10. STABLE ISOTOPES

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INTERPRETATION OF $^{18}O/^{16}O$ DATA

The $^{18}O/^{16}O$ ratio using foraminifers in marine carbonates depends on the isotopic ratio of ambient sea water and the temperature. This is apparent from the equation

$$T = 16.5 - 4.3\,(\delta_c - \delta_w) + 0.14\,(\delta_c - \delta_w)^2$$

where T is the temperature, δ_c the isotopic ratio of the sample (calcite), and δ_w the isotopic ratio of the water in which the fossil (calcite) was formed (Emiliani 1955). The δ_w normally varies between +1 (high pressure areas)

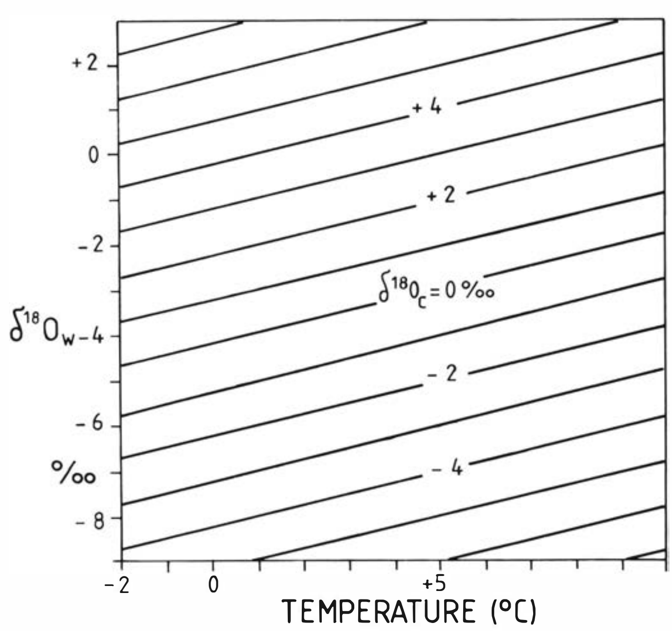

Fig. 10:1. A. Graphic relation between temperature and the $^{18}O/^{16}O$ ratio according to Emiliani (1955). δ_c is the isotopic ratio of the sample (calcite), and δ_w the isotopic ratio of the water in which the fossil was formed.

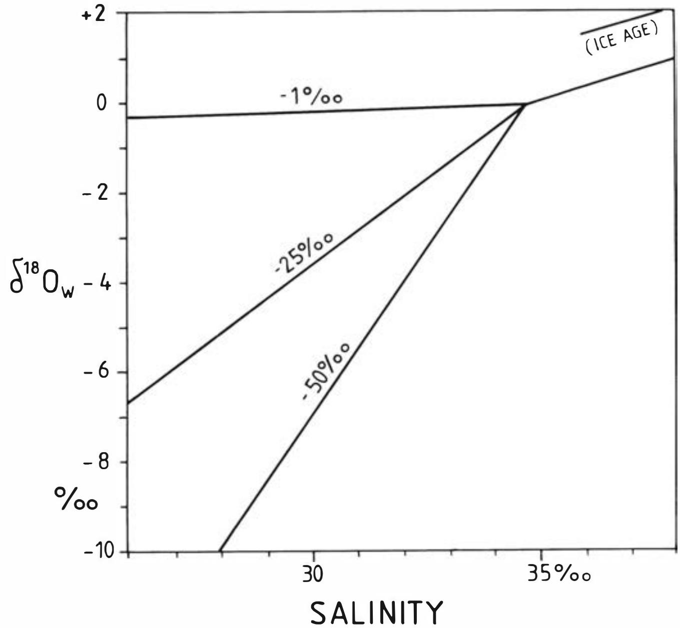

Fig. 10:1. B. The relation between salinity and the δ18 of sea water mixed with equatorial rain water (δ18 = –1 per mil), with meltwater such as that from the Scandinavian ice sheet (–25 per mil) and with very light meltwater (e.g. meltwater from central Antarctic).

and –1 per mil (where precipitation exceeds evaporation) but decreases below –1 where river supply and, particularly, meltwater contributions are appreciable. The δ18 of ice sheets is very low (–30 to –55 per mil) and meltwater injection thus exerts a strong influence on the δ_c of foraminifers. Due to the waxing and vaning of ice sheets and their gradual δ_{ice} changes, the δ_c generally has a peak-to-valley amplitude of about 1.5 per mil (see further Olausson 1981). A temperature increase also gives more negative δ_c values, as does a meltwater addition.

