboxylation] of dinoflagellates and Chlorophyceae. These groups show characteristically heavier carbon isotopic values (about -18‰) than diatoms (average: -22‰). Since dinoflagellates do not require silicon, they are probably less specialized and capable to cope with less favorable growth environments. After Codispoti [1983] and Codispoti et al. [1982], immense blooms of dinoflagellates, "red tides," are characteristic of the unfavorable chemical conditions of the El Niño phases in the world's strongest coastal upwelling zones such as that off Peru. These unusual conditions comprise: (1) a complete denitrification of the surface water as opposed to subsurface maxima of ammonia, phosphorus, and silicon, i.e., not a general nutrient depletion (except for the thin surface layer) but an unusually low N:P (Redfield) ratio; (2) extreme oxygen deficiency in the subsurface layer associated with  $\text{H}_2\text{S}$  production; and (3) occasional upwelling of  $\text{H}_2\text{S}$  to the warmer surface layer, a process that is poisoning most other organism groups. Hence by means of the dinoflagellates we recognize, once again, a specific deficit in the nutrient budget (in combination with  $\text{H}_2\text{S}$  production) as the prime factor for anomalies in  $^{13}\text{C}$  enrichment of organic matter.

Both lines of evidence, especially that of the dinoflagellates, lead to an apparent paradox: maxima in the  $\delta^{13}\text{C}$  composition of organic matter attest both long-term phases of enhanced new productivity and short-term phases of nutrient (nitrate) depletion in upwelling cells. This discrepancy may be resolved by considering the mechanism proposed by Codispoti [1983]: when (glacial) upwelling systems become "too efficient" and act as nutrient traps, reactive phosphorus and dissolved silicon may continue to increase. How-

