

upper 2,500 m of the ocean. Below that depth, deep waters presumably originating from the southern ocean were present. In contrast to this apparent lack of correlation between rates of deepwater formation and climate on these longer time scales, there seems to be a much closer relationship on shorter time-scales. During short periods of massive iceberg discharge (Heinrich Events) that punctuated the glacial period, deepwater formation in the North Atlantic may have totally ceased. The rapid warmings that followed these events seem to be the results of a rapid reinvigoration of the Atlantic MOC. Such a sequence of events has now been well documented for the last of the Heinrich Events (H1), which occurred during the early stages of the deglacial transition into the Holocene. Water mass proxies suggest similar sequences during the other Heinrich events, but confirmation with kinematic tracers is still required. The possibility that some of the abrupt climate changes in the past were associated with rapid changes in the rate of thermohaline circulation raises concerns that such events could happen in the near future.

Roger Francois

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Introduction

Ocean productivity – the uptake of dissolved inorganic carbon and its sequestration into organic compounds by marine primary producers – plays a major role in controlling the partitioning of carbon between the ocean and atmosphere. Productivity fluctuations can therefore influence climate by altering the atmospheric concentrations of the greenhouse gas carbon dioxide (Berger et al., 1989). In addition, changes in marine productivity have some bearing on the biogeochemistry of many trace elements (P, N, Si, Ba) and gases (dimethyl sulfide). The record of significant fluctuations in atmospheric carbon dioxide in air trapped within polar ice along with the increasing concern of potential climate warming induced by industrial carbon dioxide emissions has emphasized the need to understand the interrelationship between productivity, ocean chemistry, atmospheric carbon dioxide, and climate. Ocean paleoproductivity studies document past changes in the biological production of organic matter and skeletal material. These studies provide insight into the causes of such fluctuations, the consequences for biogeochemical cycles within the ocean, and their correspondence to Earth's climate.

There are two components of oceanic productivity that are of interest: (a) net primary production in the surface ocean; and (b) export production, which is the fraction of net primary production that leaves the surface ocean and sinks to the deep ocean. While the former is of interest for learning about oceanic ecosystems, and carbon and nutrient cycling within the ocean, the latter is more relevant for carbon sequestration and climate change. The unit for measuring productivity is flux of carbon ($\text{grams C m}^{-2} \text{ yr}^{-1}$) and typical values for open ocean net primary productivity today are 25–250 $\text{g C m}^{-2} \text{ yr}^{-1}$. Export production typically ranges from less than 10% and up to 50% of the net primary production.

The concept of changing oceanic productivity and the relation of such changes to climate stand at the beginning of paleoceanographic research. Arrhenius (1952) suggested such changes to explain the sedimentary record and in particular calcite accumulation and size distribution of a diatom (*Coscinodiscus nodulifer*) over time in the eastern Equatorial Pacific. Since direct measurements of carbon uptake or flux to the deep ocean cannot be done for past times, paleoproductivity reconstruction has been based on records obtained from marine sediments. Over the past 50 years, a large variety of methods has been applied to reconstruct productivity, attesting to the importance of this field. Some of these methods result only in qualitative estimates while others are more quantitative. Each of these methods (or proxy variables for productivity) has associated assumptions and limitations and therefore should be used with caution. Ideally, several proxies should be applied simultaneously at any given site or time interval to evaluate changes in marine productivity.

Reconstruction of productivity from organic matter or phosphorus in sediments

As a dominant biological component, measurements of organic carbon (C) content of sediments seem a logical choice for reconstructing biological C production. In areas removed from downslope transport of fine-grained material, it has been assumed that the flux of organic C reaching the sediment is proportional to its net export from the surface ocean (Figure O16). Indeed, sediment trap studies indicate that a general relation between the flux of organic matter to the deep sea and productivity exists. However, there is a strong depth dependence of the relation because of

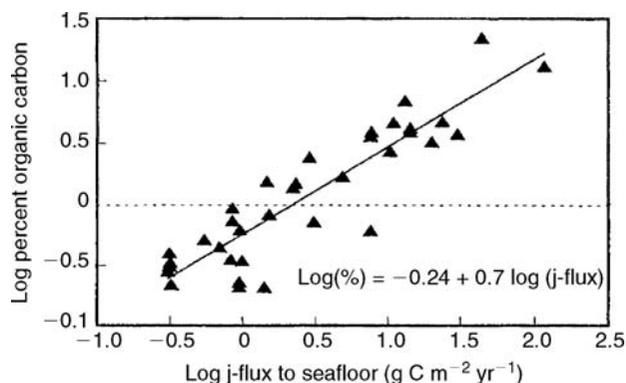


Figure O16 Correlation of organic carbon content in marine sediments with organic matter flux to the seafloor (after Berger and Herguera, 1992).

organic C degradation in the water column. Only a small fraction of the organic matter that arrives to the sediment is ultimately buried. However, at least at some oceanic locations, a relation between the abundance of organic matter in sediments and primary production has been observed. Empirical equations that quantitatively relate the accumulation rate of organic carbon in sediments to overlying productivity (Muller and Suess, 1979) or to the carbon flux to the seafloor (Sarnthein et al., 1988) have been suggested using data from the present ocean. The relation between organic matter content and productivity has been applied to reconstruct past oceanic productivity in various oceanic basins and for various time scales (Muller and Suess, 1979; Pedersen, 1983; Finney et al., 1988).

