A HISTORY OF ORGANIC SILICEOUS SEDIMENTS IN OCEANS

by A. T. S. RAMSAY

ABSTRACT. The distribution of oceanic organic siliceous sediments is considered from the Cambrian to the Recent. Mesozoic and Cenozoic cherts recovered by JOIDES from the Atlantic, Caribbean, and Pacific are considered as diagenetic derivatives of primary organic sediments rich in silica. A similar origin is also proposed for the deep-sea Mesozoic and Palaeozoic radiolarian cherts associated with ophiolites or eugeosynclinal black shales which are now contained in fold mountain belts.

Three distinct tectonic environments of ancient and modern oceanic sedimentation are recognized: a major ocean basin environment, an interarc or marginal basin environment, and an ensialic continental rise environment. The first two are comprised of oceanic crust which differs in its internal structure; crust generated in major ocean basins is characteristically sheeted, while the crust of marginal or interarc basins is layered.

The distribution of oceanic organic siliceous sediments through the past 500 million years can be explained in terms of three 'global' silica belts which in the Recent oceans are confined to areas of upwelling and high plankton productivity. This interpretation succeeds in reconciling, through space and time, the otherwise scattered remnants of ancient oceans.

Circulation patterns in the Late Mesozoic and Early Tertiary are discussed, and the occurrence of an equatorial zone of biogenic silica in the Cretaceous and Early Palaeogene is attributed to the circulation pattern which may have resulted from an open Isthmus of Panama. It is suggested that other sedimentary data which have been cited as evidence for major changes in circulation during the Palaeogene can be explained in terms of plate tectonics or fluctuations in the calcium carbonate compensation depth.

MOST of the papers included in this symposium volume attempt to relate the distribution of organic remains preserved in sediments which were deposited in ensialic sedimentary environments with the past positions of the continents. Unlike these contributions this paper is concerned with the distribution of biogenic radiolarian siliceous sediments, together with their diagenetic derivative chert, which were deposited in the deep sea.

The major modern environments of biogenic siliceous accumulation are well defined and are contained in three global belts characterized by high plankton productivity. These are restricted to areas of oceans where a combination of atmospheric and hydrospheric circulation leads to divergence of the surface water masses and consequently to an upwelling of nutrient-rich deeper water to the photic zone. The geologic record of these sediments, however, becomes increasingly fragmentary and more complex further back in time.

The more ancient records of these sediments are contained in radiolarian cherts, and not all geologists would agree with my interpretation that these sediments are the diagenetic alterations of primary organic deposits rich in opaline silica. Further problems in interpreting the ancient record are introduced by the distribution of sampled localities in the oceans (which are understandably centred on the equatorial regions) and by the almost complete obliteration of this record by processes involved in plate tectonics.

An analysis and comparison of the fragments of deep-sea basins which are preserved in the fold mountain belts with the structures of modern ocean basins suggests

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that it is necessary to consider three distinct tectonic environments of oceanic pelagic sedimentation:

1. Major ocean basin environment represented by sheeted ophiolite complexes which formed by spreading about the crests of mid-ocean ridges.
2. Interarc or marginal basin environment represented by layered non-sheeted ophiolites. This environment is similar to that of major ocean basins but is separated from these by an island arc and a consuming plate margin.
3. Ensialic continental rise environment.

Although all three environments are represented in the geologic record, the last two seem to be more frequently preserved in fold mountain belts.

Despite the complexity of the geologic record, the latitudinal pattern of opaline siliceous deposition in the Recent oceans provides a simple model with which the ancient record can be compared. In this account I describe, interpret, and comment on some of the physical and chemical parameters which may have influenced the distribution and nature of ancient sequences of organic siliceous and associated pelagic sediments during the past 500 million years.

In interpreting the distribution of these sediments through this interval of time, I adopt a strictly uniformitarian approach and consider their distribution in terms of three modern silica belts. This interpretation requires that major features of the global pattern of atmospheric circulation (i.e. westerly winds towards the poles, and easterly winds in the tropical belt) and consequently of oceanic circulation have remained constant through 500 million years; a reasonable assumption if one considers that the earth has always rotated, and was always characterized by a temperature gradient from the equator to the poles. The validity of this simple approach is, I think, vindicated by the results which reconcile, through space and time, what are otherwise scattered occurrences of sediments from the ancient oceans.