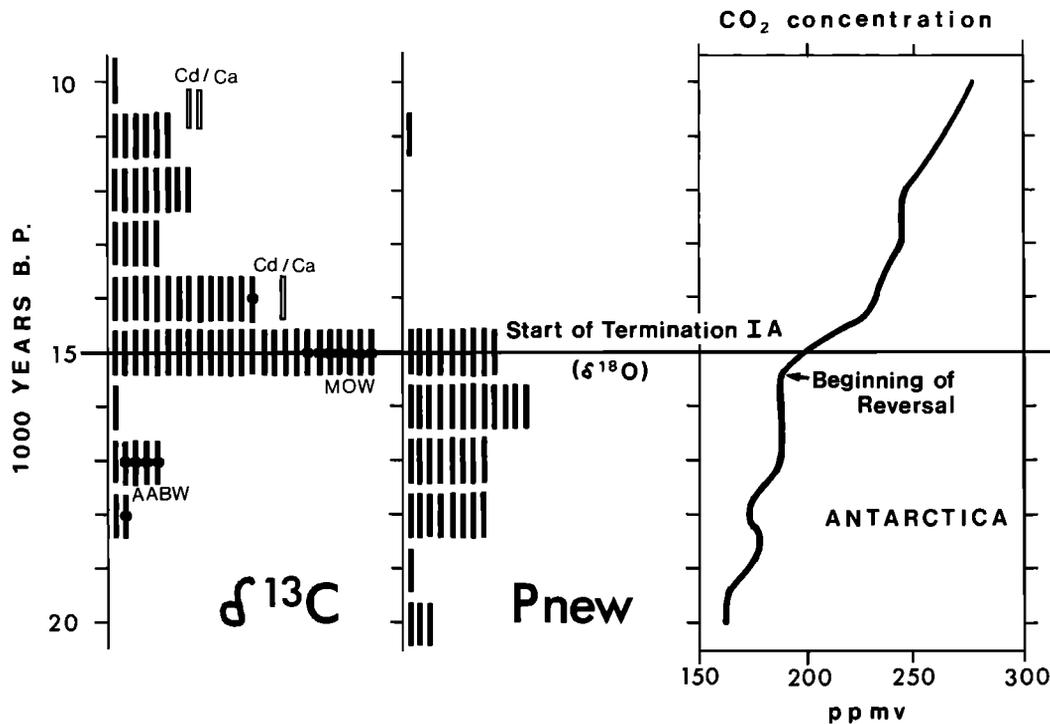


Fig. 6. Lead/lag relationships of onset ages of reversals in paleoproductivity and  $\delta^{13}\text{C}$  curves versus those in  $\delta^{18}\text{O}$  curves (Figure 2) during the onset of glacial Termination I, plotted as frequency histograms for 1000-year intervals. Age of 15,000 years B.P. for start of Termination IA in  $\delta^{18}\text{O}$  curves is best estimate out of numerous radiocarbon datings. Onset ages of reversals in Cd/Ca records (marked in the figure) from Boyle and Keigwin [1985]. Data from Mediterranean Outflow Water (MOW) and Antarctic Bottom Water (AABW) in central Atlantic are marked. Variations in atmospheric  $\text{pCO}_2$  from Antarctic ice cores from De Angelis et al. [1984].

ever, nitrate concentrations decrease as a consequence of ongoing denitrification, largely as a result of reduced or inadequate subsurface horizontal advection.

In summary, from both the red tide mechanism in upwelling cells and the  $^{13}\text{C}$  enrichment during stationary phases of algal growth we may infer that heavier  $\delta^{13}\text{C}_{\text{org}}$  values record El Niño related denitrification events and that phases of very high [coastal] upwelling productivity always imply strong El Niño cycles. More detailed studies are required for a better understanding of the complicated processes involved.

## DISCUSSION

### *Phase Relationships During Termination I*

Figure 6 compares the age of the beginning of reversals found for different paleoceanographic and paleoclimatic curves

after the LGM. The figure compares the reversals in benthic  $\delta^{13}\text{C}$  records of dissolved  $\text{CO}_2$  in the deep sea and in the records of (new) paleoproductivity with the onset age of glacial Termination IA as documented by the turning points in  $\delta^{18}\text{O}$  curves at 15,000 years B.P. (Figure 2) and with the ice core record of increasing  $\text{CO}_2$  concentrations in the atmosphere [De Angelis et al., 1984].

Problems of stratigraphic correlation were largely avoided by using only intra-core correlations. Moreover, those between the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  curves rely on data being obtained from the same specimens of *C. wuellerstorfi*. Of course, the results from this single-case phase study cannot be generalized for the phase relationships of other Quaternary climatic cycles. However, the data may well illustrate the succession of processes on a global scale during the last major climatic reversal and by these means, also display some

specific cause and effect relationships with obvious ramifications for the dramatic change in the oceanic and atmospheric CO<sub>2</sub> budgets.

Within the limits of the time control, the CO<sub>2</sub> concentrations measured in polar ice cores began to increase at about 16,000 to 15,000 years B.P. [De Angelis et al. 1984; Lorius et al., 1984; Oeschger et al., 1984; Barnola et al., 1987]. This is synchronous with or slightly prior to the  $\delta^{18}\text{O}$  shift observed in the same ice cores. On the other hand, in most cases, the  $\delta^{13}\text{C}$  records indicate that the beginning of CO<sub>2</sub> depletion in the deep sea lags behind the onset of the respective  $\delta^{18}\text{O}$  shift by about 1000-4000 years (Figure 6).

Only a small number of cores show a synchronicity in the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  signals, with many of them associated with MOW (i.e., they document a local event). Most of the remaining cores with a synchronous carbon and oxygen isotope signal are from areas with low deposition rates and/or with low concentrations of *C. wuellerstorfi* during the LGM. These factors result in strong homogenization through bioturbation or a downcore shift of the benthic  $\delta^{13}\text{C}$  signal and thus can readily explain reductions in the phase shift between the two isotopic records.

In general, the lags in the  $\delta^{13}\text{C}$  shift versus that in  $\delta^{18}\text{O}$  do not vary through the different parts of the ocean, except for a striking lead in the  $\delta^{13}\text{C}$  signal by about 2000 years in cores from the deep, restricted basins of the equatorial and southern east Atlantic (Figure 6). Their unusually high delta  $\delta^{13}\text{C}$  values exceed 0.9‰ (Figure 3) and are ascribed to an inflow of particularly <sup>13</sup>C depleted deep Antarctic Bottom Water (AABW). Accordingly, this regional lead may indicate either a very early onset of change in the chemistry of the deepest portion of Antarctic Bottom Water advected to these basins or a very early decrease in productivity in the equatorial Atlantic.