In the above equation $\delta 18_w$ is necessary in order to calculate T (temperature). By knowing the $\delta 18_w$ the salinity of ancient water can be estimated. In this context the $\delta 18_w$ derives from sea water mixed with meltwater from the disintegrating Scandinavian ice sheet. Below this ice sheet calcium carbonate was precipitated on rocks (see e.g. Samuelsson 1964). This carbonate could give us an approximate δ18 value of the meltwater. Therefore, a few such samples have been analyzed. The samples were kindly placed at my disposal by Sven-Åke Larsson, Geological Survey of Sweden. The following results (in per mil and relative to PDB) were obtained:

	$\delta^{13}O_c$	$\delta^{18}O_c$
Västra Frölunda (11°55′E; 57°40′N)	–3.7	–18.8
–"–	–4.4	–19.1
Torslanda (11°46′E; 57°43′N)	–4.3	–17.3
–"–	–4.0	–19.1
Hovenäset (11°17′E; 58°22′N)	–3.9	–21.6
–"–	–3.8	–21.4
Sotenkanalen (11°16′E; 58°22′N)	–3.5	–18.8

These data indicate that in central Bohuslän, the δ18 of the water below the ice was about –25 per mil, and about –23 per mil in the Göteborg area. The δ18 values of the carbonate support the theory that it was precipitated below an ice sheet, and the δ13 values suggest that the water was primarily non-marine. Consequently, $\delta18_w = -25$ can be used as a (minimum) value for the meltwater injections in western Sweden, which is discussed further below. The conversion from δ_w to salinity appears in Fig. 10:1.

MELTWATER SPIKES

The additional ice stored in the ice sheets during the Weichselian was of the order of $50 \cdot 10^6 km^3$. During deglaciation this water was returned either more or less gradually during the warm temperate phases or more abruptly when large ice lakes were drained. This meltwater spread on top of the sea water, retarding the mixing processes of the ocean so that a salinity stratification and, in some instances (e.g. in the Eastern Mediterranean), even a stagnation developed (Olausson 1961, 1965, 1969 and in press, Worthington 1968, Berger *et al.* 1977). These meltwater discharges are responsible for the δ18 signals named meltwater spikes. The light sea-surface layer also gave rise to a lower δ_w in precipitation, as suggested by the decline of δ_c in Swiss lakes during the Alleröd (see Eicher *et al.* 1981, Fig. 2) The large isochronous drop in δ_{ice} from –35 to –40 per mil in the Camp Century core could also be a result of the same event if Fisher's time-scale (1979) is used.

One of the largest ice-margin lakes was the Baltic Ice Lake, 1 500 km in length, which adjoined the south-eastern margin of the Scandinavian ice sheet. When this ice sheet receded from Fennoscandian terminal moraines the lake surface was lowered 26–28 m and some $10^4 km^3$ of meltwater was suddenly discharged into the Skagerrak. The drainage presumably occurred 10 163 years B.P. (Donner and Eronen 1981). During the Preboreal meltwater from the disintegrating Scandinavian ice sheet ($\sim 5 \cdot 10^5 km^3$) was also discharged into the Skagerrak. This volume is equal to a 1.5 m thick layer over the oceans, or a 12 m thick "lid" on the North Atlantic.

