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OCEANIC CIRCULATION CHANGES AND CONTINENTAL DRIFT AS THE MAIN POSSIBLE CAUSES OF PALAEOCLIMATIC VARIATIONS AND ORGANIC EXTINCTIONS

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RESUMEN

La distribución de océanos y continentes y el patrón de circulación de corrientes oceánicas han cambiado durante el transcurso de la evolución de la Tierra. Dichos cambios, a su vez, han constituido las causas fundamentales de las variaciones del clima y de los cambios evolutivos. Dentro de los procesos relacionados se tienen: procesos de tectónica de placas, tales como esparcimiento del fondo oceánico y fragmentación de continentes; procesos oceanográficos tales como transgresiones y regresiones y débil circulación oceánica; y procesos climáticos tales como clima caliente y homogéneo y desaparición de las cubiertas polares de hielo; procesos de generación y preservación de hidrocarburos; procesos orogénicos; y procesos relacionados con el campo magnético terrestre.

ABSTRACT

It seems that the evolution of the changing ocean-continent distribution and the oceanic circulation pattern have played a fundamental role in the main climatic and taxonomic changes. It is suggested that there is a link between plate tectonic processes such as rapid sea-floor spreading and continental fragmentation, oceanographic processes such as marine transgressions and weak oceanic circulation, and climatic processes such as homogeneous and warm climate with no permanent polar ice covers. The interrelated phenomena may also include other processes such as ice ages, orogenic events, oil generation and preservation, and geomagnetic fluctuations.

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INTRODUCTION

Several different relationships have been proposed between organic behaviour, vulcanism, tectonism, climate, glaciations, sea-floor dynamic depositional processes, plate tectonic events, and geomagnetic variations. Geomagnetic variations have been suggested to affect living organisms so as to produce evolutionary changes (Crain, 1971). Direct effects on common day-life functions of some organisms produced by geomagnetic variations have been shown to exist (e.g., Brown *et al.,* 1960; Barnwell and Brown, 1964; Blakemore, 1975). These relationships also are claimed to affect weathering processes (Fleisher, 1976). Other workers have suggested that geomagnetic reversals are associated to plate tectonic processes (Vogt, 1975), to volcanic activity (Watkins, 1965), and to meteorite impacts (Glass and Heerzen, 1967). Geomagnetic variations have been linked to tectonic activity, ocean floor spreading, continental drift, and core and mantle phenomena (Hide, 1967). Several geomagnetic phenomena have been associated to climatic variations (Urrutia Fucugauchi, in preparation). Geomagnetic polarity changes have been associated to volcanic activity and faunal extinctions (Kennett and Watkins, 1970). Geomagnetic polarity changes are related to climatic changes where the causal link is assumed to be global ice volume changes (Doake, 1978). Glaciation and deglaciation processes affect the sea level, thus affecting the tectonic and volcanic activity (Matthews, 1969). Sea-floor depositional processes have been associated to climatic factors (Amerigian, 1974). The literature on these subjects is growing rapidly; so one may wander what the cause and effect of these relationships are, if any.

The purpose of this work is to examine some of these possible relationships on a geological time scale and in a global context. It is my contention that all processes mentioned may be closely related and that in explaining e.g., evolutionary changes or climatic variations, many causes should be invoked. However, a separation into short- and long-term factors may be possible, and although their relative importances at any given place and time may vary, in a wider context the predominant factors could be distinguished.

EVOLUTIONARY CHANGES, GEOMAGNETIC FLUCTUATIONS AND CLIMATIC VARIATIONS

The correlation between magnetic polarity reversals and the extinction and/or radiation of marine microorganisms and climatic changes as reported from studies of deep-sea sedimentary cores (e.g. Harrison and Funnel, 1964; Opdyke *et al.,* 1966; Hays, 1971; Wollin *et al.,* 1971*a*, 1971*b*) has long provoked controversy (Wadington, 1967; Black, 1967; Harrison, 1968, 1974; Amerigian, 1974). There is now an extensive literature on the effects of the Earth's magnetic field in several phenomena (e.g., climate, cosmic radiation, biomagnetic behaviour) which, either directly or indirectly, may have exerted a selective influence on life on Earth.

Uffen (1963) and later Simpson (1966) suggested that a possible linking mechanism to explain the correlation between organic extinctions and geomagnetic polarity transitions was that during the transitions the field intensity is reduced to a low value and the cosmic and solar radiation, normally shielded by the magnetic field, is allowed to reach the Earth's surface. The higher radiation doses then cause higher mutation rates and an evolutionary discontinuity. This possibility was later considered unlikely as it was shown that the estimated increase in mutation rate would be small and insufficient to cause significant changes (Black, 1967; Waddington, 1967; Harrison, 1968). Other causal mechanisms to relate polarity transitions and evolutionary changes have been suggested. Crain (1971) proposed that direct biological effects of the Earth's magnetic field were acting on living organisms and that strong geomagnetic variations may therefore cause evolutionary changes. Harrison (1968) proposed that geomagnetic polarity transitions affect the climate, and indirectly the climatic changes produce evolutionary changes. Kennett and Watkins (1970) suggested that volcanic maxima at polarity transitions could affect the climate and hence the organic evolution. Regardless of the problem of finding an acceptable explanation, studies of correlations between geomagnetic variations, evolutionary changes and climatic variations have continued (e.g., Hays *et al.*, 1969; Harrison and Funnell, 1964; Opdyke *et al.*, 1966; Hays and Opdyke, 1967; Opdyke and Foster, 1970; Ninkovich *et al.*, 1966; Hays, 1971).