The prevailing lag of  $\delta^{13}\text{C}$  records versus the ice core record of atmospheric pCO<sub>2</sub> matches the one of the Cd/Ca signal (Figure 6), which serves as an independent record of a delayed decrease in dissolved phosphate of the deep ocean [Boyle and Keigwin, 1985]. This sequence of events contradicts the widely accepted model that changes in atmospheric pCO<sub>2</sub> are mainly controlled and/or triggered by variations in deep ocean circulation.

The phase relationship between paleo-productivity and  $\delta^{18}\text{O}$  is exactly the

inverse of that between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ . Thus the start of the low- and mid-latitude productivity reduction compares well with the timing of the ice core record of atmospheric pCO<sub>2</sub> change during Termination IA. Both processes continue for the subsequent 5000-7000 years. The onset of the decrease in productivity after the LGM leads the onset of Termination I by up to 5000 years. This phase relationship has important implications for the "shelf effect" model, which contends that the decrease in lateral down-slope discharge of organic material to the continental rise due to sea level rise is a possible control of the carbon budget in the deep sea [Walsh et al., 1981]. This process can now be virtually excluded as the major cause for both the reduction in carbon accumulation rates and the increase in  $\delta^{13}\text{C}$  during early stage 1.

Virtually no case of a productivity phase lead exceeding 3000 years is substantiated in our data. The long leads that do exist are an artifact of a low sampling density. On the other hand, most short-phase leads are associated with the better documented core sections and/or high sedimentation rates. Thus only shorter-phase leads in paleoproductivity reduction are regarded as more reliable.

Moreover, most phase leads may be strongly exaggerated because of the role of bioturbation. As soon as productivity and the flux of carbon to the seafloor decrease, the benthos will start an enhanced consumption, a "burn-down" of "fossil" carbon [Rowe, 1985]. By both this mechanism and subsequent enhanced oxidation of oxygen-depleted deposits, the carbon concentration in the sediment and the resulting paleoproductivity signal can be reduced to depths of about 6-15 cm below the paleosediment surface (i.e., below the core depth of the actual reversal in carbon supply). This depth of bioturbational mixing represents a time span of 1000-5000 years. As a result, the apparent productivity lead under discussion will probably be much reduced. In addition, the total phase lead between paleoproductivity and  $\delta^{13}\text{C}$  may shrink to a time span of 1000-3000 years.

This model on the extent and impact of bioturbational "burn-down" depth receives independent support from the  $\delta^{13}\text{C}$  records of organic matter, which are closely linked to the intensity of long-term upwelling productivity (Figure 5). In core 12392 where sedimentation rates are about 10 cm/ 1000 years, the shift in

$\delta^{13}\text{C}_{\text{Org}}$  starts at exactly the same core depth as the  $\delta^{18}\text{O}$  shift associated with Termination IA, i.e., 15 cm or 1500 years above the onset of the paleoproductivity shift (Figure 5). Thus an actual synchronicity in the onset of ice melt and the decrease of upwelling productivity appears more likely than a lead in paleoproductivity. Similar relationships are observed between the  $\delta^{13}\text{C}_{\text{Org}}$  curves and paleoproductivity shifts in other cores. Meridional trade winds probably play a crucial role as a transmission belt for the rapid teleconnection of high-latitude deglaciation and low-latitude decrease in upwelling productivity as discussed in detail by Sarnthein et al. [1987].

In summary, we can make the following observations:

During Termination IA, wind-driven upwelling productivity began to decrease across large parts of the low- and mid-latitude ocean slightly prior to or simultaneously with the onset of the global warming and ice melting. The decrease continued (in two steps) for about 5000–7000 years (Figure 2).

