Upwelling off North-West Africa: the Holocene decrease as seen in carbon isotopes and sedimentological indicators

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Received 7/9/77, in revised form 22/9/77, accepted 3/10/77.

ABSTRACT
The stable carbon composition of the planktonic foraminifera Globigerinoides ruber is correlated with abundance of radiolarians, benthic foraminifera, and organic carbon content in a core from off North-West Africa. The sedimentological measures were previously established as upwelling indices. Thus, it appears that the stable carbon composition also reflects upwelling intensity. The stratigraphic sequence suggests a period of strong upwelling during deglaciation, followed by reduced upwelling in the Holocene, and a renewed increase in the latest Holocene.


INTRODUCTION
There is evidence for periods of strong upwelling off North-West Africa during the last glacial and for a subsequent marked decrease to the present intensity. This change is recognizable in the original “Meteor” data (Berger, 1968; based on planktonic foraminifera data of Schott, 1935), and has been documented in some detail through the modern “Meteor” work (Diester-Haass et al., 1973; Diester-Haass, 1977 a, b).

The Climap group recently also reached this conclusion, showing quantitatively the associated change in temperature between the “18 Ka” level and the present (Climap, 1976).
Here we demonstrate the effect of the decrease in upwelling on the δ¹³C signal in two varieties of Globigerinoides ruber (white and pink), by comparing the δ¹³C profiles with indicators of upwelling as established by Diester-Haass (1977 b).

In the present context, we make no difference between a change in upwelling per se and a corresponding change in intensity of the coastal Canary Current. The two phenomena are closely related (see Thiede, 1977, for discussion).

MATERIAL AND METHODS

For our analysis we selected a stratigraphically “well-behaved” core from the continental slope off Cape Barbas, North-West Africa, that is Meteor-25 Core 12379-1, taken at lon. 17°44'7", lat. 23°08'.4' in a depth of 2066 m. Previous investigation of the core showed the stratigraphy expected for this area: the Holocene (oxygen isotope stage 1) is from 0 to 60 cm below the surface, the rest of the core (60-780 cm) comprises stage 2 and probably part of stage 3 (Diester-Haass et al., 1973). Here only the Holocene and latest glacial (down to about 15 000 or 17 000 years BP) have been investigated, in order to study the transition from the late glacial to the Holocene.

This core has been selected for three reasons. 1) The core has continuous sedimentation through the late glacial and Holocene and without hiatuses or erosion influence. 2) It has high sedimentation rate, reducing problems of mixing in establishing a detailed stratigraphy. 3) Supply from upslope redeposition which is rather important on the upper slope during the transgression, is very small in this water depth of about 2 000 m. Only less than 0.1% shallow water particles (glauconite, corroded shells) have been found in the sand fraction. Thus neither micropaleontological data nor isotope determinations suffer significantly from allochthonous supply.

A prominent pteropod layer occurs between 50 and 100 cm. It is thought to be the expression of a worldwide “preservation spike”, that is, an increase of carbonate saturation of the ocean, during a brief period centered on 14 000 years BP (Berger, 1977) (this spike has tentatively been explained by mass mortality by Diester-Haass and van der Spoel, 1977). This relationship gives us a date of about 14 000 years BP between 50 and 100 cm. The sedimentation rates calculated for the Holocene (0-60 cm) are 5.5 cm/1 000 years and between 10 and 20 cm for the late glacial (Diester-Haass et al., 1973). The onset of the Holocene was taken as the first appearance of Globorotalia menardii, which is coincident with the maximum change in apparent faunal temperature (Diester-Haass et al., 1973). The Holocene sedimentation rate is difficult to establish because the base of stage 4 is not reached. Comparison with other cores from the area (Diester-Haass et al., 1973; Diester-Haass, 1976) shows, that glacial sedimentation rates are 2-3 times higher than Holocene ones. Calculating with a conservative sedimentation rate of 10 cm/1 000 years the 14 000 years BP level would be at 90 cm below surface.

Determination of carbon isotopes by mass spectrometer followed standard procedures (Berger, Killingley, 1977). For the isotopic analysis the tests of Globigerinoides ruber were taken from the (sieve)-size class 250-420 µm. Two samples each from eleven horizons were analysed, each sample being picked and run in duplicate.

A quantitative coarse fraction analysis has been carried out for the determination of sedimentological parameters of upwelling influence (for method see Diester-Haass et al., 1973; Diester-Haass, 1975; 1977 b).