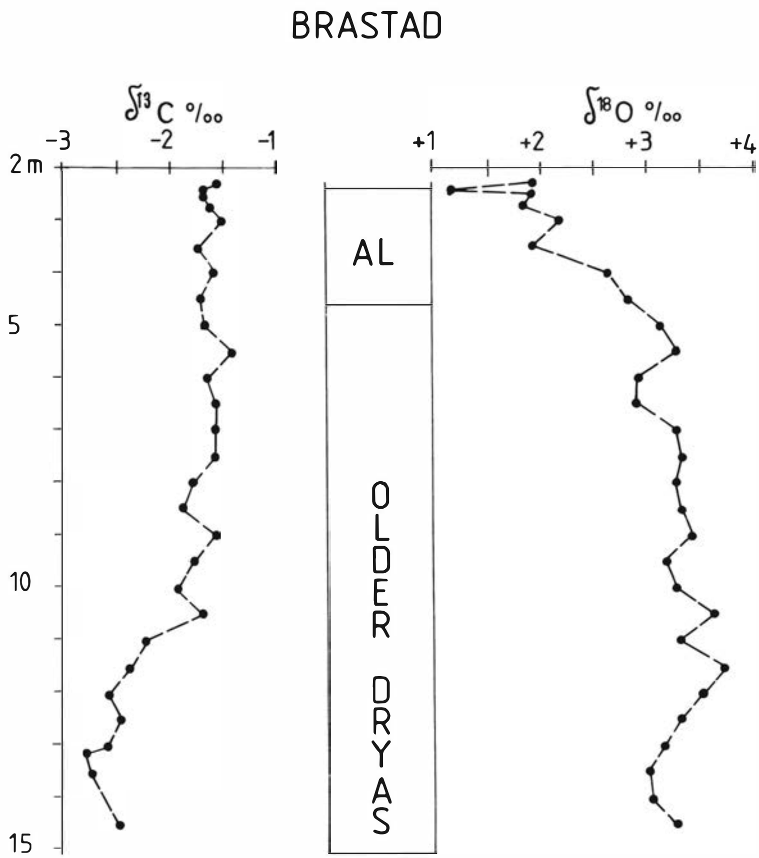

Fig. 10:2. Carbon and oxygen records relative to PDB in the Brastad core (58°23.4′N; 11°31.2′E). AL = Alleröd chronozone.

ISOTOPE ANALYSIS

Isotope analysis was performed on the benthic Foraminifera *Elphidium excavatum* from four sediment cores (Figs. 10:2–5). This Foraminifera is an indicator of the bottom-water conditions. No plankton organisms in sufficient number were available to give information regarding the surface-water conditions. The microscopical preparation was carried out by Karen Luise Knudsen (the Brastad, Moltemyr and Solberga cores) and L-M Fält (the Tuve core), the chemical treatment by Rosa Svensson, and the mass-spectrometer work by Owe Gustafsson. All data are given relative to PDB.