My comments on physical and chemical parameters in the ancient oceans are clearly speculative and represent opinions which may not be in accord with those held by other marine geologists.

THE DISTRIBUTION AND PRESERVATION OF ORGANIC SILICEOUS SEDIMENTS IN THE RECENT OCEANS

In the modern oceans the abundance of suspended opaline silica, as radiolarian tests, diatom frustules, and the less common skeletons of silicoflagellates in the surface waters (0–200 m) is determined by plankton productivity (Riedel 1959, Kozlova 1971, Lisitzin 1971). The highly productive regions of the oceans, which are also areas of maximum opaline siliceous sedimentation, are restricted mainly to latitudinal zones where the wind and current systems lead to a divergence of the surface water masses and consequently to an upwelling of nutrient-rich deeper water to the photic zone. Since radiolarians, diatoms, and possibly silicoflagellates are present in the plankton and surface sediments of most parts of the oceans (Riedel 1959, Casey 1971, Jouse *et al.* 1971, Kozlova 1971, Lisitzin 1971, Petrushevskya 1971) the global belts of opaline siliceous sedimentation reflect atmospheric and hydrospheric circulation and in this respect are independent of the organisms.

Three major latitudinal belts of high plankton productivity and biogenic siliceous accumulation are distinguished in the modern oceans (text-fig. 1):

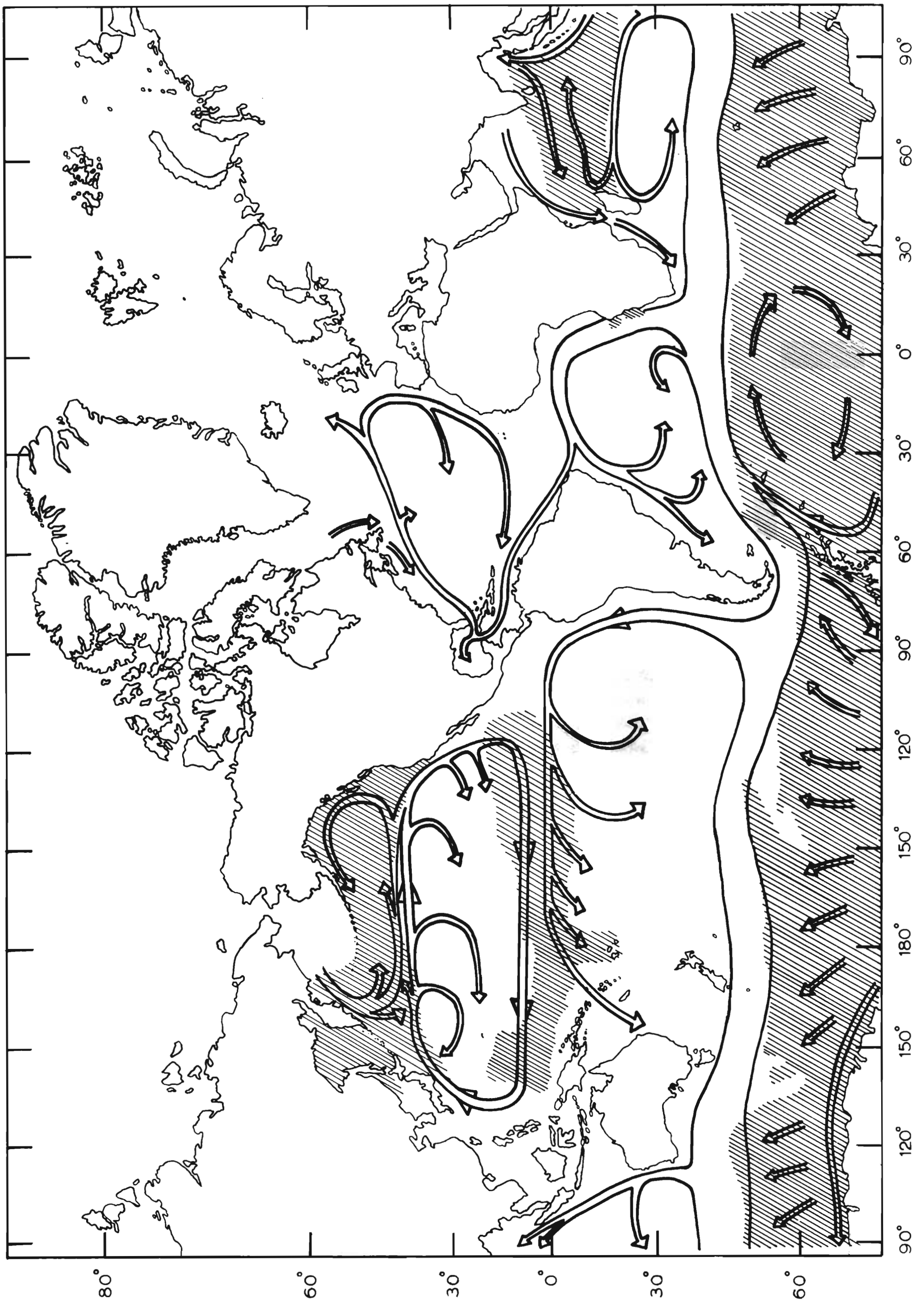