It is not certain, however, that the extinction and radiation of any marine species and geomagnetic variations are simultaneous all over the world. Hays (1971) cited, based on an extensive study of 28 deep-sea sedimentary cores, as evidence of the influence of the Earth's magnetic field in the development of life on Earth, the extinction of 6 species (from 8 examined) of Radiolaria near geomagnetic reversals. Unfortunately, from these species four lived in the Antarctic Ocean. two in the North Pacific, one in the Equatorial Pacific, and only one was in all three regions. It is interesting to note that this cosmopolitan species was one of the two species which did not become extinct near a geomagnetic fluctuation. For one of the species of the Antarctic Ocean Hays (1971) suggested the possibility that the species, or a very similar form, continued living in the North Pacific Ocean. Furthermore, Hays noticed that the number of extinctions was different in the different places, one in the Equatorial Pacific, one in the North Pacific, and four in the Antarctic; he stated, in spite of the fact that he favored the magnetic influence hypothesis, "Since there were, of course, the same number of reversals in both regions the response of the Antarctic fauna suggests that stresses other than magnetic reversals were important". Detailed stratigraphic correlations between deep-sea sedimentary cores are far from being well established, and most of the investigations have been completed with samples from one geographic locality (Harrison and Funnell, 1964; Opdyke *et al.,* 1966, 1972; Hays and Opdyke, 1967; Opdyke and Glass, 1969; Hays *et al.,* 1969). Furthermore, there is evidence that certain extinctions are not associated with geomagnetic changes, e.g., the extinction at the end of the Cretaceous period recorded in the Gubbio stratigraphic section, Italy (Alvarez *et al.,* 1977) is not close to any known geomagnetic fluctuation (Kent, 1977). It seems therefore that the diachronous extinctions of marine invertebrates may not be directly related to changes in the Earth's magnetic field, which are global in nature. On the other hand, recent investigations have suggested that land extinctions have occurred slightly later than marine extinctions (Butler *et al.,* 1977; Kent, 1977) and that terrestrial extinctions have also occurred at different times in different places (Van Valen and Sloan, 1977).

Evidences of a possible correlation between geomagnetic variations and climatic variations have also been found somewhat independently of the phenomenon of evolutionary changes. Some of the work done is discussed elsewhere (Urrutia Fucugauchi, in preparation) and only some points will be mentioned here. There is increasing evidence for a correlation between climatic variations and geomagnetic variations. The evidence is coming from a variety of sources, e.g., records of deep-sea sedimentary cores, archaeological evidences, historical observations of climatic changes, and recent short-term direct observations of geomagnetic and climatic variations. At present, there are some viable mechanisms proposed which may explain the correlations. Evidences that these relationships have been the predominant ones on a geological time scale are, however, far less convincent; mainly because of the difficulties in obtaining reliable data and also because the number of factors involved increases. One of such factors is the changing ocean-continent distribution on time. At present this could be considered fixed and the geomagnetic variations-climatic changes relationship holds, but with a changing distribution the situation is likely to alter. It is here suggested that this element is strongly controlling the relationships found.

The effects of changing ocean-continent distributions on life and climate have been evaluated in many works (e.g. Hallam, 1967; Valentine, 1971; Valentine and Moores, 1972; Robinson, 1971; Fooden, 1972; Jardine and McKenzie, 1972; Berggren and Hollister, 1972). These studies have shown that a good correspondence exists between major plate tectonic events and palaeoclimatic and evolutionary changes. However, some inconsistencies have also been found (Meyerhoff, 1970). Figure 1 (c and d) shows a correlation between rates of taxonomic change and major plate tectonic events; this correlation is also shown in Table 1 (Flesse and Imbrie, 1973). From these results we can observe that some taxonomic changes are not associated with known tectonic events and that some tectonic events do not correspond to known taxonomic changes. although this situation may be due to in-complete data, which perhaps be never filled in because of the fragmentary nature of the geological record, it may alternatively indicate that causes other than changes in the ocean-continent distribution are significative at certain times and places.

From the many possible effects that a changing ocean-continent distribution could produce, which in turn may effectively control the climate, an effect which is likely to produce profound climatic and organic alterations lies on the sea-level variations (Hallam, 1971; Hays and Pitman, 1973) and the changes in the oceanic and atmospheric circulation patterns.

