Late Cenozoic Climatic Changes as Recorded by the Equatorial Current System

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Abstract

A method has been developed for using deep sea deposits as records of oceanic productivity and its changes. The sequence of sediments below the Equatorial Current system indicates a marked periodical change in productivity with time. This periodicity is assumed to correspond closely to the world-wide climatic changes during late Pliocene and Pleistocene. It is thought that the method offers possibilities for an accurate and detailed study of the history of the late Cenozoic climate. An explanation is given of the reaction of the Equatorial Counter Current to climatic changes.

Since it became clear during the latter part of the last century that the present geological period is characterized by alternating cold and warm periods, intensive work has been carried out in order to reveal the details of climatic evolution. Several difficulties have been met with, among them is the fact that the climatic variations themselves have often disturbed the type sequences and thus distorted the records. This is the case especially in a glacial environment. In these regions of the continents where the climatic changes have not caused extremely marked changes of facies their effect has mostly been so complicated that it is difficult to interpret the variations in terms of climatic changes.

It is also difficult if not impossible to find on the continents, on their shelves or on oceanic islands, localities where all factors tending to change the environment except the climatic factor have been constant throughout Pliocene and Pleistocene time. Tectonic and volcanic disturbances are the most important ones in this respect.

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The ideal sedimentary profile for investigation of the late Cenozoic climatic changes should be situated far from the polar regions within which the violent facies changes interfere with the quantitative relationships. The environment of sedimentation should, moreover, be sufficiently extensive that the local influences can be easily recognized or be negligible.

Sediment profiles in such environments were first sampled by the German Deep Sea Expedition with the »Meteor». The pioneer work in deep sea biostratigraphy was carried out on this material by W. SCHOTT (1935) who was later followed by other workers, especially in the USA.

The present author's investigations on sediment cores, raised from the bottom of the Eastern Pacific during the Swedish Deep Sea Expedition 1947—1948, show that almost ideal conditions can be found in some, but not all, bathyal environments of sedimentation. The best relation between facies change and climatic change has thus been found in the equatorial region. This is easily understandable as the smallest displacements of facies bound-

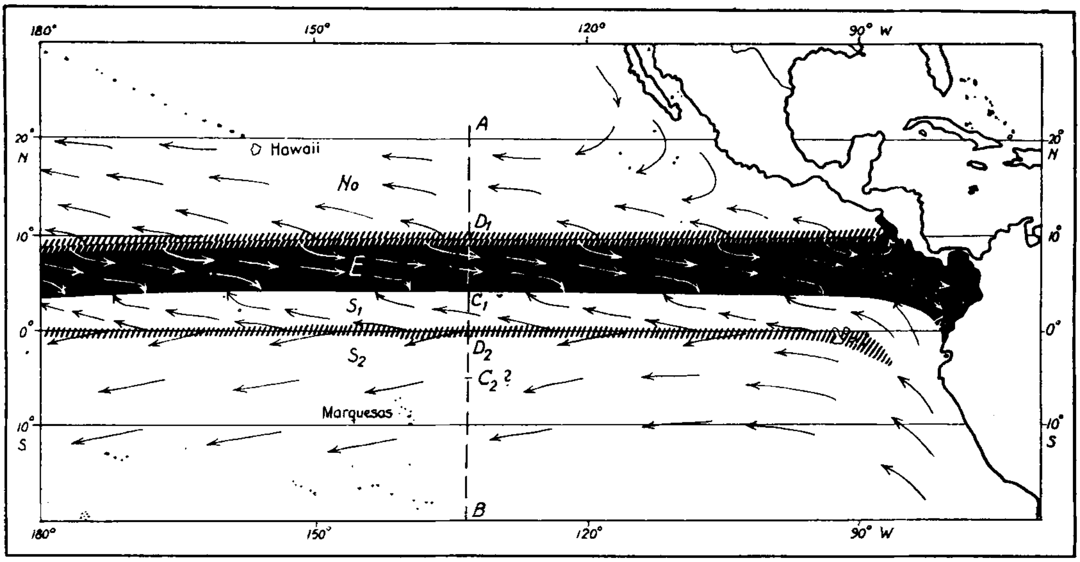

Fig. 1. The equatorial current system in the eastern Pacific. Arrows indicate schematically the direction of the surface currents. No North Equatorial current, E Equatorial Counter Current, S_1 northern and S_2 southern cell of the South Equatorial Current, N El Niño. Striped surfaces show distribution of cold upwelling deep water along the divergences. The figure refers to conditions prevailing during northern summer. D_1 and D_2 divergences, C_1 and C_2 convergences. C_2 is questionable and has hitherto not been recorded by oceanographical investigations. The possible existance of a secondary convergence at about 5° S is however indicated by the petrographical characters of the bottom deposit at this latitude.

aries will take place along the meteorological equator if simultaneous climatic changes are assumed in the Northern and Southern Hemispheres. The smallest effect of local disturbances has been found far from land in purely pelagic environments.

