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Some problems in Southern Ocean palaeo-oceanography and palaeoclimatology

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The physical and climatological significance of the major features of the Southern Ocean are shown to be poorly understood. Applications of poorly-defined concepts to palaeo-oceanography and palaeoclimatology are accordingly weak. In order to make use of the abundance of geological information on the history of the Southern Ocean, specific definitions of the Antarctic Polar Front Zone, the Sub-tropical Convergence and the Antarctic Circumpolar Current are required. These preferably should be related to climatology so as to allow prediction of conditions for past times when both geography and climates were greatly different.

Introduction

In reconstructing past climates, geologists are forced to utilise very simplified models of the complex ocean-atmosphere system. This limitation arises in part from the general lack of synchronous data, but ordinarily does not impose harsh constraints on geologic interpretations which often are concerned only with broad regional or temporal trends. It is only for times of the very recent past that more detailed climatic patterns are achievable, or necessary. If almost nothing is known of climates elsewhere on a particular continent, detailed knowledge of climate in a small area is of little advantage. The need is rather more for the broad picture of palaeoclimates, to provide a background for understanding of past environments in general.

Palaeo-oceanography plays a prominent role in deciphering ancient climates because the most abundant climatic indicators are derived from marine environments. For example, the former extent of certain water bodies may be determined from the distribution in marine sediments of fossil micro-organisms which characterise the water body. However, even such an apparently simple task is made difficult by the need to ascertain that the historical record is 'unmixed' — that all indicators are of the same age within reasonable limits. With the highest quality of such proxy evidence, palaeo-oceanography is limited to defining the geographic configurations of water bodies of similar physico-chemical properties throughout, without necessarily specifying what these properties were. Palaeotemperatures, and sometimes palaeosalinities, may be estimated by various means, but generally only for surface and/or bottom waters and seldom so as to yield a composite picture of variation over a wide area.

In considering the palaeoclimates of the Southern Ocean, further limitations arise first from the fact that regional geography was different from now. The Antarctic Circumpolar Current (ACC) was not circumpolar in its operation before about 35 million years ago, due to the Drake Passage and the gap between Australia and Antarctica being closed. Also, both the Atlantic and the Pacific oceans were narrower at their southern ends. It is a major task simply to estimate the configuration of surface currents in such a geometry, and to go beyond this one needs to know something about temperature and salinity distributions, whether oceanographic structures such as the Antarctic and Sub-tropical Convergences existed and if so, what their positions were. A host of interesting and important problems relate to changes in oceanic circulation, and attendant changes in climates, as the gap south of Australia opened and widened. Geologic evidence provides some indication of these significant variations over time, but owing to imperfect knowledge about the modern ACC and difficulties in applying principles of oceanography and climatology to ancient settings, diverse options exist in defining environments of the ancient Southern Ocean.

Southern Ocean oceanography

A most succinct description of the Southern Ocean comes from Sverdrup et al. (1942, p. 605): 'In some instances the antarctic waters are dealt with as parts of the adjacent oceans and are designated the Atlantic Antarctic Ocean, or the Indian or Pacific Antarctic Ocean, whereas in other instances the antarctic waters must be considered an integral part of all oceans.' Nowadays the northern extent of a unified 'Southern Ocean' is commonly taken to be marked by the Sub-tropical Convergence, located at an average latitude of about 43°S, between 7° and 15° north of the mean northern boundary of the West Wind Drift (Zillman 1972). The physical significance of the boundary is uncertain as it is at least in part related to latitudinally-varying temperatures and to density balances of surface and intermediate water masses, as well as to surface wind stress. At the Sub-tropical Convergence, warm surface waters of the Pacific, Atlantic and Indian ocean sub-tropical gyre systems converge on cooler surface waters of the Subantarctic Surface Water (SSW) and a sharp temperature change results. Surface water masses north and south of the convergence are characterised by distinctive microfaunas and floras, a fact which enables geologists to map out their previous extent by studying the composition of fossils in the sediment column (e.g. Bé and Tolderlund 1971).

The prevailing westerlies of the high southern latitudes contribute to the Antarctic Circumpolar Current through wind stress at the surface. However, water motions of this sense extend to the seafloor, in depths locally exceeding 5 km, as a result of northward-inclined isobaric surfaces which owe their inclination to latitudinal temperature gradients. Flow at all levels therefore is from west to east. Sverdrup et al. (1942) calculated that with surface velocities of 15 cm/s near the Antarctic Convergence, this effect could produce significant water motions at least to depths of 4 km. Deflection of the ACC by seafloor topography is well-known, thus supporting this concept.