The oceanic circulation pattern is strongly controlled by the presence of the polar ice covers. If for instance, the present ice covers dissappear, the oceanic circulation would be considerably much weaker than the present circulation. It has been suggested that no permanent ice covers may form when the geographic pole zones are occupied by oceanic plates (Ewing and Donn, 1956; Donn and Ewing, 1966). On the other hand, high concentration of land about the geographic pole zones would result in an ice age (Donn and Ewing, 1966). These arguments support the correlation found by Spjeldnaes (1961). Ice ages are accompanied by marine regressions and cold climates (Spjeldnaes, 1961). The occurrence of ice ages during most of the geological time is fairly well documented (Holmes, 1965; Harland, 1964; Turekian, 1971; Steiner and Grillmair, 1973), and supported by great amounts of geological and geophysical data. Therefore, it can be assumed that the changing ocean-continent distribution about the geographic pole zones has strongly controlled the worldwide oceanic circulation pattern, even when glaciations did not actually developed. From a comparison of polar wander curves of all continental masses (Irving, 1977, Morel and Irving, 1978), it can be deduced that the geographic pole (palaeomagnetic pole) has occupied alternatively positions in oceanic and continental or nearly continental areas (Urrutia Fucugauchi, in preparation); thus it can be expected that the oceanic circulation pattern has been strongly modified during the Earth's history, with all its climatic and environmental consequences. Changes in relative ocean-continent distribution which do not affect the geographic pole zones are also likely to provoke modifications in the oceanic circulation pattern, but probably weaker than those associated with alterations in the polar zones (i.e., practical appearance and disappearance of oceanic circulation). In periods when the geographic pole zones were occupied by oceanic plates, widespread marine transgressions flooded great extensions of continental surfaces and created great extensions of shallow and tranquil marginal seas, ice caps were not present, oceanic circulation was weaker, and climate was nearly homogeneous and warm all over the world. Therefore, major evolutionary changes are likely to occur every time these conditions were altered by continental drift events about the polar zones. We may expect that major evolutionary changes would start in certain parts of oceanic areas as a consequence of continental movements and sea-floor spreading (accompanied by changes in the oceanic circulation pattern), and then extend to cover the whole world (with perhaps worldwide oceanic circulation and climatic changes). Within these major change periods, only relatively minor taxonomic changes may have occurred, and they may relate to small sea-level and oceanic circulation variations (Figures 1*a, b* and 5).

This picture is supported in particular by Kent's (1977) conclusion about the causes of the faunal change at the Cretaceous-Tertiary boundary observed at Gubbio, Italy. He stated that the causes "should lie in a process that initially and rapidly affected the marine faunal realm and only later, perhaps indirectly, caused the crisis in the terrestrial fauna". This is consistent with the preceeding discussion, and we may add that the present world climate is highly controlled by the heat capacity of the oceans (Newell and Weare, 1976). The hypothesis being presented also takes into account the observations of diachronous extinctions occurring in different places, and local extinctions where the species continued living in other parts of the world (e.g. Hays, 1971).

Additionally, continental fragmentation is accompanied by widespread transgressions, whereas continental assembly is accompanied by widespread regressions (Valentine and Moore, 1970). Also, marine transgressions and regressions can be caused by changes in the rate of sea-floor spreading, where periods of rapid sea-floor spreading may produce rise expansion reducing the volumetric capacity of the ocean basins (Hays and Pittman, 1973). Therefore, sea-level variations and oceanic circulation changes are related to plate tectonic processes. Finally, we may mention that Spjeldnaes (1961) showed that a worldwide correlation between climate and marine transgressions and regressions was present during the Ordovician and parts of the Cambrian and Silurian times, when regressions were represented by cold climate, whereas transgressions were represented by warm climate.

One of the most dramatic and well documented extinctions is the crisis occurred at the end of the Cretaceous period. The relatively warm and tranquil conditions of the extensive Cretaceous seas were drastically changed by the generation of a stronger circulation pattern, the formation of polar ice caps (which later advanced during the ice ages), and the modification of the world climate. During this time, it is documented a widespread transgression (Hays and Pittman, 1973). At this point it is of interest to note that the Late Cretaceous marine transgression extended from about 100 Myr to about 65 Myr, with a maximum between about 90 Myr and 70 Myr (Hays and Pittman, 1973), and that most of the world's oil (about 60%) was generated between 110 Myr and 80 Myr (Irving *et al.*, 1974). Thus, we may speculate that during the Late Cretaceous the conditions for oil generation were extremely favorable, probably as a result of the occurrence of numerous and extensive shallow seas with stagnant and anerobic conditions which resulted of the widespread transgression, warm climate and weak oceanic circulation pattern, enough only to provide the organic supply. At the end of this interval, tectonic processes of continental assembly which also produced marine transgressions (and associated phenomena) provided the necessary structural conditions for the preservation of oil (e.g., Dickinson, 1974). These conditions have been present at other geological times at different scale, as it is shown by the occurrence of worldwide oil deposits of different ages (Figure 5).

THE LATE PALAEOZOIC GLACIATION, PALAEOMAGNETISM, PLATE TECTONICS AND PALAEO-OCEANIC CIRCULATION

The hypothesis appears suggestive but there are still several problems to solve. To illustrate the point that the presence of continental plates or small enclosed sea basins may be a necessary but not a sufficient condition to occur, some aspects of the Late Palaeozoic glacial age are examined. It should be mentioned that the arguments refer to the glacial stages or fluctuations within a glacial age and also to the initiation and ending of a glacial age.

The Late Palaeozoic glacial age has been extensively studied by many workers (e.g. Crowell and Frakes, 1970, 1971*a, b,* 1972, 1975; Frakes and Crowell, 1969, 1970; Frakes *et al.,* 1971, 1975; Robinson, 1969; Kemp, 1975; Martin, 1961; David, 1950; Harrington, 1956). The presence of this glaciation over several areas dispersed in South America, Africa, Australia, India and Madagascar was recognized long time ago (DuToit, 1921, 1937; Martin, 1961) and in fact information on this glacial age added considerable support to the ideas of continental drift and the possible existence of Gondwana (Wegener, 1924). More recently, information on the plate tectonic evolution of Gondwana has been used to study the Late Palaeozoic glaciation. Despite the extensive studies, the nature of this glacial age remains unknown. Some workers have suggested that during that period a large ice sheet of continental dimensions was present (e.g. Ahmad, 1970; Robinson, 1969; Lindsay, 1970), whereas other workers have suggested the presence of smaller ice sheets located in different places with somewhat different evolutions (e.g. Crowell and Frakes, 1971, 1975; Frakes *et al.,* 1975; Hamilton and Krinsley, 1967).