The interpretations of the fluctuations of organic carbon content in terms of paleoproductivity are complicated by processes affecting organic matter preservation such as sediment accumulation rates, deep water oxygen content, exposure time, and mineral surface area (Emerson, 1985; Keil et al., 1994). In addition, supply of organic C from terrestrial origin may result in overestimation of the oceanic productivity in coastal environments (Goni et al., 1998).

One of the elements directly related to organic matter is phosphorus (P). Phosphorus is an important nutrient to all living organisms. In general, marine phytoplankton incorporate P at a relatively constant ratio to their C content (the Redfield molar ratio of 106 C to 1 P). Accordingly, mapping past P accumulation may provide an indirect estimate of C flux and thus productivity (Delaney, 1998). Indeed, this proxy has been used to reconstruct past ocean productivity, typically over long geological time frames where organic C data is more likely to be compromised (Filippelli, 2002).

It must be kept in mind, however, that only a small fraction of P is preserved in the sediment (like C) and that, within the sediment after burial, P is transformed from the organic forms to authigenic minerals (Ruttenberg and Berner, 1993). To account for this complication, the “reactive P” fraction, which is the P that presumably was associated with organic matter, is used for paleoproductivity reconstruction (Delaney, 1998). In addition, post burial redox diagenesis may alter the P association and preservation in the sediment and therefore care must be taken to avoid samples that have been compromised by such processes (Delaney, 1998).

Reconstruction of productivity from carbonate or opal

Geologists have long recognized that variations in sediment composition parallel surface primary production. Indeed calcium carbonate and biogenic opal in marine sediments are predominantly composed of the hard parts of marine organisms (coccolithophores and diatoms). Sediment traps show a good correlation between the organic C flux and carbonate flux under certain conditions in the open ocean above the lysocline (Deuser et al., 1981; Ruhlemann et al., 1996) (Figure O17a). Similarly biogenic opal flux in sediment traps and on the seafloor generally correlates with the organic C flux (Calvert, 1966) (Figure O17b). These empirical relations based on traps and core top sediments can be used as a basis for reconstructing changes in location and intensity of export production. Indeed, Lyle et al. (1988) demonstrate linkage between mass accumulation rates of organic C, calcite, and biogenic opal and tie these to biological productivity.

Both these proxies, however, represent only changes in the export production of the specific organisms precipitating these minerals. One must therefore assume a predictable relation between total export production and the production of specific groups of organisms that are responsible for the precipitation of these minerals. Moreover, opal fluxes to the sediment may be dominated by event production such as during diatom blooms. In addition, both proxies are affected by a variety of physical and chemical oceanographic processes and not only by productivity. In particular, because the ocean is undersaturated everywhere with respect to opal, there is a major problem in quantitatively relating the amount of opal preserved in sediments to its production in the water column. Opal preservation rates depend on several factors including the global silica budget, pore water dissolved silica concentration, the thermal history of the sediment column, and the degree of silicification of the frustules (DeMaster, 1981; Treuger et al., 1995; Hutchins and Bruland, 1998). As a result, areas with high opal accumulation do not always correspond with areas of high productivity such as in the present-day Southern Ocean. Nevertheless, there do appear to be major trends in the history of opaline sedimentation over time and this proxy has been used to suggest qualitative changes in export production. Similarly, calcium carbonate accumulation in marine sediments may also suffer severe diagenetic modification of the original productivity-driven signal due to dissolution. This process, however, will occur predominantly in the deeper parts of the ocean where

seawater is undersaturated with respect to calcite. With proper site selection, or after accounting for dissolution (Mekik et al., 2002), it is possible to obtain representative patterns of carbonate production in most areas of the world's ocean.

Reconstruction of productivity from barite and Ba accumulation

Marine barite (BaSO_4), the major carrier of particulate Ba in the water column, is related to the marine carbon export flux (Bishop, 1988; Dymond et al., 1992). Barite precipitation in the water column is associated with decaying organic matter (Ganeshram et al., 2003). This results in a positive correlation between barite and excess-Ba (the Ba fraction not carried by terrigenous material – $\text{Ba}_{\text{excess}}$) and organic carbon fluxes in sediment traps and filtered particulate matter (Dehairs et al., 1980; Dymond et al., 1992). Based on this relationship in sediment traps, Dymond et al. (1992) predicted a positive correlation between the accumulation of $\text{Ba}_{\text{excess}}$ in marine sediments and carbon export (Figure O18a).

$\text{Ba}_{\text{excess}}$ has been used in many studies, to infer paleoproductivity (Nürnberg et al., 1997; Bonn et al., 1998; Bains et al., 2000). $\text{Ba}_{\text{excess}}$ is determined from the total Ba concentration in the sediment after subtracting the Ba associated with terrigenous material, which is calculated from total Al or Ti, and normalization to a constant detrital Ba/Al or Ba/Ti ratio. This calculation assumes that (a) all sedimentary particulate Ba besides the fraction associated with terrigenous aluminosilicates is predictably related to carbon export, (b) all of the Al (or Ti) is associated with terrigenous material, and (c) the Ba/Al (Ba/Ti) ratio used for normalization is in fact representative of each sample's terrigenous component and is constant in space and time. If the above assumptions are correct then $\text{Ba}_{\text{excess}}$ accumulation in sediments could be used to estimate carbon export.