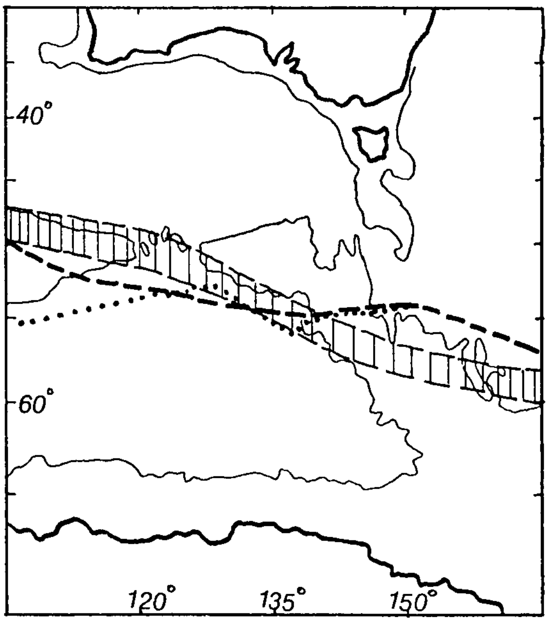
Embedded within the ACC is the Antarctic Convergence, where SSW converges with the Antarctic Surface Water (ASW). The structure normally is defined near the surface as a marked temperature drop towards the south, although the precise definition is quite variable (Deacon 1937; Gordon 1971; etc.). Also, the more common name now in use is the Antarctic Polar Front Zone (APFZ), a name which better suits the character of the structure. In the South Pacific and Indian oceans, Gordon (1967, 1972) recognised a zone of transition as wide as almost 4° of latitude and with marked temperature discontinuities at the boundaries. From a study of 200 m temperatures, Emery (1977) showed seasonal and longitudinal variations in the positions of the boundaries; such variations, also detected at depth as 'interleaving', probably indicate the presence of microscale thermal structures (rings, meanders) (Gordon et. al. 1974, cited in Emery 1977; Patterson and Sievers 1979). As would be expected, the biota of the Antarctic waters south of the APFZ differs substantially from that of the Subantarctic water mass.

The Antarctic Divergence marks the southern limit of the ACC, in that farther south the winds from the polar high-pressure zone are easterlies. Yet, given the fact that temperature gradients are unchanged and isobaric surfaces thus still are inclined to the north, it would be expected that intermediate and deep waters would flow to the east. This has not been demonstrated and represents another large problem of oceanography in high southern latitudes.

Southern Ocean sedimentation

The distinctive feature of sediment distribution in the Southern Ocean is the separation of northern (calcareous oozes) from southern types (siliceous oozes) by the APFZ (Frakes 1975). This separation is not complete as might be expected, but instead is gradational through mixed types of oozes. In fact, the APFZ tends to separate siliceous oozes from mixed oozes rather than from calcareous oozes in the region south of Australia. Lisitzin's (1972) data on suspended sediments in surface waters document a sharp transition from high proportions of siliceous micro-organisms to low abundances along a line nearly coincident with the APFZ (Fig. 1). It

Fig. 1 Important features of the Southern Ocean in the southeast Indian Ocean region. Band with vertical ruling represents the transition zone between southern surface waters containing more than 10 per cent and northern waters with less than 5 per cent amorphous silica (Lisitzin 1972, Fig. 139). Heavy dotted line divides southern siliceous oozes from mixed oozes containing carbonate to the north on the seafloor (Frakes 1975). Heavy dashed line is the Antarctic Polar Front Zone and thin solid line indicates the position of the 2000 fathom (~3600 m isobath).



commonly has been thought that this biological phenomenon represents a temperature effect, but the transition zone corresponds most closely with the APFZ which, as defined by Gordon and Goldberg (1970), delineates a salinity minimum band at 200 m depth. Temperature is no doubt important but its relative significance is not known; the problem deserves further work.

Sedimentation is also affected by the Sub-tropical Convergence although in just what manner is difficult to determine. In the southeast Indian Ocean the convergence is positioned approximately above the 4.5 km isobath, which is the dividing line between distinctive sediment types — foraminiferal oozes to the south and coccolith muds to the north. This isobath also approximates the calcium carbonate compensation depth (Frakes 1975). It is likely that sediment distributions reflect foraminifera abundance in the upper 300 m, as Bé and Hutson (1977) have indicated a considerable decrease in these micro-organisms to the north of the Sub-tropical Convergence and related this to nutrient distributions in the Indian Ocean. However, the relationship of the convergence to the carbonate compensation depth remains unexplained.