The process of decreasing carbon extraction from the surface ocean occurred almost simultaneously with the rapid increase in atmospheric  $\text{pCO}_2$ . Also, El Niño type events that occasionally depleted nitrate in coastal upwelling zones as suggested by  $\delta^{13}\text{C}$  records of organic matter immediately ended abruptly at this time.

The much larger and more sluggish  $\text{CO}_2$  reservoir in the deep ocean started to respond to the paleoproductivity reduction with a delay of 1000 years or more. Also, the gradual  $\text{CO}_2$  depletion of the deep water continued for about 5000 years.

#### *Implications for $\text{CO}_2$ Cycling Between Deep Ocean and Atmosphere*

As shown on Figure 3, the deep ocean below 1500–2000 m showed an average  $^{13}\text{C}$  increase of about 0.4–0.5‰  $\delta^{13}\text{C}$  during Termination I, which is equal to a loss of 580–720 Gt C during about 5000 years. This change started at least 1000 years after the simultaneous onset of the increase in atmospheric  $\text{pCO}_2$  and a 25–80% reduction in new production in most of the highly productive upwelling zones (Figures 4 and 6). Thus we infer that the transfer of particulate carbon from low- and mid-latitude upwelling zones has largely contributed to the change of the deep ocean and atmo-

spheric  $\text{pCO}_2$ , as was proposed by the Rain-Ratio model of Berger and Keir [1984] and by model calculations of Dymond and Lyle [1985] and Boyle [1986a].

In the following we quantitatively estimate the changes in the exchange of oceanic and atmospheric  $\text{CO}_2$  during Termination I based on our data and the following assumptions:

1. The deglacial reduction in calcium carbonate production, that is, the decreasing supply of alkalinity to the deep ocean linked to decreasing paleoproductivity, can be largely neglected in our calculations for two reasons: (1) The "rain ratio" between carbonate carbon and organic carbon is as low as 0.16–0.1 in the high-productivity regions and has distinctly increased with decreasing productivity and increasing temperatures [Berger and Keir, 1984; Dymond and Lyle, 1985]; and (2) an eventual minor postglacial decrease in carbonate production within the upwelling zones will be partly balanced by a synchronous productivity growth found outside, in some warm, low-latitude low-productivity regions of the ocean where the "rain ratio" is about 1 (e.g., Sierra Leone Rise; Curry and Lohmann [1984]).

2. Recent reconstructions of the paleo-deep-water circulation in the Atlantic during the LGM [Broecker, 1987; Duplessy et al., this issue; JS, 1988] show a persistent source of Antarctic Bottom Water and a continuous, but somewhat reduced formation of North Atlantic Deep Water. Thus the impact of circulation changes on the  $\text{CO}_2$  budget during the LGM is likely but smaller in magnitude than originally suggested [e.g., Broecker, 1984].

3. The estimates and distribution patterns of primary production in the modern ocean as published by Koblentz-Mishke et al. [1970] (improved version in the work of FAO [1981] and Romankevich [1984]) and by De Vooy [1977] are regarded as the best approximations available.

4. We accept that the equation of Eppley and Peterson [1979] is widely settled. This implies that the proportion of new (export) production in the total production increases exponentially from low- to high-productivity regions. On a global average, new production may amount to about one third of total production [Platt and Harrison, 1985].

5. The nutrient pool probably did not seriously limit a major glacial increase

TABLE 4a. Balance of Changes in New Productivity, Based on Estimates of Koblentz-Mishke et al. [1970]