Paytan et al. (1996) and Eagle et al. (2003) proposed an algorithm for paleoproductivity reconstruction based directly on barite accumulation in core top sediments (Figure O18b). In these studies, as in Dymond et al. (1992), the applicability of the proxy relies on the observation that barite forms and accumulates in proportion to biological productivity and the organic matter flux in the water column. In addition, barite shows promise as a paleoproductivity proxy because it is a highly refractory mineral with preservation as high as 30% in oxic sediments (Dymond et al., 1992). The barite accumulation

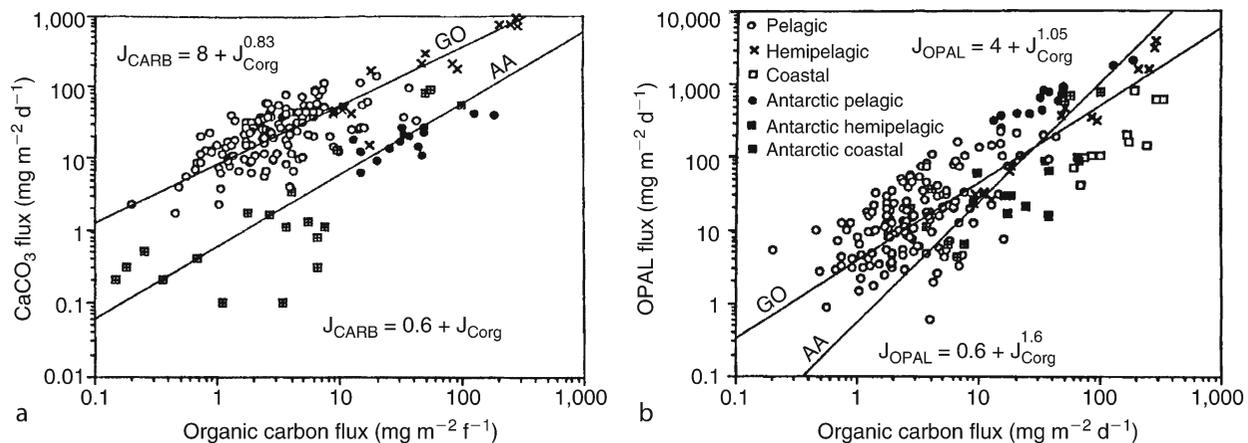


Figure O17 Relationship between (a) carbonate and (b) opal flux and organic carbon flux in sediment traps from various regions in the ocean. GO: global ocean; AA: Southern Ocean (after Berger and Herguera, 1992).

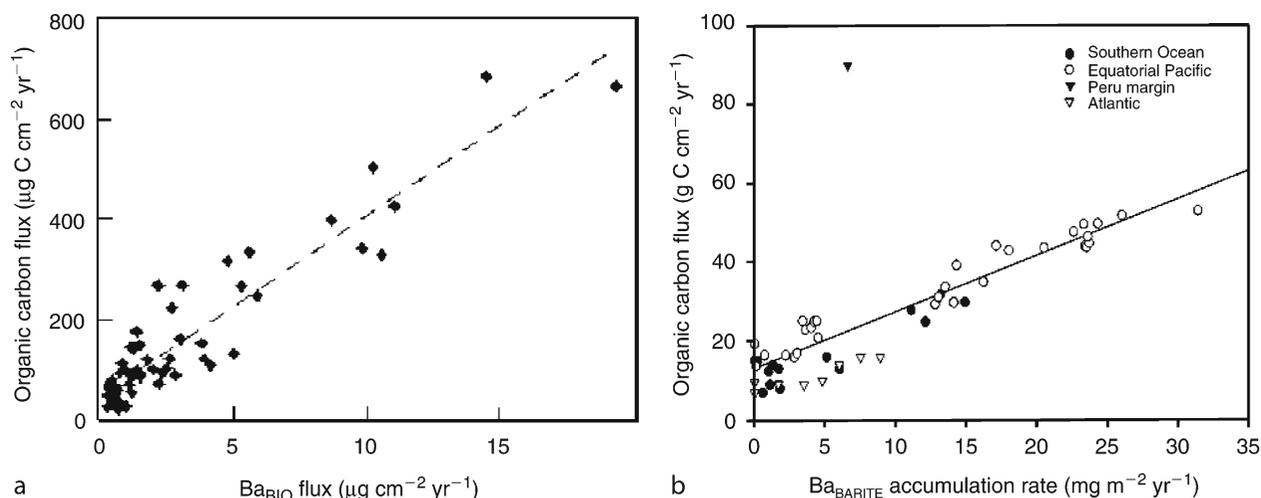


Figure O18 (a) Relation between excess Ba and organic C export in sediment traps (modified from Dymond et al., 1992). (b) Relation between barite accumulation rate in core top sediments and carbon export in the overlying water column (modified from Eagle et al., 2003).

rate in oxic sediments could therefore serve as a proxy for estimating paleocarbon export if the processes controlling barite formation and preservation are known and operate globally in the ocean.