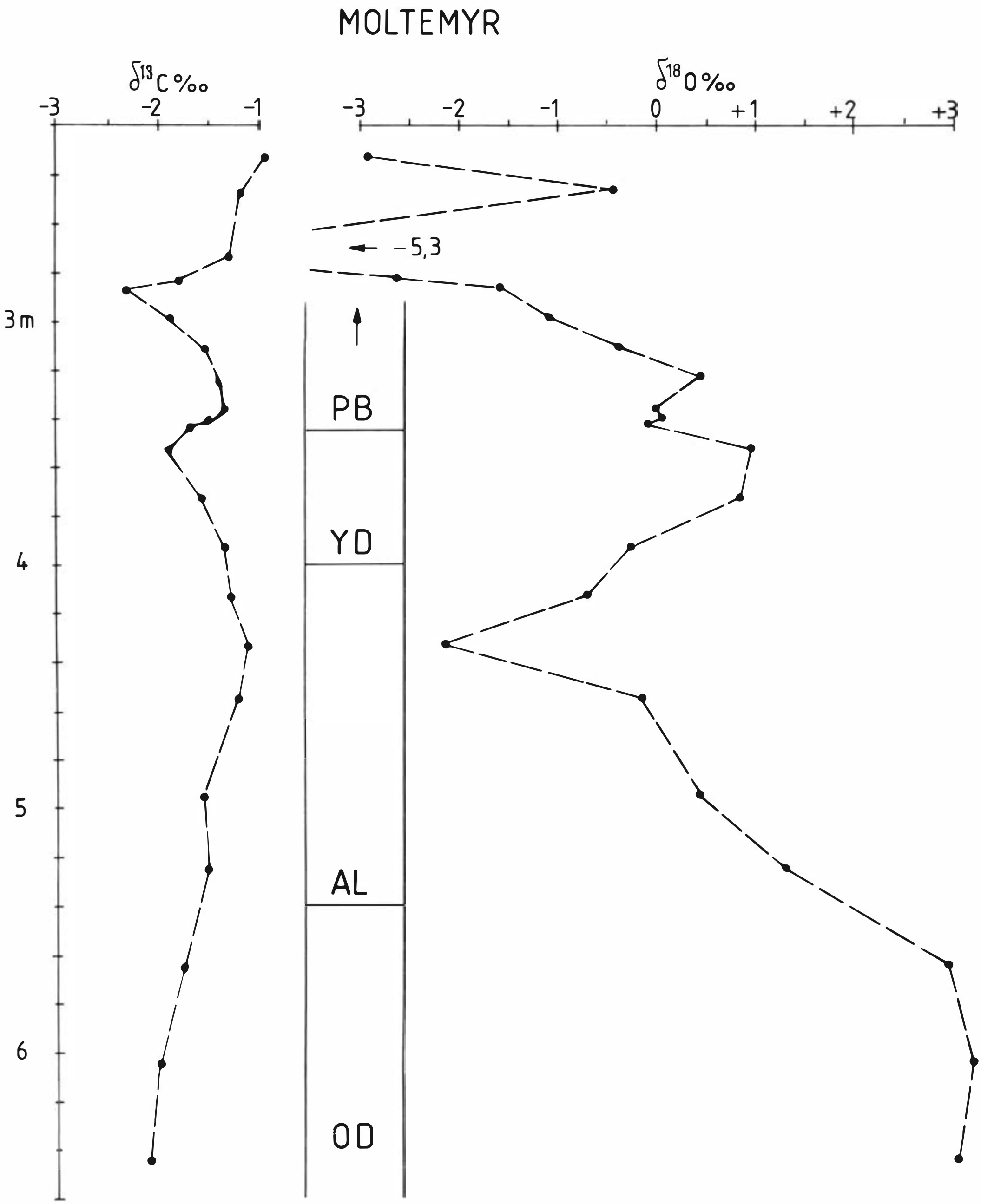

Fig. 10:3. Carbon and oxygen records relative to PDB in the Moltemyr core (58°26.5′N: 11°32.4′E). OD = Older Dryas, AL = Alleröd, YD = Younger Dryas, and PB = Preboreal.