| Oceanic Regions                                     | Area<br>10°km <sup>2</sup> / %  | Modern Primary<br>Production Rates |                                          | Modern Primary<br>Production            |                                        | % Average<br>Decrease<br>in P <sub>new</sub><br>since LGM <sup>1</sup> | P <sub>new</sub> LGM,<br>Gt C/yr    |
|-----------------------------------------------------|---------------------------------|------------------------------------|------------------------------------------|-----------------------------------------|----------------------------------------|------------------------------------------------------------------------|-------------------------------------|
|                                                     |                                 | Total,<br>g/m <sup>2</sup> yr      | New, <sup>5</sup><br>g/m <sup>2</sup> yr | Total,<br>Gt C/yr                       | New, <sup>5</sup><br>Gt C/yr           |                                                                        |                                     |
| 1. Neritic waters                                   | 11/ 3.0                         | 365.0                              | 182.5                                    | 3.9 / 17.0                              | 1.95/ 36.0                             | ?0 ?-110 <sup>2</sup>                                                  | ?1.95                               |
| 2. Coastal waters                                   | 39/ 10.6                        | 124.0                              | 38.5                                     | 4.8 / 21.0                              | 1.5 / 27.8                             | (40-80) <sup>3</sup>                                                   | 3.0                                 |
| 3a. Equatorial<br>divergence                        | 43/ 11.7                        |                                    |                                          | 3.15/ 13.7                              | 0.58/ 10.7                             | (35-50) <sup>3</sup>                                                   | 1.0                                 |
|                                                     |                                 | 73.0                               | 13.5                                     |                                         |                                        |                                                                        |                                     |
| 3b. Subpolar zones                                  | 43/ <u>11.7</u><br><u>37.0</u>  |                                    |                                          | <u>3.15/ 13.7</u><br><u>15.0 / 65.2</u> | <u>0.57/ 10.6</u><br><u>4.6 / 85.2</u> | (13-93) <sup>4</sup><br>(50)                                           | <u>0.65-1.15</u><br><u>6.6 -7.1</u> |
| 4. Transitional<br>waters                           | 83/ 22.7                        | 51.0                               | 6.5                                      | 4.2 / 18.3                              | 0.55/ 10.2                             | -(20-80)<br>-(50)                                                      | 0.37                                |
| 5. Oligotrophic<br>waters<br>(subtropical<br>gyres) | 148/ <u>40.3</u><br><u>63.0</u> | 25.6                               | 1.65                                     | <u>3.8 / 16.5</u><br><u>8.0 / 34.8</u>  | <u>0.25/ 4.6</u><br><u>0.8 / 14.8</u>  | (13-31)<br>(22)                                                        | <u>0.33</u><br><u>0.7</u>           |
|                                                     | 100.0                           |                                    |                                          | <u>23.0 /100.0</u>                      | <u>5.4 /100.0</u>                      | (33-37)                                                                | <u>7.3 -7.8</u>                     |

<sup>1</sup> Compare Table 1 and Figure 3

<sup>2</sup> Few values available. In subtropical regions, possibly reduced during LGM due to reduced chemical weathering. In Mediterranean latitudes, possibly increased, i.e., in total, no change.

<sup>3</sup> Key regions of change well documented.

<sup>4</sup> Few values available. LGM to Holocene decrease at 45°N: >90%; at 45-55°S: 13.5-68%. Lower estimate is more probable because of lower production in polar latitudes during LGM.

<sup>5</sup> Applying equation (2) of Eppley and Peterson [1979] to average values of P<sub>total</sub>.

in upwelling productivity in middle and low latitudes. Sufficient nutrients are supplied by intermediate water currents. They spread below the thermocline at 100-1000 m depth from the convergence zones in southern high latitudes far into the northern hemisphere. During glacial times, they provided an efficient mechanism to redistribute additional nutrients from (mostly southern) high latitudes that were sea ice covered and free of production. For example, the South Atlantic Central Water has fed east Atlantic upwelling up to 26°N [Fraga, 1974; Labracherie, 1980; Tomczak, 1984]. Likewise, intermediate water currents play an important role in east Pacific and Indian ocean upwelling [Codispoti, 1981]. Hence the (wind-driven) turnover rates of the surface ocean and its nutrient content are regarded as largely decoupled from the long-term, slow upward nutrient flux in the deep ocean, which is driven by vertical eddy diffusiv-

ity and general horizontal deep water ventilation.