Barium, however, is contained in other phases, some of which are biogenically-related (e.g., organic matter, biogenic silica, and biogenic carbonate), and others that are not directly related to carbon export (e.g., terrigenous silicates, Fe-Mn oxides, and hydroxides). The non-barite phases that are included in Ba_{excess} would not necessarily yield a predictable global $C_{\text{org}}/Ba_{\text{excess}}$ relationship as found by Dymond et al. (1992). This is because the ratio of organic carbon to these other biologically-related Ba phases varies spatially in the ocean, and because factors controlling Ba incorporation into Fe-Mn oxides and hydroxides are not directly biologically mediated. Although barite accumulation is not affected by the above factors, its preservation is affected by the dissolved Ba concentration in seawater; thus, some estimate of past oceanic Ba concentrations is needed for quantitative use of this proxy. In addition, barite in marine sediments is remobilized under sulfate-reducing conditions, so this proxy can only be applied when pore waters have remained saturated with respect to barite throughout the sedimentary record.

Reconstruction of productivity from microfossil assemblages

The use of species distribution has been widely applied for reconstructing productivity. Plankton assemblages in the surface ocean respond to nutrient concentrations, thus productivity. A number of foraminifera species have been identified as indicative of high productivity (*Globigerina bulloides*, *Neogloboquadrina dutertrei* and *Globorotalia tumida* at low latitudes, *Globigerina quinqueloba* in temperate latitudes and *Neogloboquadrina pachyderma* in cold upwelling waters). Single species abundances, however, may be more indicative of upwelling or other hydrographic physical processes rather than biological productivity. Multi-species based indexes using all of the foraminifera species in sediment cores to construct a quantitative estimate of productivity using standard transfer function

techniques are more robust (Imbrie and Kipp, 1971). The transfer functions (modern analogs) are constructed using modern primary production rates and a global coverage of core top foraminifera abundance data (Mix, 1989). The high abundance and diversity of foraminifera allows statistical analyses of small sediment samples (Figure O19a).

Similarly, the benthos biomass and the structure of the benthic community (species composition and size) reflect the supply of organic matter to the seabed, thus export production (Rowe, 1983). In particular, benthic foraminifera, which constitute a major portion of the benthic biomass, respond to changes in supply of organic carbon to the seafloor. Accordingly, changes in benthos abundance (population size) and benthic population composition (assemblage) have been used to qualitatively indicate changes in export production (Figure O19b). The biomass of total benthic foraminifera is positively correlated with the estimated local annual flux of organic C into the deep sea (Herguera, 2000). Specific species such as *Uvigerina peregrina* and *Globobulimina* sp. are characteristic of high nutrient fluxes, whereas *Cibicides wuellerstorfi* and *Cibicides kullenbergi* biofacies dominate areas of low productivity (Altenbach and Samthein, 1989). Transfer functions based on benthic communities and diatom assemblages have also been developed and applied to reconstruct past oceanic productivity (Loubere, 1999).

Many uncertainties remain, however, because our knowledge of the biology of the common fossil groups is limited. It is not clear to what extent the plankton assemblage reflects primary production, export production, or food availability. In addition, assemblages respond to a complex suite of environmental parameters that are not easily separated, thus are affected by other environmental variables (temperature, salinity, oxygen, etc.). Problems may arise from non-analog situations where the calibration using present-day core top samples does not represent past conditions. In addition, for all the species indices, there may be preservation effects and post-deposition changes in assemblages due to preferential dissolution, which will limit our ability to see true biological relationships. For longer time frames, evolution of species will also limit the utility of this type of index.

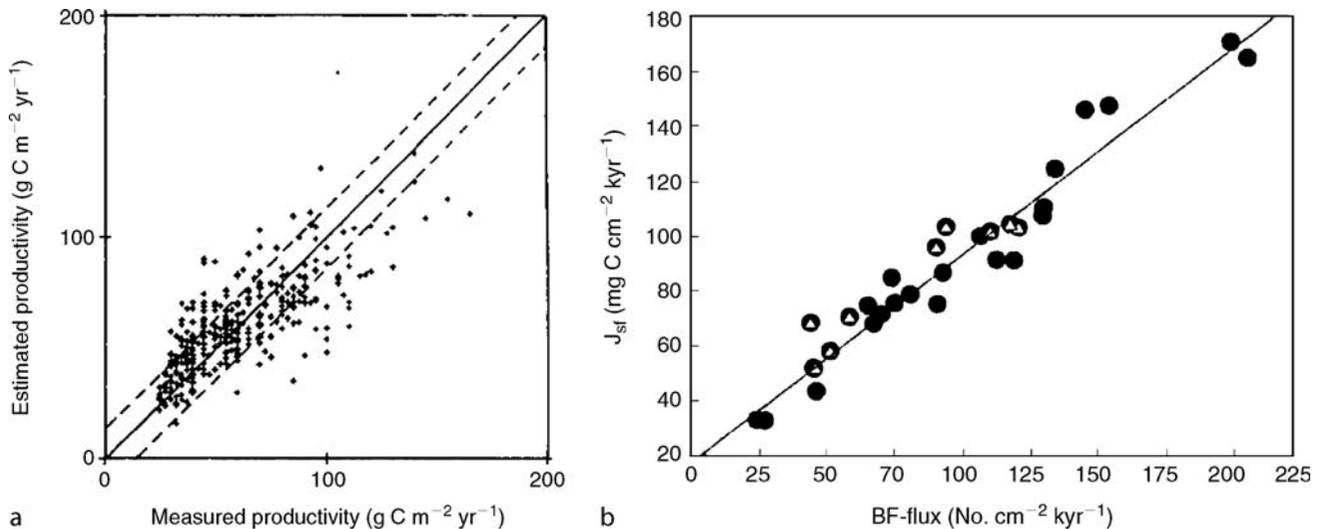


Figure O19 (a) Estimated versus measured values for productivity as generated from foraminiferal transfer functions. (b) Accumulation rate of benthic foraminifera (*BF-flux*) as a function of calculated flux of organic matter to the seafloor (*J_{sf}*) (after Berger and Herguera, 1992).