It should be noted that if an enclosed basin or a large land mass over the polar zones were necessary and sufficient conditions for a glacial age, then during the early Cenozoic when the Artic basin was formed on the North polar zone a glaciation should be developed, yet this did not develop until practically the end of the Tertiary. This suggests that other causes are also important. Consequently it is of interest to check if during the passage of Gondwana across the South polar zone, glaciers were always present or not.

Figure 2 shows the location of major outcrops and basins of deposition of Late Palaeozoic glacial deposits in Gondwana (Kemp, 1975). The apparent polar wander path (APWP) for Gondwana (Embleton and Valencio, 1977) is also included which suggests an eastward movement of Gondwana across the South pole. Du Toit (1921) and later King (1962) had suggested an eastward shift of climatic zones in Gondwana. Recent evidence suggests that the glaciation started in South America during the Early or Middle Carboniferous and progressed eastward into Australia across Africa, India and Antarctica until the middle Late Permian (e.g., Crowell and Frakes, 1975). It is interesting to note that land was occupying the south pole from practically some time during the Late Ordovician, when glaciation took place in Africa and India, to some time during the Permian, and that southern Africa remained near the pole from the Late Silurian to the Early Carboniferous, and yet the main glaciation did not occur until the Early or Middle Carboniferous. The earliest evidence of glaciation has been found in isolated basins in several places of South America (McClung, 1975; Kemp, 1975). In southern Bolivia the glaciation started during the Early Carboniferous and ended during the Late Carboniferous (Helwig, 1972). Evidence of glaciation is also found in Argentina, for example, in the Paganzo basin where glacial deposits are near the base of the section of sediments deposited during the Early Carboniferous (Frakes and Crowell, 1969); later the Paganzo basin was filled by a thick sequence of continental sedimentary deposits (nowadays forming a red bed sequence) interbedded with some marine beds within the lower section. In the Brasilian basins like the Paraná basin the glaciation ended during the Early Permian (Rocha Campos, 1967). With respect to the possible ice movement directions, the evidence usually is ambiguous and shows a complex array of possible directions. In the Paraná basin ice moved possibly from the east (Rocha Campos, 1967) and from this dominant basin to the west and south into other basins. There were also some glaciers in the highlands of southwestern South America and the Pampas Ranges, west of the Bolivian basins (Crowell and Frakes, 1975; Frakes and Crowell, 1969). In southern Africa glacial deposits have been recognized in several basins (Frakes and Crowell, 1970; Crowell and Frakes, 1972). The studies suggest that the ice age began in the Early Carboniferous and ended rapidly in the earliest Early Permian. The ice moved from north to south in some places like in the Karroo basin and from east to west in other places like the Durban area (Crowell and Frakes, 1975). These authors have suggested the presence of some smaller ice centers in some areas like Zire, Gabon and the area east of lake Nyasa extending to Madagascar. In the Antarctica part of the evidence is covered by ice of the present polar cap. The ice age again started in the Early Carboniferous and ended in the Early Permian (Frakes *et al.*, 1971). From ice movement directional data Crowell and Frakes (1975) suggested a series of ice caps, and Lindsay (1970) suggested an ice cap of continental dimensions. In India the glacial.deposits are of latest Late Carboniferous age, though the timing of the glaciation is poorly known (Frakes *et al.*, 1975). The ice movement information is confusing and series of ice caps (Frakes *et al.,* 1975) as well as larger ice caps of continental dimensions (Robinson, 1969; Ahmad, 1970) have been suggested. Finally in Australia the timing of glaciation is from mid-late Carboniferous to the beginning of the Late Permian (Crowell and Frakes, 1971*a, b*). The information about ice movement is again inconclusive and opposite interpretations have been proposed.

The evidence is here interpreted in terms of an eastward movement of the glaciation across Gondwana (Figure 2), which could be constituted by series of local ice caps or ice caps of continental dimensions which started, grew, waxed and waned with time. Additional evidence that the ice cover came and went during this glacial age comes from records of sea level fluctuations. This agrees well with the model suggested here; as mentioned earlier the glaciation and deglaciation are accompanied by marine regressions and transgressions. Several stratigraphic studies on cyclic sedimentation patterns have suggested glacial control on sedimentary processes (e.g. Wanless, 1972). Cyclic sedimentary patterns or cyclothems have been recognized in Late Carboniferous and Permian rocks in many areas of the world. In Figure 3 an example of a cyclothem record from North America (Moore, 1964) is presented; this shows several sea level fluctuations for the Late Carboniferous and Permian times. Further evidence on the displacement of the maximum glaciation zone comes from comparing the sea level variation during this period with records on a geological time scale (Vail *et al.,* 1977; Wise, 1974), which show that the sea level did not varied in a drastic and significant form during the Late Palaeozoic indicating that a glaciation was present with migration of the zone of maximum intensity. Finally, we may mention that Gravenor (1979) has recently presented analyses of heavy minerals from different areas of Gondwana and stated a warning which also applies for this model. He stated (p. 1102) that "Finally, it should be pointed out that while migrating continental-sized ice sheets are envisaged as the best solution to account for the observed facts, at the same time such concepts does not rule out glacial centers starting to form ahead or on the sides of the advancing region of maximum glaciation, nor does it preclude ice caps remaining on its wake. It simply states that the heart land of Gondwana was covered in successive stages by glaciers of continental dimensions".