RESULTS

There is a good visual correlation between the stratigraphies of radiolarian/planktonic foraminiferal ratios, benthos/plankton ratios of foraminifera and δ¹³C values (Fig. 1). Low radiolarian/planktonic foraminifer ratios and low benthos/plankton ratios of foraminifera type the Holocene, and high ones the late glacial. Correspondingly, δ¹³C values are high in the Holocene and low in the late glacial. The uppermost Holocene values (0-20 cm) show a trend towards "glacial values", in all indices.

Organic carbon determinations have been made in only a few samples (Müller, 1976), but the trend is comparable to the described results: low values in the Holocene and high ones in the late glacial. Accumulation rates of organic carbon are 0.061 g/cm²/1 000 years in 0-60 cm, and at least 0.45 g/cm²/1 000 years in the late glacial, assuming a sedimentation rate of 10 cm/1 000 years. Thus, there is a decrease by a factor of 7 or more, through the transition period. The organic carbon is mainly of marine origin.

Under conditions of normal fertility, opal skeletons of the primary producers diatoms and of radiolarians are completely dissolved in the underlying sediments. When fertility increases opal production of diatoms increases, thus the SiO₂ input to the sediment increases and opal preservation is possible. So in fertile periods and areas off North-West Africa one finds opal skeletons both of diatoms and radiolarians.

Diatoms are rare or absent in fractions >40 µm which are investigated here. But as radiolarian preservation reflects the opal input by diatoms, radiolarian amounts are a valuable indicator of fertility changes too.

The radiolarian amount is not expressed in percent of the coarse fraction, because these percent values suffer from dilution by other components, mainly terrigenous material. Radiolarian content is expressed as a ratio with planktonic foraminifera, the latter having been found to show no or only minor variations in accumulation rates in this core (Diester-Haass, 1976), where dissolution can be neglected. So the radiolarian/planktonic foraminifer ratios show variations in radiolarian- and total opal-input and thus in opal preservation in the sediments.

A Holocene decrease of this ratio, compared to the Pleistocene one, could be observed in all investigated cores (8) of the continental slope off North-West Africa between 21 and 27°N. Diatoms, absent in the >40 µm fractions of this core, form up to 150 individuals per
millilitre wet sediment in the <40 μm fractions in the late glacial section and are absent in the Holocene (Schrader in Diester-Haass et al., 1973).

Benthos/plankton ratios of foraminifera also have been found to depend on fertility in addition to water depth (Diester-Haass, 1977 b). In surface sediment samples from similar water depths off North-West Africa benthos/plankton ratios are higher off Cape Blanc (21°N), where upwelling influence is very strong, than off Cape Barbas (23°N) where it is less strong (Schemainda et al., 1975). The high organic production in the surface waters of upwelling areas results in high food supply to the bottom and thus in increased production of benthos. Off Cape Blanc, for instance, at a depth of 2000 m surficial benthos/plankton ratio of foraminifera is 4.3, compared to ratios between 1
and 3 in the Holocene of core 12379-1 off Cape Barbas. With increasing water depth the ratios decrease off Cape Blanc (1 000 m: 16.7; 3000 m: 2.4) and also in the less fertile area off Cape Barbas (1 000 m: 9.7; 3000 m: 1.3) (Fig. 9 in Diester-Haass, 1977 b). During periods of strong upwelling accumulation rates of benthic foraminifera as well as other benthic organisms increase considerably more than those of planktonic ones (Diester-Haass, 1977 a). Thus the ratios of benthic to planktonic foraminifera increase under the influence of upwelling, at each depth level.

Supply by upslope redeposition of benthic foraminifers in core 12379-1 is of minor or no importance. As mentioned, the indicators of shallow-water supply, such as glauconite and reworked shallow water shells form less than 0.1% of the sand fraction.

The organic carbon content in the sediments largely reflects the organic production in the overlying surface waters. The high organic carbon contents and accumulation rates in the late glacial are due to high fertility (Müller, 1976; Diester-Haass, 1977 b).

In summary, the various sedimentary parameters described: opal (radiolarian) content in the sand fraction, benthos/plankton ratios of foraminifera and organic carbon content in the total sediment all point to high fertility during the late glacial. Thus it appears that upwelling was stronger during the late glacial than during the Holocene off North-West Africa. In the uppermost Holocene (0-20 cm) fertility apparently was higher than in the rest of the Holocene.