Reconstruction of productivity from carbon isotope records

A link between ocean productivity and carbon isotopes was first postulated by Tappan (1968), who suggested that change in $\delta^{13}\text{C}$ of carbonates towards heavier values is indicative of increased deposition of organic carbon, thus export production. The principle underlying this relation is carbon mass balance. During photosynthesis, since isotopically light carbon (^{12}C) is preferentially incorporated into the produced organic matter, the residual inorganic pool will become enriched in ^{13}C . This signature will be recorded in carbonate shells and therefore higher $\delta^{13}\text{C}$ of carbonates indicates increased burial of organic matter (with low $\delta^{13}\text{C}$ values) and hence higher productivity.

The difference between planktonic and benthic $\delta^{13}\text{C}$ compositions is a refinement of the above proxy (Figure O20). This difference is controlled by both the photosynthesis of organic matter in the surface ocean, which depletes the inorganic pool of ^{12}C , and the regeneration of this organic matter at depth, returning the ^{12}C to the deep-water inorganic pool. Thus, the larger the difference between the benthic and planktonic $\delta^{13}\text{C}$ (typically referred to as $\Delta^{13}\text{C}$), the higher the productivity (Shackleton et al., 1983; Curry and Crowley, 1987; Schneider et al., 1994).

It must be kept in mind that changes in oceanic circulation may modify the deepwater $\delta^{13}\text{C}$ independently of productivity. Moreover, when benthic foraminifera species are used for $\delta^{13}\text{C}$ analyses, it is important to choose species that indeed record the isotope ratio of dissolved inorganic carbon in seawater and not that of water within the sediment; thus only epifaunal species (organisms living on top and not within the sediments) should be used. In addition, because the isotopic fractionation during photosynthesis and shell production may vary between species and within each species depending on environmental parameters ($p\text{CO}_2$, carbonate ion concentrations, nutrient availability, etc.) a record obtained from a single species is preferable (Duplessy et al., 1984). Reconstruction of paleoproductivity via carbon isotopes becomes less reliable the farther back in time we go in the geological record. With now-extinct

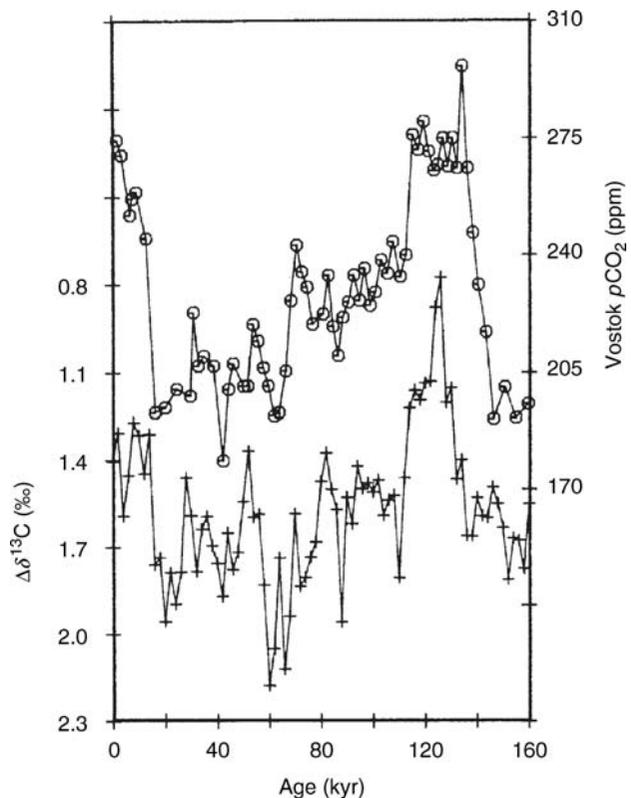


Figure O20 $\delta^{13}\text{C}$ difference ($\Delta\delta^{13}\text{C}$) between the benthic foraminifera *Uvigerina* sp. and the planktonic foraminifera *Neogloboquadrina dutertrei* in core V19-30 in the eastern Equatorial Pacific (+ symbols) (data from Shackleton and Pisias, 1985). Also plotted is the VOSTOCK ice core $p\text{CO}_2$ data from Barnola et al., (1987) (o symbols). The similarity between the records confirms the importance of export productivity variations (the biological pump) to atmospheric CO_2 (figure modified from Mix, 1985).

species, we can only indirectly verify the faithfulness of the C signal in their skeletons to the ambient water $\delta^{13}\text{C}$. In addition, the extent of diagenetic modification of carbonate $\delta^{13}\text{C}$ increases with time after burial and may be significant in areas where pore fluids contain “light” methanogenically-derived C.