DISCUSSION

It seems that there is a link between plate tectonic processes such as rapid sea floor spreading, continental fragmentation and plate subduction, oceanographic processes such as marine transgressions and regressions, and weak and strong oceanic circulation, changing atmospheric and oceanic circulation patterns, climatic changes, glaciations and evolutionary changes. The interrelated phenomena may also include other processes such as orogenies, oil generation and preservation, and sedimentary depositional patterns. On a global scale such processes are likely to have internal causes and effects, and therefore, phenomena in the mantle, mantle-core and core are related to these more superficial processes (as it is implied by the plate tectonic model). This may explain the correlations between the variations of the Earth's magnetic field and certain phenomena described here. Another favourable aspect of linking plate tectonic processes, continental drift and oceanic circulation changes as the main factors of change is that they well explain the observed global sedimentary depositional pattern. Furthermore, it has been suggested that certain taxonomic changes may not be real changes but only an effect of the sedimentary record (e.g. Raup, 1972, 1976; Milner, 1977). In many studies of stratigraphic sections the apparent abrupt extinctions and radiations of organisms may then have to be attributed to imperfections in the stratigraphic records. The distribution of hiatuses in the sedimentary deposition record of the Equatorial Pacific has been explained in terms of oceanic circulation changes (Kennett *et al.,* 1972; Van Andel *et al.,* 1976). Ewing *et al.,* (1973) interpreted the sedimentary thickness distribution in the Atlantic ocean as a result of the oceanic circulation, glaciation and continental drainage patterns. Eastern palaeobasins generally contain thicker and more complete records of deposition of sediments (and of taxonomic records) than western palaeobasins. The actual sediment thickness in the Atlantic eastern basins is roughly 65 % of that in the western basins (Ewing *et al.,* 1973). Thus, hiatuses in the sedimentary record are also closely related to the processes discussed here and may have certain influence in explaining diachronous and local taxonomic changes.

With the improvement of simulation models of the oceanic circulation (Gill, 1975; Cox, 1975 Pond and Bryan, 1976), the possibility of computer modelling which include changes in geometry of ocean basins due to plate tectonic processes as determined from e.g. palaeomagnetic and sea floor spreading information, becomes highly attractive. Such an investigation is being in progress and the results will be reported elsewhere (Urrutia Fucugauchi, in preparation).

Donn and Shaw (1977) have recently shown by using the thermodynamic meteorological model of J. Adem (e.g., see Adem, 1964) that continental drift explains the main changes and features of the northern hemisphere temperature pattern since Mesozoic times. Thus, the fact that the changing ocean-continent distribution plays an important role in explaining most of the phenomena of the world producing a fairly coherent picture, is a working hypothesis, if only for its unifying characteristics.

CONCLUSIONS

Many different hypothesis to explain the palaeoclimatic and evolutionary changes have been proposed, many more than the ones mentioned here; reviews of some hypotheses can be found in Simpson (1966), Newell (1967), Rhodes (1967), Robinson (1973), and Flessa and Imbrie (1973). Obviously I do not deny the possibility that other mechanism not mentioned here may be the main cause of the palaeoclimatic and evolutionary changes. I think that most workers proposing specific mechanisms are aware of the complexity of the problems and that the solution may not be as simpler as it has been sought, but a complex one.

In figures 1, 4 and 5 are summarized some of the results discussed. From these figures and previous discussion, it could be emphasized the general overall correlation between the different phenomena.

Table 1. Plate tectonic events, palaeoceanic circulation changes, and marine and terrestrial fauna changes

Plate tectonic event	Oceanic circulation response	Marine fauna	Terrestrial fauna
Uplift of Gibraltar sill	YES	YES	YES
Central American strait closes	YES	YES	?
Strait of Gibraltar opens	YES	YES	?
East and West Tethys form	YES	NO	?
Asia-Africa close	YES	YES	YES
Artic Atlantic opens	YES	?	YES
Rio Grande rise and Walvis ridge subsidence	YES	YES	YES
Africa/South America separate	YES	YES	YES
South Atlantic opens	YES	YES	NO
Central American strait opens	YES	YES	?
? ? ? (Late Jurassic)	?	NO	YES
Eurasia/Africa separate	YES	YES	NO
North Atlantic opens	YES	YES	YES
Gondwana fragments	YES	YES	YES
Uralian suture, Pangaea forms	YES	YES	YES
Appalachian/Hercinian suture	YES	YES	?
? ? ? (Middle Carboniferous)	?	YES	YES
Acadian suture	YES	YES	YES
Caledonian suture	YES	YES	YES
? ? ? (Ordovician/Silurian)	?	YES	
Taconian trench	YES	YES	
Fragmentation of supercontinent	YES	YES	

Data after Flessa and Imbrie (1973) and Urrutia Fucugauchi (in preparation).