1. A wide (900–2000 km) southern circumpolar belt, which is related to upwelling associated with the West Wind Drift, accounts for the deposition of over 75% of the world's opaline silica (Lisitzin 1971). The northern boundary of this zone coincides with the subtropical convergence.
2. A discontinuous northern belt which is related to upwelling associated with the cyclonic circulation of the Alaskan, Bering, Okhotsk, and northern part of the Japan seas. Its southern boundary coincides with the subarctic convergence (Hays 1970). In the North Atlantic this belt is insignificantly developed, and is disrupted by the Gulf Stream (Lisitzin 1971). The discontinuous nature of this belt is a function of the distribution of the continents and ocean basins which inhibit the development of a continuous circumpolar flow in the Northern Hemisphere.
3. An equatorial belt, which is associated with upwelling near the equator, can be defined in the Pacific and Indian Oceans. In both oceans opaline siliceous sedimentation occurs within a zone extending from 20° N. to 20° S., and is concentrated in areas which lie below the calcium carbonate compensation level (Lisitzin 1971). Above this level, which ranges from 4800 to 5300 m in the equatorial Pacific and from 5000 to 5500 m in the equatorial Indian Ocean, the contribution made by siliceous tests to the bottom sediments is diluted by the extensive deposition of calcareous organic remains (Riedel 1959, Lisitzin 1971).