Reconstruction of productivity from geochemical indicators

Several geochemical indicators that record particle flux in the water column have also been used as proxies for productivity (Al/Ti, Ba/Ti, $^{231}\text{Pa}/^{230}\text{Th}$, $^{10}\text{Be}/^{230}\text{Th}$). In vast areas of the open ocean, most of the particulate matter sinking in the water is of biogenic origin and thus is related to productivity.

Application of bulk Al/Ti and Ba/Ti ratios assumes that changes in the delivery of Al and Ba in non-lithogenic material are proportional to particle flux, which may then be related/converted to productivity. These proxy applications assume that in specific open-ocean locations (with low terrigenous input), total particle flux is proportional to C_{export} (Murray et al., 2000). Since Al is particle reactive, the adsorbed fraction of Al should increase with increasing particle flux; therefore, the excess Al content of deep-sea sediments (i.e., the fraction of Al not associated with aluminosilicate material) will increase with increasing particle flux (Murray and Leinen, 1996). Similarly, Ba/Ti should co-vary with bulk particle flux, and thus C_{export} (Figure O21; Murray et al., 2000). Bulk ratio proxies apply so long as Ti is exclusively of terrigenous origin, the fraction of Al or Ba associated with lithogenic Ti does not change significantly through time, and the excess Al or Ba is related to C_{export} in a predictable and consistent manner. The benefit of a normalizing ratio is that it does not require conversion of concentrations to accumulation rates, thus avoiding errors associated with such conversions.

In open ocean areas, a relationship exists between the mass flux of particulate matter and the unsupported $^{231}\text{Pa}/^{230}\text{Th}$ and $^{10}\text{Be}/^{230}\text{Th}$ activity ratios of recent sediments (Anderson et al., 1983; Rutsch et al., 1995). These ratios have been used as tracers to assess changes in productivity. The production rate of ^{231}Pa and ^{230}Th from dissolved U in seawater and the input of ^{10}Be to the ocean are known; however, the removal of these elements is not homogenous because they have variable residence times in

the ocean. Because ^{230}Th is more effectively scavenged, its flux to the seafloor is nearly equal to its rate of production; in contrast ^{231}Pa and ^{10}Be have longer residence times, which allows transport and preferential removal in high particle flux regions (Anderson et al., 1983). Therefore, high $^{231}\text{Pa}/^{230}\text{Th}$ and $^{10}\text{Be}/^{230}\text{Th}$ ratios indicate regions of extensive particle flux. The major advantage of the radionuclide ratios is that they are less sensitive to post-depositional diagenetic alteration. However, changes in ocean ventilation rate and dependence of scavenging efficiency in particle composition may influence the reliability of these proxies (Walter et al., 1999).

Accumulation of redox-sensitive metals in marine sediments is indirectly related to productivity, or more accurately, to the flux of C to the sediment. The higher the export production and organic C accumulation the more oxygen is consumed in the water column and sediment. As pore waters become sufficiently reducing, some metals precipitate and accumulate in the sediments. An example of an element that has been linked to organic C flux is uranium, which forms authigenic minerals in the sediment under reducing conditions (Kumar et al., 1995). Laminated sediments have also been linked to very high organic C fluxes. When the organic matter flux to the bottom waters is high, all of the dissolved oxygen is consumed, resulting in anoxic waters and low abundance of benthic organisms. This in turn reduces the degree of bioturbation and preserves the lamination in sediments. The above proxies, however, will also respond to changes in bottom water oxygen over time that are related to circulation and ventilation of the ocean and not to productivity, thus they are hard to interpret directly as reflecting changes in biological productivity.

It has recently been suggested that another geochemical proxy, the Sr/Ca ratio in coccolithophores, changes in proportion to calcification rates, which are higher when coccolith productivity is high (Stoll and Schrag, 2000). This proxy has been used for qualitative reconstruction of paleoproductivity; however, such reconstruction will only represent changes in coccolith productivity, which may be decoupled from total production. In addition, species-dependent Sr uptake rates and diagenetic alteration of original Sr/Ca ratios have not been completely ruled out and may complicate interpretation.

Reconstruction of productivity from nutrient content

Nutrient (N, P, Fe, Si) availability in many places controls the productivity in the surface ocean. Therefore, it has been suggested that knowledge of nutrient concentrations or their degree of utilization can be examined in the sedimentary record and may provide indirect information about past productivity. Such proxies include the nitrogen isotopic composition of organic matter (Altabet and Francois, 1994; Farrell et al., 1995), silicon isotopic composition of diatom frustules (De La Rocha et al., 1998), and the Cd/Ca ratio of planktonic foraminifera (Cd serves as an analog for P; Elderfield and Rickaby, 2000). The basic concept behind these proxies is that in areas where the nutrient pool (N, Si, P) in the surface ocean is not fully utilized, progressive assimilation of nutrients from surface seawater, accompanied by fractionation, produces strong gradients in the isotopic or elemental composition within the euphotic nutrient pool, which is then recorded by the plankton. This in turn leads to corresponding changes in the composition of particles that sink in the water column and accumulate in the sediment. For example, at high nutrient content relative to uptake (low utilization rates), ^{14}N is preferentially taken up by the phytoplankton and the organic matter, which under such conditions will have low $\delta^{15}\text{N}$ values. As nutrients are more efficiently utilized, less isotopic discrimination occurs and the $\delta^{15}\text{N}$ of organic matter shifts towards heavier