For the recording of the climatic events an additional factor is, however, necessary, viz. a sedimentation machine driven by an agent depending directly upon the global atmospheric circulation. The equatorial current system acts as such a machine and is maintained by the trade winds and thus, ultimately, by the thermic potential decrease between the equator and the poles.

Because of the important rôle of the Equatorial Current System, a brief summary will be given below of the dynamic relations, especially with regard to the Counter Current.

Strong currents are restricted to the surface layer of the oceans, whereas the movements of the deep water are believed to be very slow. In tropical regions the surface layer is heated by the radiation of the sun and the specific gravity of the water is therefore low. This lighter and warmer surface water is spread out over the deep water which is characterized by its high density due to the low temperature. The supply of nutrients such as phosphates, nitrates, silica, etc. is rapidly used up by the phytoplankton in the surface layer and transported down into the deep water as the dead organisms settle. The stable stratification prevents a rapid restitution of the nutrients to the surface through convection, and tropical waters are thus often characterized by a low plankton production and high transparency.

The trade winds drive before them the surface water thus giving rise to the Northern and Southern Equatorial Currents. Owing to the transport action of these currents, water is accumulated at the western borders of the oceans and a westward ascent in the ocean level is maintained in the tropical region. The accumulated masses of water find their way back to the East within the calm belt, thus forming the Equatorial Counter Current (fig. 1). As a result of the unequal distribution of the continents between the northern and southern hemispheres the line of symmetry

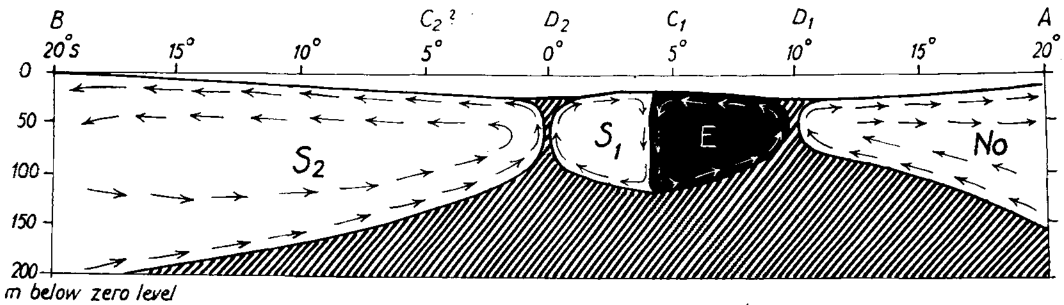

Fig. 2. Section through the equatorial current system along the meridian A—B in fig. 1. Indications as in fig. 1. Striped surface indicates the deep water body with tongues of upwelling. Zero level is arbitrarily chosen. Partly after SVERDRUP, JOHNSON and FLEMING (1946).

of the trade system and of the calm belt is displaced several degrees north of the geographical equator. Because of this the friction along the southern border of the current will be stronger than that along the northern border. An individual mass of water at the surface of the Counter Current will, therefore, not move straight eastwards but move over to the southern border of the current where it dives downwards and moves to the northern border on the under side of the current (fig. 2). A gyratory motion is thus superimposed on the eastward motion of the Counter Current, and owing to friction the adjacent masses of water of the Equatorial Currents are put into a similar but oppositely directed gyratory motion.

The existance of this mechanism is of decisive importance in the production of plankton in the equatorial region of the ocean. The upwelling along the divergences brings cold deep water rich in nutrients up to the surface, where the radiation from the sun makes an extensive assimilation possible. A strong production of plankton takes place, therefore, in the narrow divergence belts which run in the direction east—west across the oceans associated with the Equatorial Current System.

Further details of the dynamics and production of the present Equatorial Counter Current may be found in surveys and bibliographies such as in SVERDRUP, JOHNSON and FLEMING (1946). Detailed investigations based upon the material collected during the Swedish Deep Sea Expedition are at the moment being carried out by the hydrographers of the expedition, Dr. N. G. Jerlov and Dr F. Koczy.