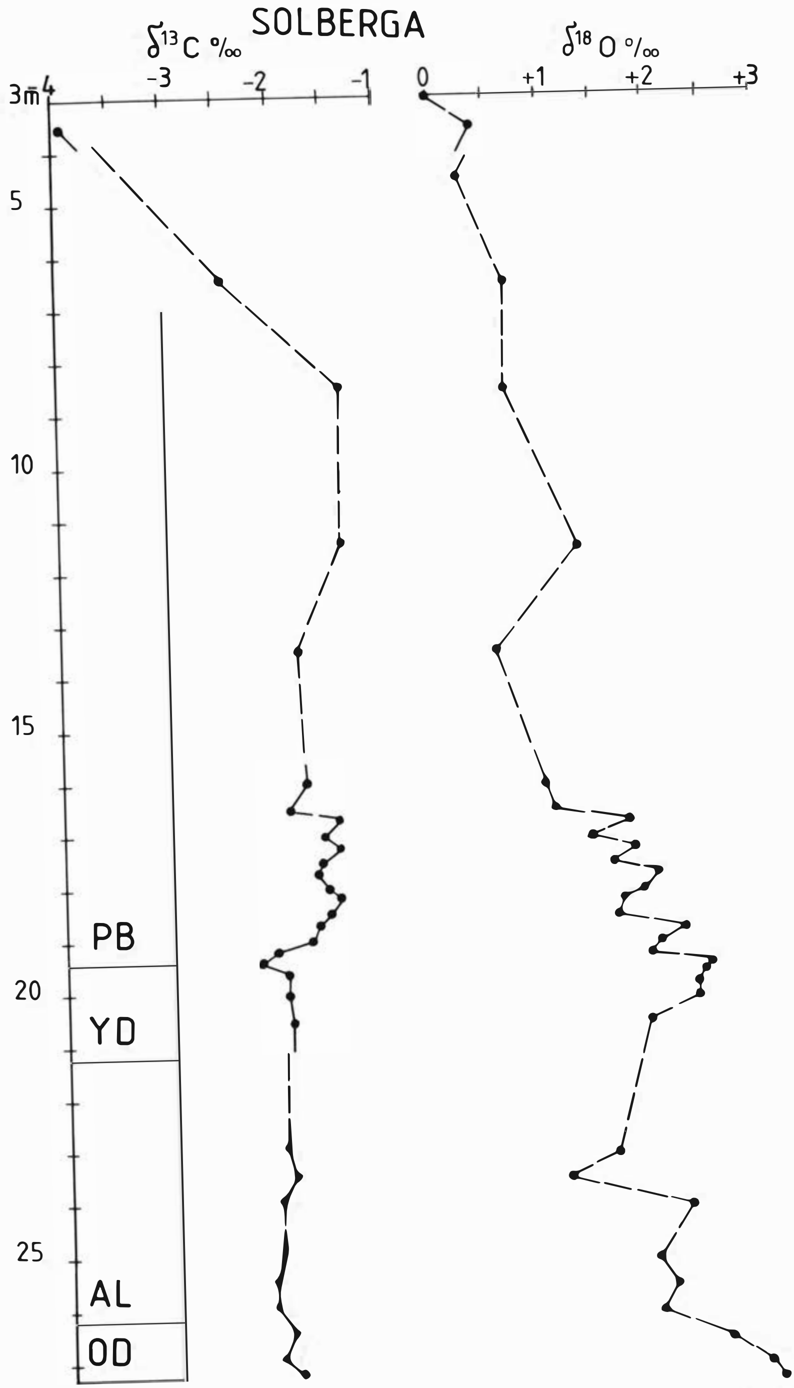

Fig. 10:4. Carbon and oxygen records relative to PDB in the Solberga core (57°57′N; 11°47.4′E). OD = Older Dryas, AL = Alleröd, YD = Younger Dryas, and PB = Preboreal.

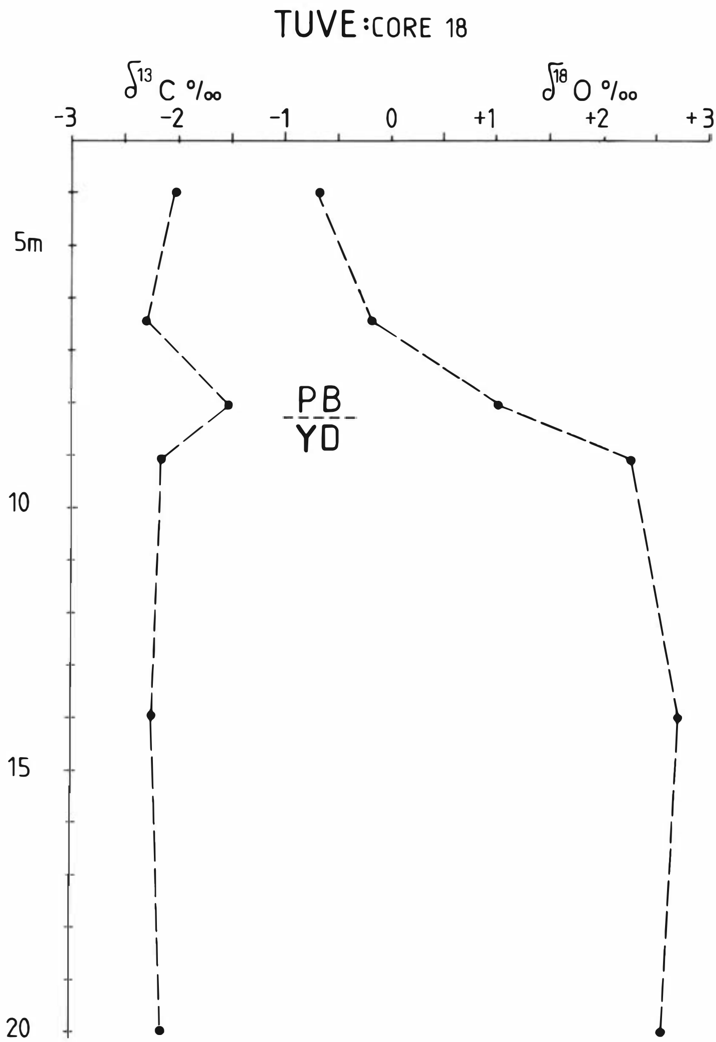

Fig. 10:5. Carbon and oxygen isotope records relative to PDB in the Tuve core (57°45′N; 11°56′E). YD = Younger Dryas and PB = Preboreal.