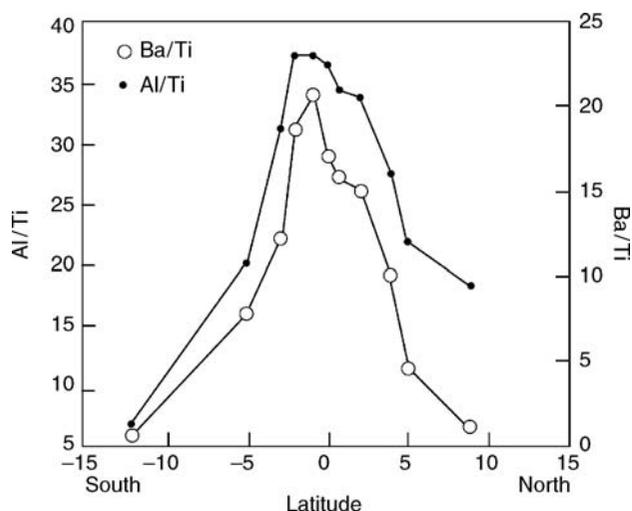


Figure O21 Profiles of Al/Ti and Ba/Ti trace productivity across a meridional transect at 140° W in the central equatorial Pacific Ocean (modified from Murray et al., 2000 and references therein).

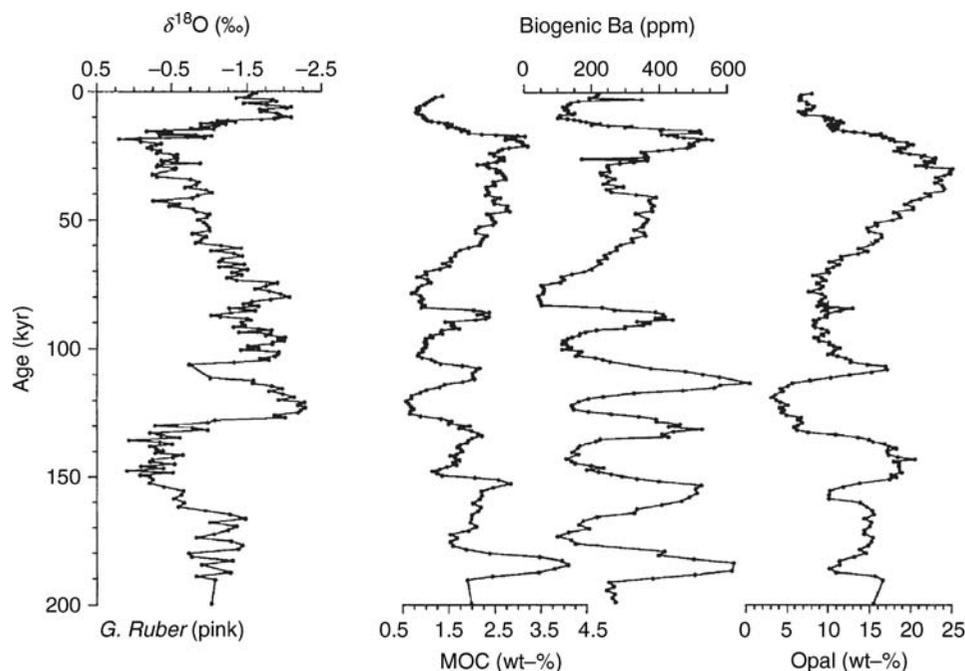


Figure O22 A multi-proxy approach for reconstructing marine productivity. Marine organic carbon (MOC), biogenic Ba, and opal co-vary down-core and show higher values during glacial periods (as indicated by the oxygen isotope record) in core GeoB 1008-3 from the South Atlantic (modified from Schneider et al., 1997).

values. Similar uptake effects result in changes in the $\delta^{32}\text{Si}$ of diatoms and the Cd/Ca ratio in planktonic foraminifera.

It must be kept in mind, however, that the relation between nutrient input and uptake (i.e., utilization) and biological productivity is not straightforward. In addition, changes in the isotope ratio or elemental composition of the bulk oceanic reservoir and post-depositional changes cannot be ruled out and may affect the sedimentary record (Montoya, 1994).

Reconstruction of productivity from organic biomarkers

Algal class structure is intimately related to overall water productivity and nutrients. Knowledge of the phytoplankton community can help distinguish high productivity from low productivity areas.

Marine phytoplankton, zooplankton and bacteria all synthesize a large number of organic compounds, many of which are taxon specific. The relation between the occurrence of certain compounds (biomarkers) and abundance of particular phytoplankton groups has been utilized to distinguish between marine and terrestrial organic matter and, in principle, could be used to reconstruct community structure.

Efforts to develop these proxies are underway; however, diagenesis is a major hurdle for quantitative reconstruction. In addition, the extraction of specific organic compounds from bulk sediment using solvents results in only partial recovery and the resulting extracted fraction may not be necessarily representative of the total organic matter.