The conditions for production of organic matter in the surface layer of the ocean greatly influences the bottom deposits. MURRAY and RENARD (1891) and REVELLE (1944) have pointed out the agreement between the path of the Equatorial Counter Current and the northern border of the Pacific Globigerina ooze area.

The present investigation of sediment cores from the Eastern Pacific confirms the correlation between distribution of currents and type of deposit. The biogenous component and simultaneously the rate of sedimentation increase strongly below the convergence C_1 (fig. 1 and 2), where a biolith, rich in fossils of foraminifera, radiolaria and diatoms is thus deposited.

The fact that the sedimentation is most intensive below the convergence in spite of the greatest production being found in the divergences (GRAHAM 1941) may be explained by fig. 2. The phytoplankton produced in the divergences D_1 and D_2 is assumed to be carried to the convergence C_1 where it is withdrawn from the euphotic zone, dies and settles (cf. JOHNSON in SVERDRUP e. a. 1946). The biogenous sedimentation also increases at latitude 5° S which might possibly indicate a secondary, hitherto unknown convergence at this latitude.

The abundant supply of organic matter below the Counter Current makes possible the existence of a comparatively rich bottom fauna. The activity of the mud eating animals is easily recognized in the sediment in the form of crushed shells (ARRHENIUS 1950 a), skeletal remains, coprolithes, digging structures, etc.

North of the convergence (C_1 in figs. 1 and 2) of the Equatorial Counter Current, the share of the biogenous component in the sedimentation decreases and the fossil-rich biolith turns into a clay, poor in fossils and with a low intensity of sedimentation (0—0.4 cm per 1,000 years). The boundary between the calcium carbonate ooze and the red clay area is astonishingly sharp and the diffusion caused by lateral transport of settling particles and by the seasonal changes in the path of the current system is obviously not big enough to disturb the general distribution pattern.

The sediment cores offer an opportunity for studying the changes in the Equatorial Current System during the Pliocene and Pleistocene epochs. For the recording of the displacement of the current path and of changes in the intensity of production the author has chosen to measure the absolute content of dominating fossils, integrity degree of foraminafera and size distribution of certain radiolaria (compare WEIBULL 1949) in the sediments, and the content of carbonates, humus carbon, nitrogen and phosphorus. Approximately 2,000 samples have been extracted, representing on an average each ninth centimeter of the East Pacific cores. Of chief interest here are the results of the quantitative microfossil investigations, as these clearly indicate a rhythmical change in plankton production with time. The concentration in the sediment of foraminifera, for example, shows that the present production is fairly low. In subrecent layers the concentration is higher and if we move backwards in time we will pass a marked maximum, a layer with decreasing concentration and then a minimum, obviously caused by a still lower production than the present one. Then follows a series of five maxima and minima of considerable amplitude and thereafter two maxima of a smaller order of magnitude. The two youngest maxima are the greatest, and both are complex with four to five subordinate peaks.

Of the minima the third from the top (the present one included) is the most marked. The minima are also often complex, the next youngest one shows, for example, a small but marked subordinate maximum. This stratification can be traced in an east — west direction over the whole area investigated, comprising approximately 4,800 km and the observations made by the author during the expedition indicate that the phenomenon is a global one. However, within the equatorial biolith belt marked latitudinal changes are obvious. In isochronous layers the highest concentrations are met with below the convergence of the Equatorial Counter Current. A tentative explanation of this has been given above. The greatest changes in concentration of shells with time are also found below the zones of downwards movement of the surface water. The content of shells of foraminifera $>150\,\mu$ varies in this environment between approximately 900 and 30,000 shells per gram of air dry sediment.

Below the ten meter thick layer series which is characterized by strong variations in the supply of plankton, the content of shells decreases to 500 to 1,000 shells/g sediment and the marked stratification mentioned above disappears. These lower layers are believed to be of late Pliocene age.

North of the convergence of the Counter Current the concentration of fossils in the sediment decreases rapidly as has already been mentioned. A sediment core at latitude N 8°25′ longitude W 128° 48′ consists of a red clay, almost free from calcareous fossils. At a depth of 380 cm the clay changes gradually to a calcareous sediment with several hundred shells per gram. According to Dr. F. Brotzen, the benthonic foraminifera indicate that this fauna is very likely to be Tertiary. Stratigraphically these layers are associated with the series mentioned above, which as assumed to be late Pliocene. At latitude N 13° 17′, longitude W 127°25′ a ten meter long core appeared to consist entirely of red clay, poor in fossils. The Tertiary area with a comparatively high plankton production has thus a northern border somewhere between N 8° 25′ and N 13° 16′. This limit is approximately parallel with the border of the present production belt.