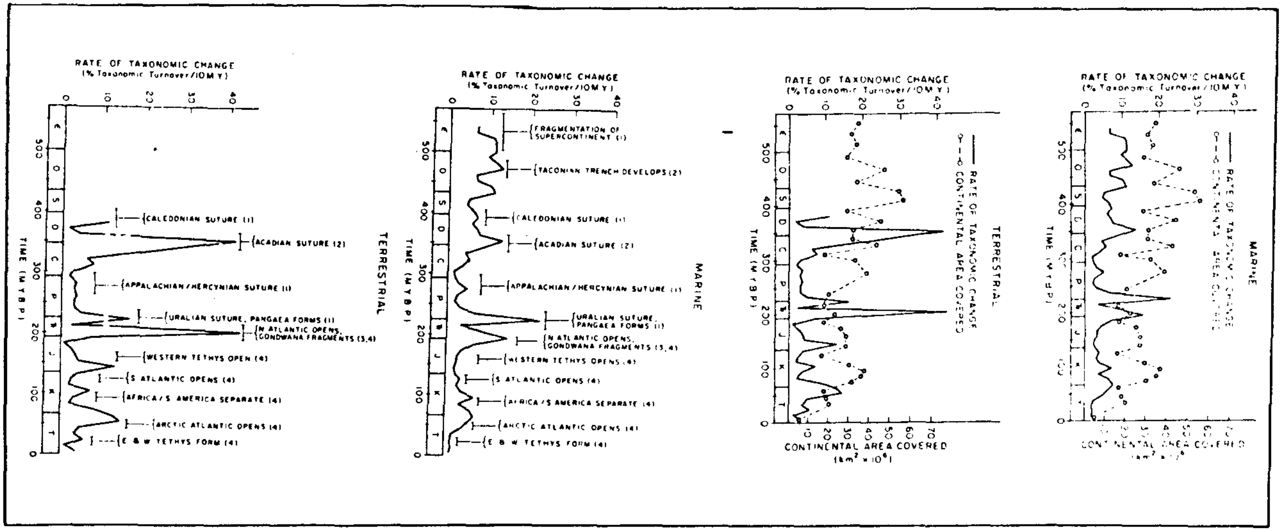

Fig. 1. Comparison between rates of taxonomic change (Flessa and Imbrie, 1973) and changes of continental areas covered by seas (Hallam, 1971) for marine fauna (a) and terrestrial fauna (b); and comparison between these taxonomic change rates and some major plate tectonic events (Valentine and Moore, 1972; Berggren and Hollister, 1972; Urrutia Fucugauchi, in preparation), again for marine fauna (c) and Terrestrial fauna(d).

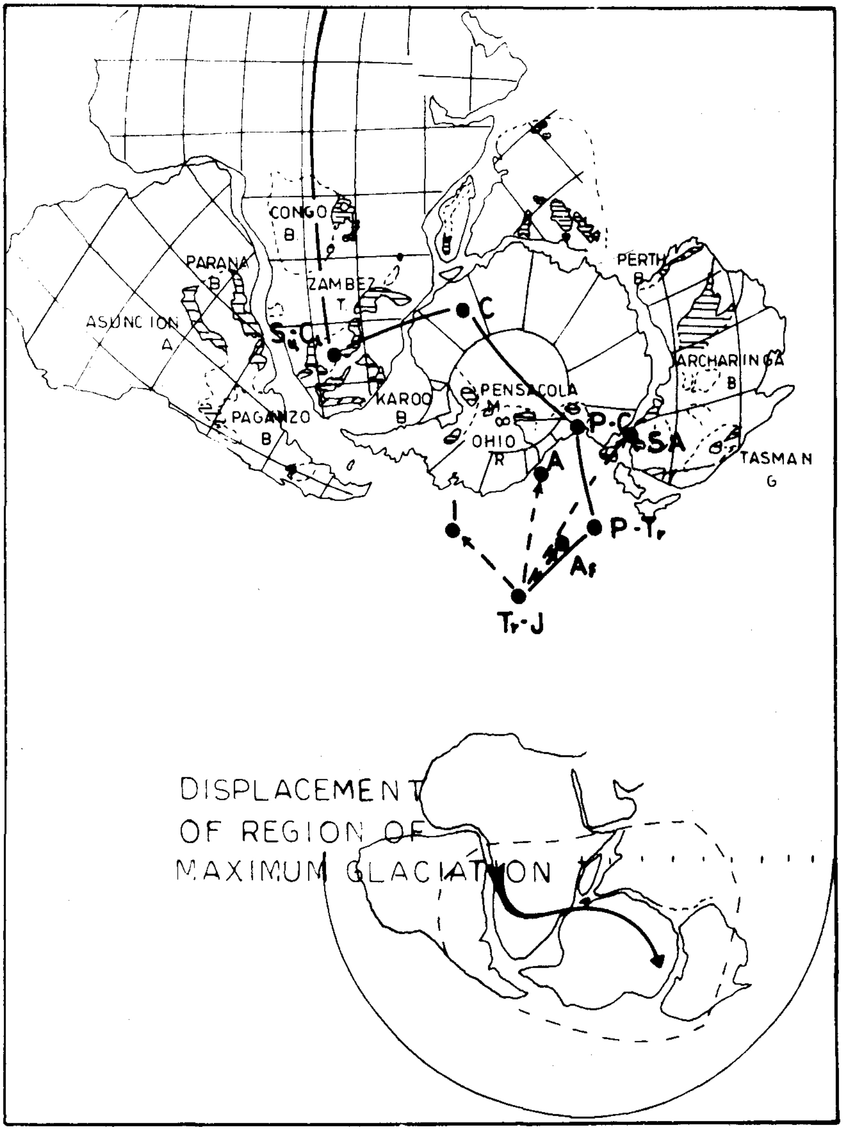

Fig. 2 The apparent polar wander path for Gondwana for the period Cambrian-Ordovician until Middle Jurassic (Embleton and Valencio, 1977). The curve represents the joint path for the several continental blocks of South America (SA), Africa (Af), India (I) and Australia (A). Mean pole positions are for Late Silurian-Early Carboniferous (S_u-C_1), Carboniferous (C), Permo-Carboniferous (P-C), Permo-Triassic (P-Tr) and Triassic-Jurassic (Tr-J). The post Middle Jurassic dispersion of pole positions indicates the break-up of Gondwana and subsequent drifting apart of the continental blocks. The location of major basins (B), troughs (T), ranges (R), mountains (M) and geosynclines (G) representing outcrops of Late Palaeozoic glacial deposits is included (Kemp, 1975). In the diagram on the bottom, the speculative maximum extent of the ice sheet and the proposed displacement of the region of maximum glaciation are plotted. See text. The palaeogeographic reconstructions used are after Smith and Hallam (1970).