The absence of a belt of opaline siliceous sediments in the equatorial Atlantic is usually attributed to a reduction in its surface productivity which results from the flushing of nutrients (phosphates, nitrates, and silicates) out of the Atlantic basin. This process is effected by the exchange of deep and bottom waters between the North and South Atlantic (text-fig. 2). In this exchange northward flowing nutrient-rich Antarctic Intermediate and Bottom waters become partially mixed with the southward flowing North Atlantic Deep Water (Western Boundary Current) in the western basin of the South Atlantic, and this mixed water is returned to the Antarctic (Sverdrup *et al.* 1963). In the eastern South Atlantic the Walvis Ridge impedes the flow of all but the Antarctic Intermediate Water.

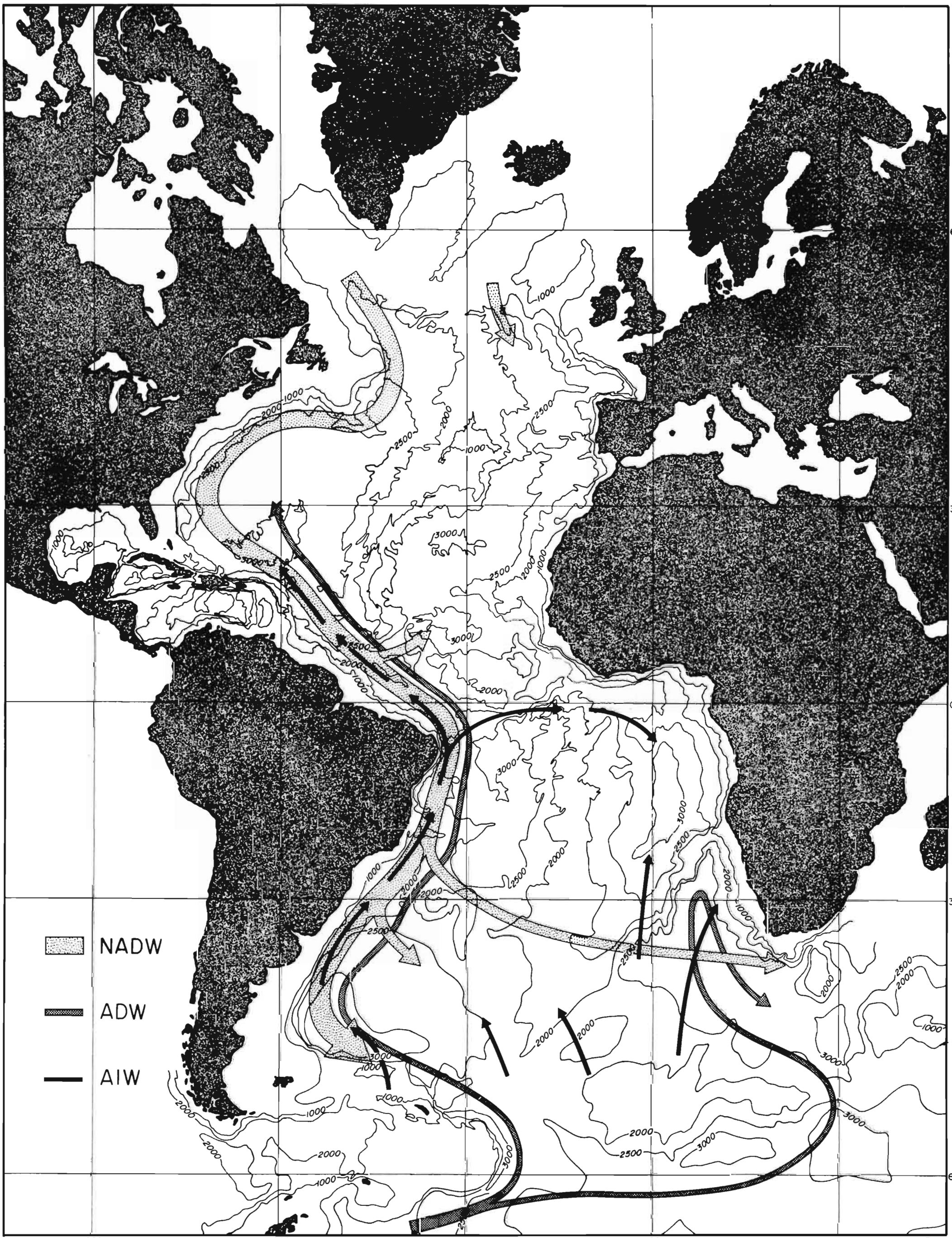
Outside the three major high productivity belts the accumulation of biogenic amorphous silica is restricted to the regions associated with local divergences off the western coasts of the continents; so far only two regions have been defined (see text-fig. 1).

The accumulation and preservation of opaline siliceous tests beneath the oceans' fertile regions is attributed to the absence of a critical depth for its preservation and to the resistance of radiolarians, silicoflagellates, and the more robust species of diatoms to solution in the water column (Lisitzin 1971).

Also the depressed pH of sea water, which is attributed to the abundance of organic carbon and the concomitant production of carbon dioxide in the sediments which underly the fertile regions (Berger 1968, Berger and Parker 1970), results in a decrease in the solubility of skeletal opaline silica and enhances its preservation at the sediment water interface (Tappan and Loeblich 1971).



TEXT-FIG. 1. Representation of the relationship between oceanic circulation and the distribution of Quaternary to Recent organic siliceous sediments. Based on information published by Hays (1970), Lisitzin (1971), Petrushevskya (1971), and Riedel (1971).



TEXT-FIG. 2. Diagrammatic representation of deep-water circulation in the modern Atlantic. Based on data published by Wüst (1958, 1964).