Palaeo-oceanography and palaeoclimatology

Generalisations about the character of major ocean features such as the APFZ, particularly as they affect sedimentation, can be used in reconstructing past climates. I emphasise here, however, that understanding of these modern oceanographic singularities is of primary importance in understanding their roles in controlling or reflecting palaeoclimates. It seems likely that we do not yet sufficiently comprehend the workings of Southern Ocean circulations to be able to infer their previous operation under markedly different geographic and climatic constraints. And yet, studies of the history of the earth clearly require an ability to make such applications. On the other hand, modelling experiments are now beginning to be helpful in some phases of this area of research and it is to be hoped that eventually what may be regarded as inconsequential by physical oceanographers and meteorologists will soon be accommodated in models of greater flexibility and scope.

In the meantime, geologists interpret their data from the Antarctic seafloor in keeping with several assumptions. First, the various convergences and divergences of the Southern Ocean give rise to environmentally-controlled biotas, which in turn generate distinctive sediment belts. The placement of these belts on the globe gives an indication of the climatic state of the earth, and changes in their positions signify changes in climate. By examining sedimentary sequences in cores from the seafloor, it is possible in some cases to discern such changes.

An example of this kind of work serves to illustrate the potential of the technique while at the same time showing the type of oceanographic-meteorologic-climatologic problems that result. From results of deep-sea drilling in the Southern Ocean in 1972, Kemp et al. (1975) established that ancient sediments in the region south of Australia consist of southern siliceous and northern calcareous types, in an arrangement similar to that of the modern situation. It is tempting to conclude that the APFZ or a similar feature was in existence for the last 40 million years or so. However, other factors not related to the APFZ may have contributed to biological dispersals and consequently to sediment distributions, and the conclusion is thus not warranted. On the other hand, whatever factors contributed, a strong temperature effect will have operated in biogeographic distributions and changes in the resulting sediment distributions are taken as indications of climatic change.

Kemp and her colleagues showed that about 40 million years ago calcareous (warm water) organisms characterised surface waters as far south as about 62°S lat. and that as the southeast Indian Ocean opened due to seafloor spreading, the southern boundary of this relatively warm water mass shifted gradually northward (Fig. 2). South of the boundary and near the continent, cooler-water micro-organisms of siliceous composition flourished; the northward migration of the boundary indicates latitudinal expansion of a cold water mass away from Antarctica. Expansion of the cold-water belt at about 4 to 6 cm/year, twice the rate of seafloor spreading, indicates a long-term cooling of high southern latitudes, assuming that temperatures at the boundary approximate those at the APFZ today. There is abundant independent evidence to support global cooling since 40 million years ago (Frakes 1979), although at irregular and poorly determined rates; the scenario here would allow calculation of an overall rate, providing reasonable assumptions could be made about the overall structure of the Southern Ocean during this evolutionary process. Such calculations might also reveal unknown properties of the APFZ and Southern Ocean palaeo-oceanography in general.