According to the estimates of Koblentz-Mishke et al. [1970] and Romankevich [1984], the total modern primary production of organic carbon in the ocean amounts to 23 Gt carbon/year (Table 4a). About two thirds of this sum are derived from one third of the ocean. This uneven distribution is far more pronounced in the budget of new production (in total 5.4 Gt carbon/year). It extracts less than 5% of the total organic carbon from oligotrophic waters constituting 40% of the sea surface but about 85% from narrow high-productivity belts along the equator, the subpolar divergence zones, and along the continental margins (regions 1-3 on Table 4a). In comparison, Jahnke and Jackson [1987] claim that as much as 50% of all the benthic oxygen consumption is concentrated in regions within 500 km distance from continental margins.

Table 4b. Balance of Changes in New Productivity, Based on Estimates of De Vooy's [1977]

| Oceanic Regions                                     | Area<br>10 <sup>6</sup> km <sup>2</sup> / % |                                          | Modern Primary<br>Production Rates |                                         | Modern Primary<br>Production           |                              | % Average<br>Decrease<br>in P <sub>new</sub><br>since LGM <sup>1</sup> | P <sub>new</sub> LGM,<br>Gt C/yr |
|-----------------------------------------------------|---------------------------------------------|------------------------------------------|------------------------------------|-----------------------------------------|----------------------------------------|------------------------------|------------------------------------------------------------------------|----------------------------------|
|                                                     | Total,<br>g/m <sup>2</sup> yr               | New, <sup>5</sup><br>g/m <sup>2</sup> yr | Total,<br>Gt C/yr                  | New, <sup>5</sup><br>Gt C/yr            | %                                      | %                            |                                                                        |                                  |
| 1. Neritic waters                                   | 11/ 3.0                                     | 527.0                                    | 264.0                              | 5.6 / 17.0                              | 2.8 / 28.3                             | 20 ?-110 <sup>2</sup>        | 2.8                                                                    |                                  |
| 2. Coastal waters                                   | 39/ 10.6                                    | 179.0                                    | 80.1                               | 6.9 / 21.0                              | 3.1 / 31.3                             | (40-80) <sup>3</sup>         | 6.2                                                                    |                                  |
| 3a. Equatorial<br>divergence                        | 43/ 11.7                                    |                                          |                                    | 4.55/ 13.7                              | 1.2 / 12.1                             | (35-50) <sup>3</sup>         | 2.1                                                                    |                                  |
|                                                     |                                             | 105.4                                    | 27.8                               |                                         |                                        |                              |                                                                        |                                  |
| 3b. Subpolar zones                                  | 43/ <u>11.7</u><br><u>37.0</u>              |                                          |                                    | <u>4.55/ 13.7</u><br><u>30.7 / 65.2</u> | <u>1.2 / 12.1</u><br><u>8.3 / 83.8</u> | (13-93) <sup>4</sup><br>(50) | <u>1.37-2.4</u><br><u>12.5-13.5</u>                                    |                                  |
| 4. Transitional<br>waters                           | 83/ 22.7                                    | 73.7                                     | 13.6                               | 6.05/ 18.3                              | 1.1 / 11.2                             | -(20-80)<br>-(50)            | 0.55                                                                   |                                  |
| 5. Oligotrophic<br>waters<br>(subtropical<br>gyres) | 148/ <u>40.3</u><br><u>63.0</u>             | 37.0                                     | 3.4                                | <u>5.5 / 16.5</u><br><u>11.55/ 34.8</u> | <u>0.5 / 5.1</u><br><u>1.6 / 16.2</u>  | (13-31)<br>(22)              | <u>0.6</u><br><u>1.35</u>                                              |                                  |
|                                                     | 100.0                                       |                                          |                                    | <u>33.2 / 100.0</u>                     | <u>9.9 / 100.0</u>                     | (40-50)                      | <u>13.8-14.9</u>                                                       |                                  |

<sup>1</sup> Compare Table 3 and Figure 5

<sup>2</sup> Few values available. In subtropical regions possibly reduced during LGM due to reduced chemical weathering. In Mediterranean latitudes possibly increased, i.e., in total, no change.

<sup>3</sup> Key regions of change well documented.

<sup>4</sup> Few values available. LGM to Holocene decrease at 45°N: >90%; at 45-55°S: 13.5-68%. Lower estimate is more probable because of lower production in polar latitudes during LGM.