OLDER DRYAS

The $\delta 18_c$ in the Older Dryas sections approaches +3 per mil in all three cores (Fig. 10:6). This means a δ_w somewhere between –1 and –2 per mil (and uniform bottom-water conditions). The glacial δ_c of benthic foraminifers from the Atlantic is around +5 per mil (Shackleton 1977) which indicates a 2 per mil lighter bottom water in the inner Skagerrak than in the Weichselian Atlantic and about 3 per mil lower salinity if the excess water was of glacial origin with a $\delta 18$ = –25 per mil.

ALLERÖD

The $\delta 18_c$ declines in the early Alleröd substage and diminishes by 5 per mil to –2 o/oo in the Moltemyr core, and 2 per mil, down to +1 o/oo, in the Brastad and Solberga cores. This is the first real meltwater injection observed in these cores (the supposed Böllig interstadial at ~14 m in the Brastad core revealed only a 0.25 o/oo lowering in δ_c). One possible explanation is that the deglaciation during the Bölling was comparatively slow in Bohuslän (cf. Mörner 1969) so that the ice front during the Alleröd could have been rather close to Moltemyr (the Berghem terminal moraine) or, at least, that a meltwater outlet was relatively near. – The δ_c drop in the Moltemyr core would correspond to a salinity reduction in the bottom water by some 6 per mil.

YOUNGER DRYAS

The meltwater content decreased in the bottom water during the Younger Dryas. The increased δ_c in the Moltemyr core was +1 and in both the Solberga and the Tuve core +2.5 per mil.

THE PLEISTOCENE/HOLOCENE BOUNDARY AND THE PREBOREAL

There is again a decrease in the $\delta 18_c$ at the presumptive Pleistocene/Holocene boundary. During the Preboreal it drops 6 per mil in the Moltemyr core, down to –5.3 o/oo followed by an increase. In the Solberga core the drop is less than half of that in the Moltemyr core from +1.5 to –1 per mil, and in the Tuve core the δ_c decreases from about +2 to –0.7 o/oo. – The salinity of the bottom water in the Moltemyr region could have decreased to near 3/4 of that which prevailed during the Younger Dryas. A much smaller salinity decrease occurred in the Göteborg region.

The water depth at the onset of the Holocene was about 50 m at Solberga, around 30 m at Moltemyr, Brastad and Tuve and around 10 m at the Botanical Garden, Göteborg, (Miller, Chapter 16). We have no direct information as to the δ_w of the surface water and how well the water was mixed or stratified. However, the hydrographic conditions in present estuaries (see e.g. Bowden 1980, pp. 40–41) suggest that a salt wedge estuary existed in the Uddevalla–Dalbo area and in the Göta River almost throughout the period following deglaciation. The main outlet was through the Uddevalla Sound. When the outflow was high the salt wedge was more or less ejected from the estuary, and the water flowing through the sound was only meltwater. Due to the higher discharge through the Sound at Uddevalla, the flow created stronger erosive conditions in central than in southern Bohuslän. Outside, in the easternmost Skagerrak, part of the meltwater mixed with the bottom water; twice as much in the Moltemyr area as in the calmer and less mixed waters in the Göteborg region.

This interpretation of the ancient hydrography allows better understanding of the formation of the gigantic shell beds in Uddevalla at that time (the Bräcke shell bank is the largest Quaternary shell bank in the world). Further, the hiatus in Brastad could be due to a strong reaction current. Only in well protected areas, such as Moltemyr, (and nearby Sämstjärn; see Fries 1951, p. 171) could sedimentation continue through the period when the connection with the Baltic existed.

^{13}C

There is an increase in the $\delta^{13}C$ of *Elphidium excavatum* in the Brastad core, from the minimum in the 'Bölling' section up to 7.5 m (from –3 to –1.5 °/∞). Above this level the δ13 is rather constant. In the adjacent Moltemyr core the same trend can be found (from –2 to –1 o/oo). The variation is larger in its Holocene section, which suggests a limnic influence.

The $\delta^{13}C$ in the Solberga section starts from –2 o/oo, becomes irregular in the Preboreal, but remains around –1.5 o/oo up through the clay section. The terrestrial-limnic influence is obvious in the uppermost 6–7 m.

CONCLUSION

The best indications of a global change from glacial conditions to an interglacial are meltwater spikes. There are two large ones in our data: in the Alleröd and in the Preboreal chronozones. The intervening, cooler Younger Dryas substage, assumed to be 800 years in length, has not been identified in the southern hemisphere. Furthermore, such a short interval can hardly be recognized in deep-sea cores with their generally low resolution (±2000 years; see Berger, Chapter 22). Therefore, the isotopic meltwater anomaly in deep-sea cores is, at present, recognized only as a single, continuous phase.