Summary

Although ocean productivity is very important for understanding the operation of the global carbon cycle at present and in

the past, reconstruction of past ocean productivity patterns using empirical relations derived from present-day ocean characteristics is not a trivial undertaking. Each one of the proxies (methods) developed so far, although it contributes to our overall knowledge, has important limitations and therefore the best approach is to use multiple proxies (Figure O22). Critical evaluation of the validity of assumptions associated with each existing proxy and development of additional proxies will result in more robust reconstructions of paleoproductivity and understanding of the coupling and feedbacks between productivity, tectonics, and climate.

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Cross-references

Animal Proxies, Invertebrates
 Carbon Cycle
 Carbon Dioxide, Dissolved (Ocean)
 Carbon Isotopes, Stable
 Carbonate Compensation Depth
 Coccoliths
 Diatoms
 Dinoflagellates
 Foraminifera
 Geochemical Proxies (Non-isotopic)
 Iron and Climate Change
 Marine Biogenic Sediments
 Marine Carbon Geochemistry
 Organic Geochemical Proxies
 Paleoclimate Proxies, an Introduction
 Paleooceanography
 Phosphorus Cycle
 Stable Isotope Analysis
 Transfer Functions

OCEAN PALEOTEMPERATURES

Ocean paleotemperatures are the principal characteristics of past ocean scenarios. Over geological time, ocean temperature patterns underwent large changes, responding on long timescales ($\times 10^6$ yr) to different plate tectonical configurations, favoring either circum-equatorial flow and promoting a generally warmer ocean, or circum-polar flow with steep low-to-high latitude temperature gradients. On shorter timescales ($\times 10^4$ – 10^5 yr), ocean temperatures respond to insolation changes controlled by Earth orbital parameters which determine the amount of radiation the Earth's surface receives. High-amplitude, short-term temperature fluctuations are superimposed on decadal-to-millennial time scales and match the short-term temperature fluctuations recorded in Greenland ice cores during glacial times. This is a recent discovery that has immediately focused interest in climate research because of the potential analogy to human-induced climate change.

Because ocean temperatures are a key component of the climate system, deciphering ocean paleotemperatures from “marine climate archives” reflecting the climatic state of the Earth continues to be a longstanding aim. Sea surface temperatures

(SSTs) exert an immediate impact on the atmosphere, driving atmospheric circulation in terms of heat and moisture transport, and oceanic-atmospheric gas exchange. Moreover, aside from salinity, temperature determines the density of surface water, which drives thermohaline deepwater circulation. Thus, paleo-SSTs allow conclusions to be drawn about oceanic and atmospheric circulation. Deepwater temperatures depend on the loci where they are formed by sinking of dense surface waters; paleo-deepwater temperatures reflect the state of thermohaline circulation.

Different concepts are used to reconstruct water temperatures of past times, including micropaleontological, stable isotope, biomarker, and geochemical approaches. Several micropaleontological and geochemical data sets have been calibrated with the aim of yielding quantitative paleotemperature proxies. A variety of studies of past ocean scenarios (e.g., of the Last Glacial Maximum, Cenozoic warm climates), based on paleotemperature proxies, has greatly improved our understanding of the climate system over the last few decades. In particular, ocean paleotemperatures may serve as boundary conditions to initiate and validate climate model calculations that aim to predict the magnitude of future global warming.

History

Geological and paleontological studies aiming to reconstruct Earth's climate are perhaps as old as these disciplines. The oldest paleoclimate records based on marine fossils from land outcrops date back to the late eighteenth and early nineteenth century, when Cretaceous boreal, tropical, and austral provinces were identified in mollusk, ammonite and other faunas and changes in biogeographical distribution patterns were interpreted in terms of climatic change (e.g., Hutton, 1795; Cuvier, 1817).

The earliest climate records aiming for quantitative temperature reconstructions from microfossils were based on the identification of key species in Pleistocene marine sediments; species that could be related to climate zones (e.g., Phleger et al., 1953). However, it was not until the second half of the twentieth Century that an array of studies on the biogeographical distribution of modern planktonic foraminifera in the world ocean and in marine sediments became available, the potential of this species group as a tool for climate studies was discovered (e.g., Bradshaw, 1959; Bé, 1977; and others), and a conceptual framework for quantitative faunal approaches was found (Imbrie and Kipp, 1971).

Stable isotopes began to flourish as a tool in paleooceanography in the mid-twentieth century. Urey (1947) first explored the potential of oxygen isotope fractionation in natural carbonates as a paleotemperature indicator. Epstein et al. (1953) established the first paleotemperature equation based on oxygen isotopes. They found a 0.2‰ decrease in oxygen isotopic composition (expressed as $\delta^{18}\text{O}$) per 1 °C temperature increase for mollusk calcite. Emiliani (1955) published the first “paleotemperature records” based on $\delta^{18}\text{O}$ variations of foraminifera in Caribbean sediment cores, which he interpreted purely in terms of temperature fluctuations of 6–8 °C. However, it was yet not fully recognized to what extent the oxygen isotopic composition of the ocean changes through time. Shackleton (1967) discovered $\delta^{18}\text{O}$ fluctuations of similar amplitude in benthic foraminifera of the deep Pacific where deepwater is continuously close to freezing temperature. Here it became evident that the major portion of the $\delta^{18}\text{O}$ fluctuations observed in deep sea sediments are a result of waxing and waning continental ice