The changes in upwelling intensity, as recorded in the sedimentary parameters, go parallel to a change in the carbon isotope signal, of the order of 0.7%. This is true both for the pink and the white variety of Globigerinoides ruber (Fig. 1 A). The oxygen isotopic composition shows that the white form lives in colder water than the pink one, the difference being about 3°C. This difference may be due to a depth effect, or to a seasonal effect, or both. In either case, cooler waters being nutrient rich, the lighter δ13C values are to be expected for the white variety. It is interesting that the difference in carbon composition between white and pink forms is of the same magnitude as the size of the stratigraphic signal.
The plot of δ13C values against radiolarian/planktonic foraminiferal ratios (Fig. 2) shows a good correlation between these two parameters (rank difference correlation \( r_d = 0.80 \)). The correlation is less good for the benthos/plankton ratio of foraminifera and δ13C (\( r_d = 0.67 \)) (Fig. 3). Both correlations are much improved if the square root of the faunal parameters is taken as index. Ratio data, of course, are notoriously non-linear with respect to environmental parameters they tag. Thus, the use of square root transformations is no more arbitrary than the use of the straight ratios, for comparative purposes.

**DISCUSSION**

Our results indicate that the δ13C signal from a surface-dwelling planktonic foraminifer goes parallel to upwelling intensity. Further work is necessary to calibrate the amplitude of the δ13C signal to the amplitude of the rate of carbon fixation. To the extent that carbon fixation is limited by nutrient supply (nitrate and phosphate) from subsurface waters such a calibration should be possible since the ratio \(^{12}\text{C}/^{13}\text{C}\) in the bicarbonate dissolved in sea water acts itself like a nutrient. \(^{12}\text{C}\) is preferentially fixed during photosynthesis and subsequently released at the time of nutrient remineralization (Sackett et al., 1965; Deuser, Hunt, 1969; Craig, 1970; Duplessy, 1972; Broecker, 1973; Kroopnick, 1974). However, there are some difficulties in interpreting the stable carbon composition purely in terms of excess supply of \(^{12}\text{C}\) from upwelling subsurface water: 1) there is a temperature effect (Emrich et al., 1970); 2) the precipitation of calcareous shells of the plankton is not in thermodynamic equilibrium with dissolved bicarbonate (Berger, Killingley, 1977); 3) where there is partial dissolution of carbonate, the δ13C signal will be affected (Berger, Killingley, 1977). Dissolution of calcite can be excluded as an important factor in the core here studied. The temperature effect is small (~0.2°/° for or 5°C range, see Emrich et al., 1970) compared with disequilibrium, that is, metabolic effects. To separate out the
disequilibrium (growth) effect from the supply of $^{14}$C by upwelling it will be necessary to study a number of species with differing ecologic requirements, including slow-growing deep-living forms.

Metabolic effects on carbon composition appear to be most pronounced in small, surface-living forms, which presumably are fast-growing (Berger et al., 1977). The presence or absence of symbiotic unicellular algae also may play an important role. This has been shown for corals (Weber, Woodhead, 1970; Weber, 1973).

Whatever the difficulties in calibrating the δ$^{13}$C signal and the other upwelling indices with carbon fixation, the trend from high to low upwelling intensity at the transition from glacial to Holocene now appears well established. The oxygen isotope values of the samples analyzed for δ$^{13}$C also show this. The intraspecific isotope range is larger (1.5‰) during the late glacial, when a shallow thermocline juxtaposes warm and cold water. It is small (0.5‰) during the time of the δ$^{13}$C minimum.

The apparent increase of upwelling within the youngest Holocene (Thiede, 1977) may reflect the effects of “Neoglaciation” (Flint, 1971). This period had its peak expression in the “Little Ice Age”, well known for producing glacial advances in North America and Northern Europe (Curry, 1969; Denton, Karlén, 1973; Bray, 1974). The “Little Ice Age” apparently was characterized by increased upwelling off Southern California, judging from a foraminiferal stratigraphy, given by Kipp and Towner (1975) for the Santa Barbara Basin.

Acknowledgements

One of us (W. H. B.) wishes to thank Prof. E. Seibold of the Geologisch-Paläontologisches Institut, Universität Kiel, for providing for a six month’s sabbatical visit and for the opportunity to participate in the marine geology program in Kiel. We are also indebted to Prof. Seibold for his encouragement and interest in the work here presented. We are grateful to Dr. E. Vincent, SIO for discussion and for supervising selection of the planktonic foraminifera for isotopic analysis and to Dr. H. Erlenkeuser for critical discussions on this interpretation of stable isotope signals.

The research was supported by the US National Science Foundation (W. H. B., J. S. K.) and by the Deutsche Forschungsgemeinschaft (L. D.-H.).

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