In the Bohuslän part of the expanded Skagerrak area the meltwater supply was stronger in the Preboreal than in the Alleröd substage. The Baltic Ice Lake and the subsequent deglaciation of Scandinavia should have contributed enormously during the Preboreal substage. This meltwater supply should also be recognized in the deep-ocean sediment as an isotopic signal,

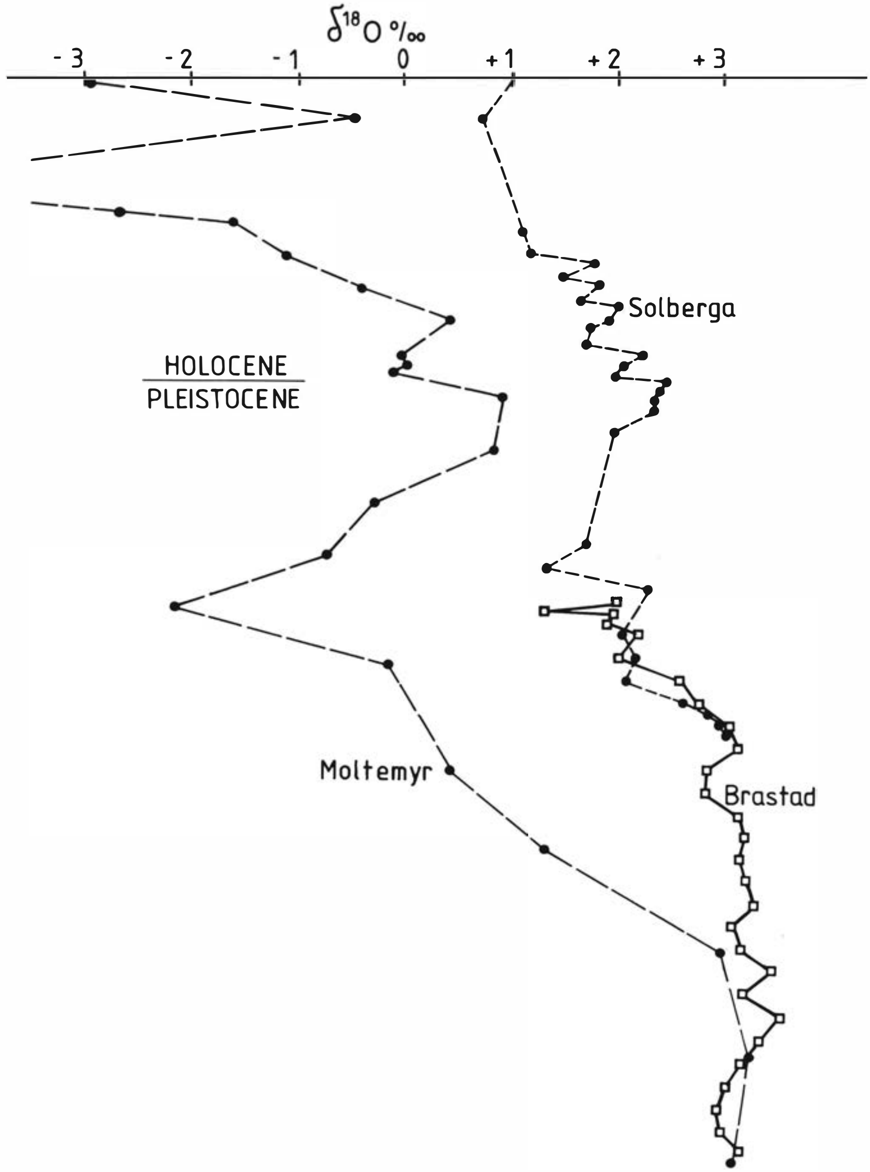

Fig. 10:6. Chronostratigraphical correlation of the oxygen records given in Figs. 10:3–5.

enlarged by the meltwater addition through other outlets of disintegrating ice sheets and drainages of peripheral lakes. As shown in Figs. 10:3–4, the meltwater spikes are obvious in both the Moltemyr and Solberga cores. The δ18 changes are, however, stronger in the former area than in southern Bohuslän.

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