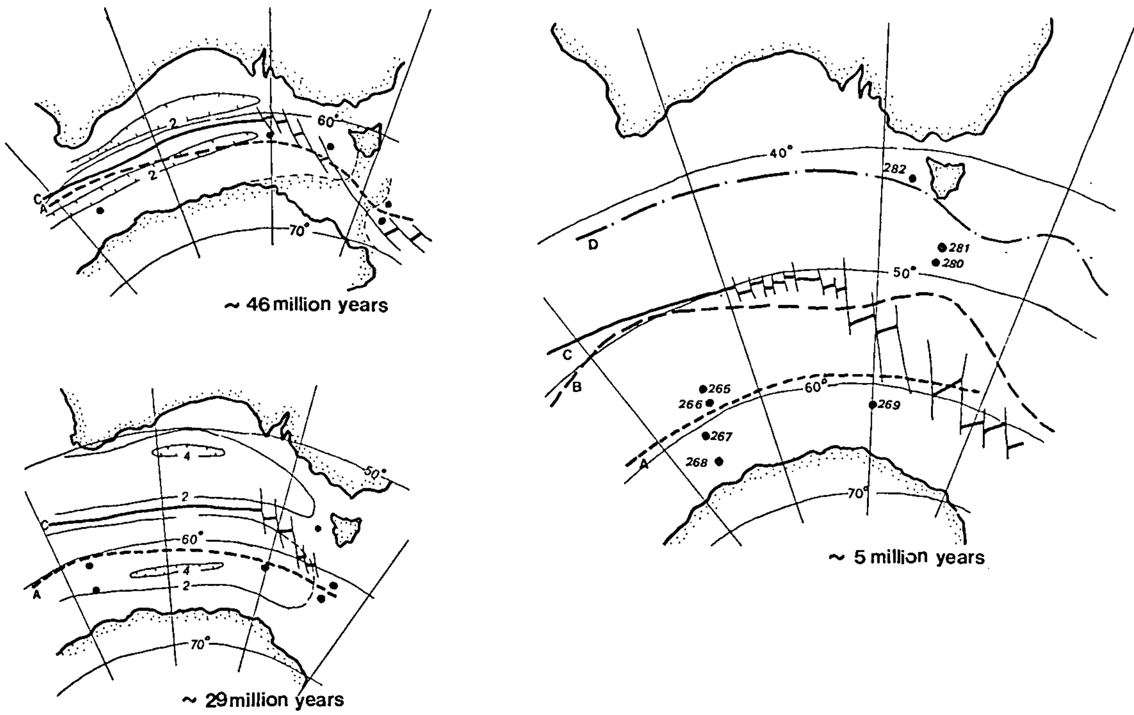
Another significant feature of Southern Ocean history is that at about four million years ago the calcareous-siliceous boundary moved abruptly northward over a distance of some 300 km, to the position now occupied by the APFZ (Kemp et al. 1975). At about this time the nature of the dominant calcareous organisms present also changed — from (the older) calcareous nannoplankton to (the younger) foraminifera. Since nannoplankton are now most abundant north of the Sub-tropical Convergence, this suggests that subtropical surface waters earlier abutted directly against the Antarctic Surface Water and that Subantarctic Surface Water only came into existence about four million years ago. Also, the Sub-tropical Convergence, as now known, would have originated at that time. We can be relatively confident that the APFZ came into being simultaneously; earlier it may have had different characteristics.

Figure 2 illustrates the stages of development of the ACC. Until about 25 million years ago circumpolar circulation did not exist due to blocking by continents. Australia and Antarctica were still joined and the Drake Passage had not yet opened. Independent gyre systems operated in the Pacific, Atlantic and Indian oceans, and the degree to which they were effective in transporting heat poleward no doubt contributed to middle and high-latitude climates. At about 25 million years ago these obstructions were removed and the ACC began to function. One of the important effects of change should have been to isolate Antarctica from large sources of warm surface water for evaporation and, hence, precipitation. Yet, the comparatively small ice volume on Antarctica increased enormously after establishment of the ACC, particularly in the interval since about fifteen million years ago. Schnitker (1980) explains this by development of North Atlantic Deep Water, which upwells near Antarctica thus providing a moisture source. Early construction of sizeable ice masses in the Pacific sector of Antarctica are not explained satisfactorily by this hypothesis.

Conclusion

The unresolved problems of Southern Ocean oceanography and climatology are magnified when one attempts to apply these techniques to palaeo-oceanography and palaeoclimatology. In many cases, the relationships between oceanography and climatology are too poorly understood to allow reconstruction of past climates, and yet geologists are forced to apply generalised concepts to their data. A few examppes of palaeoclimatological problems show that more comprehensive understanding of the interrelationships of such variables as temperature and salinity is required before the large-scale features of the Southern Ocean make sense, for the present time and for the past.

Fig. 2 Palaeogeography of the Southern Ocean in the southeast Indian Ocean sector, at about 46, 29 and five million years ago. A = Boundary between siliceous (south) and calcareous (north) oozes for the time interval specified. B = Antarctic Polar Front Zone at present. C = Approximate position of mid-ocean ridge crest. D = Mean position of Sub-tropical Convergence. At 46 million years, the gap between Australia and Antarctica is closed to the east and only a small part of the area is greater than 2 km deep (thin solid lines). By about 29 million years the gap has opened and the basins north and south of the mid-ocean ridge have deepened to more than 4 km (Deighton et al. 1976). At about five million years the siliceous-calcareous ooze boundary has migrated to a position north of 60°S Lat. The large shift of the boundary to a position coinciding with the modern APFZ took place soon after five million years ago.



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