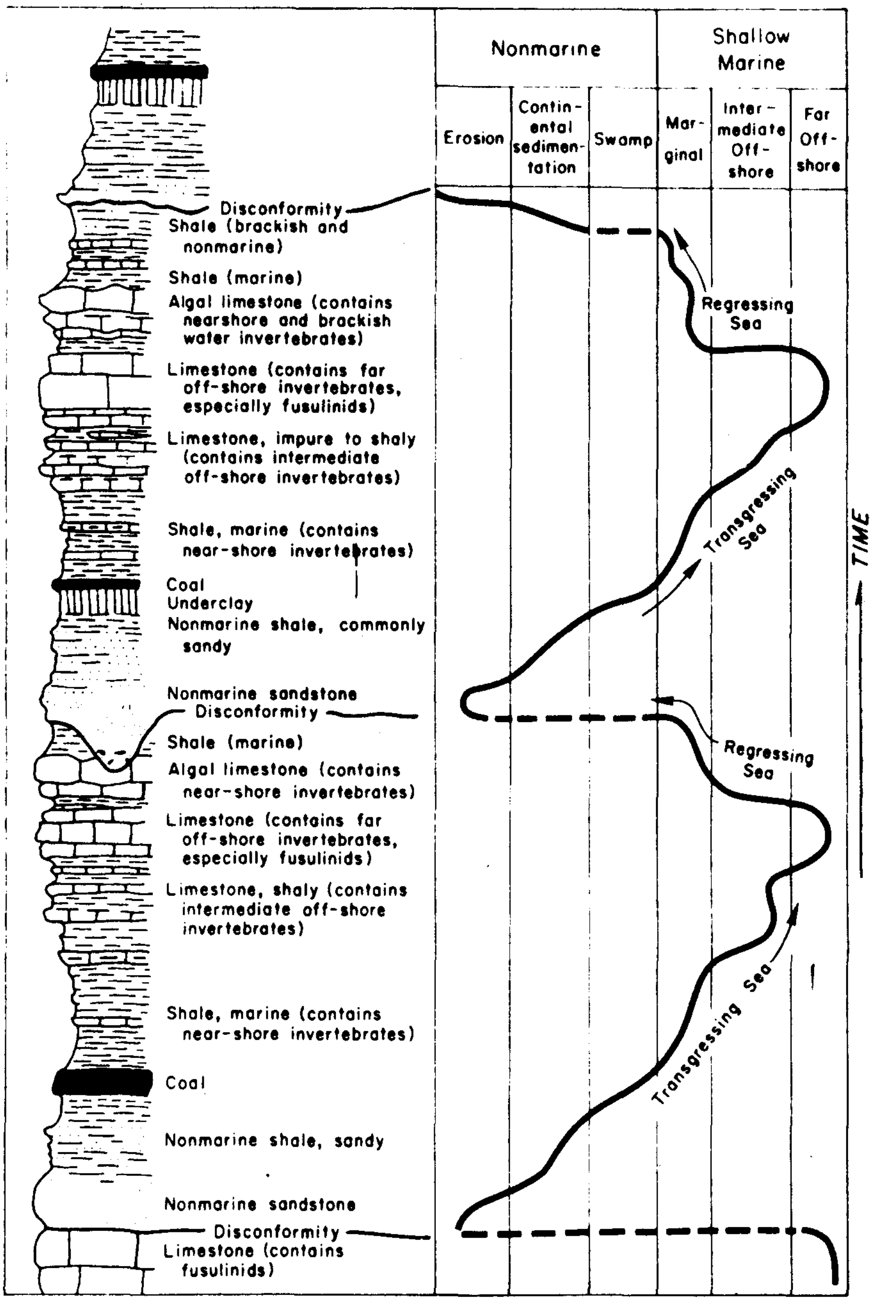

Fig. 3 Example of a cyclothem record from Pennsylvanian and Permian strata of Kansas, North America (Moore, 1964).