<sup>5</sup> Applying equation (2) of Eppley and Peterson [1979] to average values of P<sub>total</sub>.

The same narrow regions are also expected to be crucial for any budget changes during the past. Global productivity estimates of De Vooy's [1977], which claim for an upward correction of the values of Koblenz-Mishke et al. [1970] by at least 44%, reveal the same uneven regional distribution pattern but raise the global sum of new production by about 85% to 9.9 Gt carbon/year (Table 4b).

Based on the estimates of Koblenz-Mishke et al. [1970] and a conservative evaluation of our data, P<sub>new</sub> reached a global sum of 7.3-7.8 Gt carbon/year during the LGM, which means 1.9-2.4 Gt carbon/year more than today (Table 4a). Based on De Vooy's [1977], P<sub>new</sub> amounted to 13.8-14.85 Gt carbon/year during the LGM, i.e., 3.9-5.0 Gt carbon or 40-50% more than today (Table 4b). This increase in productivity occurred primarily in upwelling regions with frequent events of plankton blooms (Table 2), and we surmise that it was largely wind-driven [Sarnthein

et al., 1987]. If persistent over prolonged periods, the difference in P<sub>new</sub> might readily account for the observed glacial-to-interglacial loss of about 650 Gt carbon from the deep to the surface ocean and atmosphere within a time span of less than 300 or 150 years, respectively. In reality the response of the deep ocean was delayed by more than 1000 years. From these data it is not surprising that new ice core data [Barnola et al., 1987] exhibit an increase in the atmospheric CO<sub>2</sub> content by about 150 Gt carbon in less than 1000 years.

Changes in sea surface temperature paralleling the variations in upwelling productivity will further enhance the effect of P<sub>new</sub> changes on pCO<sub>2</sub> [Newell et al., 1978; Flohn, 1982]. Glacial phases of strong upwelling produced a local lowering of sea surface temperatures by up to 4°-8°C [CLIMAP, 1981], which in turn reduced the physical degassing of excess CO<sub>2</sub> at the sea surface. This effect may counter-

act that of enhanced glacial turnover rates of upwelling water masses, a process which several models suggest as a crucial constraint for the CO<sub>2</sub> exchange in low latitudes [e.g., Toggweiler and Sarmiento, 1985; W. S. Broecker, personal communication, 1987].

## CONCLUSIONS

1. Based on  $\delta^{13}\text{C}$  estimates of the benthic foraminifera species *C. wuellerstorfi*, the average  $\delta^{13}\text{C}$  values in the deep ocean below 1500 (to 2000) m increased by 0.4–0.5‰ from the last LGM (17,000–21,000 years B.P.) to the Holocene (last 8,000 years). This rise equates to a release of about 580–720 Gt carbon from the deep to the surface ocean and to the atmosphere.

2. The  $\delta^{13}\text{C}$  values of intermediate waters in the north Atlantic decreased by up to 0.2–0.5‰ from glacial to interglacial times. Off southern Greenland at about 1850 m depth and deeper, enriched  $\delta^{13}\text{C}$  values reveal the formation of oxygen-rich NADW during the LGM [Duplessy et al., this issue]. At 1000–1600 m water depth in mid and low latitudes they indicate an increased synglacial supply of both North Atlantic Intermediate Water and well-oxygenated Mediterranean Water [Zahn et al., 1987].

3. Glacial to interglacial  $\delta^{13}\text{C}$  differences increased by 0.2–0.5‰ to values of 0.5–0.9‰ in regions where the productivity of the LGM surface ocean was strongly enhanced. We relate this additional  $^{13}\text{C}$  depletion during the last LGM to local high concentrations of isotopically light organic carbon near the seafloor. More extreme  $\delta^{13}\text{C}$  differences of 0.9–>1.2‰ occur in the deep basins of the southeastern Atlantic and record a synglacial advection of  $^{12}\text{C}$  enriched AABW below 4000–4500 m water depth.