In this connection it may be mentioned that a secondary dissolution of calcareous shells in red clay facies should probably not be ascribed the great importance often given it. Secondary dissolution influences all the more the final distribution of radiolaria and diatoms, especially in sediments low in calcium carbonate. The final distribution of planktonic foraminifera in bathyal deposits is believed primarily to depend upon the production in the surface layer of the ocean and upon the crushing by mud eating bottom organisms.

The general sequence of the Pacific deep sea deposits presented above indicates that the equatorial production belt of the ocean surface was comparatively broad during late Tertiary time but produced farily small amounts of plankton. The transition to Pleistocene time involved the Counter Current becoming compressed and that the intensity of production increased. This effect is believed to have been caused by an intensification of the trade winds. Such an intensification ought to have caused an increased transportation of water by the Equatorial Currents and by the Counter Current and therefore an increased upwelling in the divergence belts. If this was in fact the case the strong rhytmic changes in plankton production recorded in the Pleistocene part of the sequence ought to have been caused by changes in the strength of the trade winds and thus ultimately by periodical variations in the global distribution of atmospheric temperature and pressure.

The suggestion has been made elsewhere as an explanation of the obvious stratification also observed in equatorial areas other than the Eastern Pacific — that the Equatorial Counter Current was subjected to considerable latitudinal displacements during the Pleistocene climate changes. This hypothesis is clearly contradicted by the results from the investigation of the East Pacific sequences, which indicate great constancy in the path of the Counter Current throughout Pleistocene time. The stability of the location of the current is explained by the theory outlined above regarding the reaction of the Counter Current to simultaneous intensity changes of the northeast and southeast trade winds. Reinforced trades will ultimately have a compressing effect upon the Counter Current, but this effect will be increasingly counteracted by the swelling of the current due to the more intensive transportation of water. At a certain intensity of the trade winds equilibrium is practically attained, where an increase in intensity does not markedly influence the breadth of the current. This approximate equilibrium appears to have been established during the climatic change at the transition between the Pliocene and Pleistocene epochs. It is very likely that smaller displacements of the current system took place later, but they are too insignificant to be recorded by the net of stations of the Swedish Deep Sea Expedition. The lack of significant displacements of the Counter Current during Pleistocene time appears to be a definite proof that the climatic changes were synchronous in the Northern and Southern Hemispheres. The results presented here are thus in conflict with the heat distribution theory of climatic changes put forth by Milankovitch e. a. (see for example survey in ZEUNER 1945). If the Simpson hypothesis (SIMPSON 1934, 1940) is applied to the present results, each major production period should correspond to two glacial and two interglacial ages. Simpson's theory would thus demand twelve or more glacial periods. At present it seems more probable, therefore, that each glacial period corresponds to one single period of intensified atmospheric circulation.

What has been said above regarding the stability of the Counter Current's location during quarternary refers only toopen ocean areas where the current runs undisturbed by continental coasts and archipelagos. Off the South American coast the periodical intensifications of the Counter Current's transport of water have probably resulted in corresponding expansions of El Niño (fig. 1) to the south. The material of the Swedish Deep Sea Expedition does not, however, include cores permitting a study of such changes.

Changes in the species distribution of planktonic foraminifera recorded in pelagic equatorial deposits have hitherto been interpreted as caused by cooling of the surface water due to decreased radiation from the sun or to invasion of cold water from higher latitudes. The present results make it probable that changes in the temperature of equatorial surface water in the oceans may be largely due to changes in the upwelling of cold deep water. Changes in distribution of planktonic species will, therefore, be a complex result of variations in temperature and in the supply of nutrients.

Strong trade winds ought to indicate a great decrease in temperature from the equator to the poles and as a result hereof intense atmospheric circulation, whereas faint trade winds indicate the contrary conditions. Thus it appears to be highly probable that the changes in production in the Equatorial Current System correspond closely with the worldwide climatic changes, which characterize especially the Pleistocene epoch. Superior and subordinate maxima should in this case correspond to ice ages and subages whereas minima should indicate interglacial ages and subages. If this interpretation is correct, petrographical and paleontological investigations of pelagic bathyal deposits influenced by the Equatorial Current System should permit a much more detailed study of the history of the Late Cenozoic climate than has hitherto been possible.

This paper is to be regarded as preliminary. The complete presentation of the East Pacific material including analyses and stratigraphical correlations will follow in the Reports of the Swedish Deep Sea Expedition.

The programme for working on the East Pacific investigation has been summarized elsewhere (ARRHENIUS 1950 b).

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