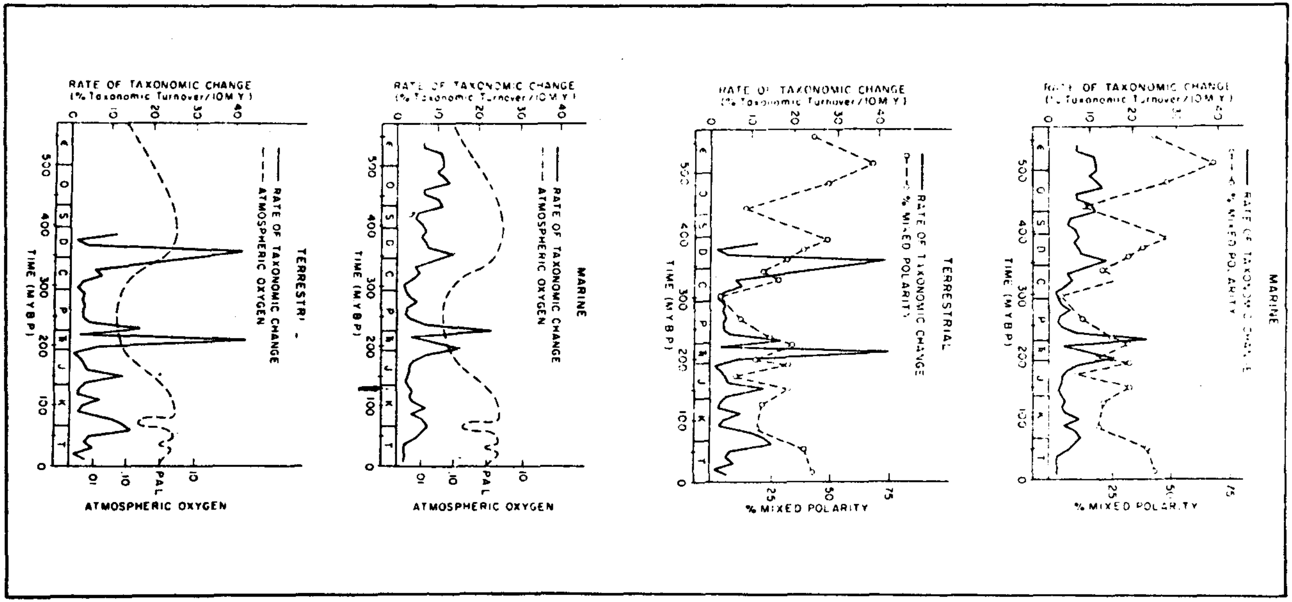

Fig. 4 Comparison between rates of taxonomic change (see figure 1) and percentage of mixed polarity of the Earth's magnetic field (McElhinny, 1973) for marine fauna (a) and terrestrial fauna (b). A similar comparison was presented by Crain (1971). Curves of mixed polarity which differ from this have been presented by other workers, e.g. Creer (1976). Comparison of rates of taxonomic change and the abundance of atmospheric oxygen (Tappan, 1968) for marine fauna (c) and terrestrial fauna (d). According to Tappan (1968) changes in atmospheric oxygen result from changes in continental physiography and phytoplancton productivity. These changes led to cummulative nutrient depletion, scarcity of food, marked reduction of microflora and increased carbon dioxide contents. The changes in phytoplancton productivity are related to sea level variations and oceanic circulation changes, as do the changes in continental physiography which are also related to plate tectonic processes.

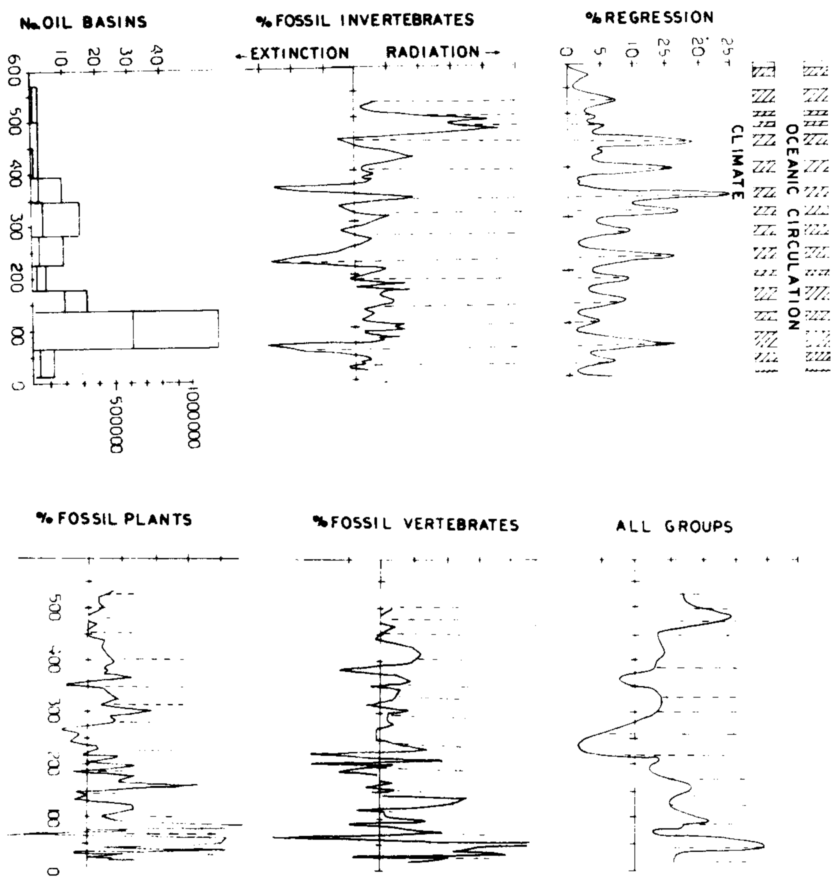

Fig. 5 Comparison between speculative changes of oceanic circulation and climate (a) (weaker circulation and cold climate are dashed, whereas stronger circulation and warmer climate are blank) with percentage of marine regression (b), percentage of fossil invertebrates (c), number of oil basins and average content of oil (d), percentage of all taxonomic groups, including fossil invertebrates and vertebrates and plants (e), percentage of fossil vertebrates (f) and percentage of fossil plants (g), (after Urrutia Fucugauchi, in preparation).

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