4. Based on carbon accumulation rates derived from a global set of 65 deep-sea cores, the rates of global new (export) ocean production ( $P_{\text{new}}$ ) declined by more than 2–4 Gt carbon/year during the last glacial Termination. To a large extent, this decrease was linked to diminished carbon export from pulsating plankton blooms and resulted from a strong reduction in oceanic upwelling in middle and low latitudes.

5. At the onset of deglaciation the rise in atmospheric pCO<sub>2</sub> as recorded in ice cores and the decrease in paleoproductivity started about simultaneously with a

decrease in the strength of meridional surface (trade) winds [Sarnthein et al., 1987] and slightly prior to the  $\delta^{18}\text{O}$  record of glacial melting. On the other hand, benthic  $\delta^{13}\text{C}$  curves show that the onset of large-scale CO<sub>2</sub> emission from the deep ocean was delayed by 1000 years and more.

6. It is likely that fluctuations of mid- and low-latitude  $P_{\text{new}}$  have largely controlled the changes in ocean and atmospheric chemistry, whereas the deep ocean chemistry slowly responded to the differential fluxes of particulate organic matter. Variations in  $P_{\text{new}}$  are likely to form a highly sensitive response to the external forcing of the Earth's orbital parameters because  $P_{\text{new}}$  changes are driven by meridional surface winds, which in turn are linked to the extent of high-latitude sea ice and insolation. If persistent over prolonged periods, changes in paleoproductivity in theory could drive the glacial-to-interglacial changes in atmospheric pCO<sub>2</sub> within 150–300 years. This model is in harmony with those originally proposed by Newell et al. [1978] and Flohn [1982].

7. The glacial maximum of  $P_{\text{new}}$  in upwelling zones is highly correlated to an increase in the  $\delta^{13}\text{C}$  ratio of organic matter by up to 2‰. This increase may be due to immense dinoflagellate plankton blooms associated with El Niño type events of local denitrification. In the modern east Pacific [Codispoti, 1983] they may result from an extreme utilization of the ambient nutrient reservoirs in glacial coastal upwelling cells, which became "too efficient" and acted as nutrient traps.

*Acknowledgements.* The authors are most appreciative of the valuable and critical comments from a number of colleagues, in particular, M. Arthur, M. Leinen, W. S. Broecker, and T. Takahashi, when the first author (M.S.) spent a sabbatical leave at the University of Rhode Island, Narragansett, and the Lamont-Doherty Geological Observatory, New York, with the support of funds from the Deutsche Forschungsgemeinschaft, Bonn. We thank an anonymous careful reviewer and John Schumacher for their numerous valuable improvements on the manuscript. N. J. Shackleton, Cambridge, United Kingdom, L. Peterson (Miami, formerly of Brown University), J. H. F. Jansen (Texel), R. Zahn-Knoll (Oregon State University, Corvallis, formerly Kiel), M. Hartmann, H. Kassens, F.

Sirocko, and E. Vogelsang (Christian-Albrechts-Universität, Kiel) kindly provided unpublished  $\delta^{13}\text{C}$  and sediment data from the Indian and the eastern and northern Atlantic oceans, T. Pedersen (Vancouver) supplied core samples and carbon data from the eastern equatorial Pacific. U. Pflaumann (Kiel) assisted with the supply of valuable computer software. Both the Bundesanstalt für Geowissenschaften und Rohstoffe and the PREUSSAG, Hannover, permitted extensive sampling of their sediment cores from the Pacific ocean. This work was generously supported by findings from the National Climate Project of the German Federal Ministry for Research and Technology (BMFT), grant KF 2004/1 and by the French Centre Nationale de la Recherche Scientifique - Commissariat de l'Énergie Atomique (CNRS-CEA), Groupement de Recherche Coordonnés Carbon Dioxide (Programme Interdisciplinaire de Recherche sur Environnement) (GRECO  $\text{CO}_2$  (PIREN)), and Terre Austral et Antarctique Française (TAAF). This paper is in honor of E. Seibold on the occasion of his 70th birthday.

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(Received December 6, 1987;  
revised April 7, 1988;  
accepted April 13, 1988.)