The zones of divergence and high productivity are separated by more stably stratified and less fertile central water masses, which are characterized by the accumulation of organic calcareous ooze or unfossiliferous red clay. The distribution of these sediments is determined by the elevation of the sea floor relative to the calcium carbonate compensation depth. Although opaline siliceous tests are frequently recorded from the upper layers of these deposits (Riedel and Funnell 1964) it appears that their preservation is inhibited by solution at or near the sediment water interface (Riedel 1971) and that their duration in the sediments can be measured in tens of thousands of years.

THE PRE-QUATERNARY RECORD OF ORGANIC OPALINE SILICA: PROBLEMS OF INTERPRETATION

Origin of opaline silica in chert

Since the distribution of Recent and Quaternary deposits of skeletal silica evidently reflect regions of divergence and high surface productivity it seems reasonable to assume that a similar relationship existed in earlier geologic time; and that the distribution of pre-Quaternary organic siliceous sediments together with their diagenetic derivative chert provides information concerning the past distribution of major current systems and fertile water masses.

Clearly no problem exists in recognizing the pelagic nature of radiolarian or radiolarian/diatom ooze, and few marine geologists would dispute Riedel's (1971) data which demonstrate the presence of an equatorial belt of high productivity for the Pacific since the Eocene. There are, however, conflicting opinions concerning the origin of cryptocrystalline silica in deep-sea cherts, and in cherts associated with ophiolites. Grunau (1965) in his comprehensive account of ophiolite chert complexes, and more recently Gibson and Towe (1971) in their discussion of Eocene Atlantic cherts, favour an inorganic volcanic origin. Grunau concludes that the silica precipitated inorganically from silica exhalations which originated from ophiolite extrusion and ultrabasic intrusion, while Gibson and Towe suggest that the Eocene Atlantic cherts were derived from the silica released during the decomposition of volcanic ash. Ramsay (1971*a*, *b*) implies that the Mesozoic and Tertiary cherts, recovered by JOIDES, from the Atlantic, Caribbean, and Pacific are the product of the diagenetic alteration of primary organic sediments rich in opaline silica. This opinion is reasoned on the grounds that cherts of these ages are closely associated with deposits of radiolarian ooze which accumulated in the equatorial zone. If oceanic cherts are really produced by inorganic precipitation from magmatic emanations then the formation of oceanic crust as a result of igneous processes at the crests of mid-ocean ridges (Vine and Matthews 1963; Cann 1968, 1970) demands that their distribution be unrestricted; the JOIDES results, however, demonstrate conclusively that this is not the case. Calculations of the silica balance in the modern oceans (Calvert 1968) also show that submarine vulcanicity contributes considerably less silica to the oceans than is supplied by rivers. A wholly biogenic origin is also attributed to Mesozoic and Palaeozoic radiolarian cherts which are associated with ophiolites in orogenic belts.

Sample distribution

Difficulties in interpreting the past distribution of biogenic silica are introduced by the distribution of oceanic samples. Although oceanic sediments have been extensively sampled during the past two decades, there are still considerable gaps in our coverage for pre-Quaternary deposits. Areas which merit and still require detailed investigation include the high northern and southern latitudes of the Pacific and Atlantic oceans and almost the whole of the Indian Ocean. Thus the interpretation of the few data from these regions is of necessity speculative.

Obliteration of the ancient record by tectonic processes

The subduction of oceanic crust beneath ocean trenches results in the loss of the bulk of the older oceanic crust together with the metamorphic obliteration of its sediments at the consuming plate margins. Vine (1970) suggests that as much as 5000 km of oceanic crust may have been destroyed between the Alaskan peninsula and the Magnetic Bight at 50° N., 160° W., and implies that much of the Mesozoic oceanic crust has been eliminated in this manner. Certainly JOIDES have not recovered sediments from the oceans which are older than Late Jurassic, and the results to date support the assumption by Hess (1962) that the ocean basins are a relatively young feature.

TECTONIC ENVIRONMENTS OF DEPOSITION

Much of the information which relates to Early Mesozoic pelagic sedimentation and all of the information concerning deposition in the Palaeozoic oceans is contained either in ophiolite chert sequences or in eugosynclinal sediments.

The ophiolite chert sequences are interpreted as slices of deformed oceanic crust and upper mantle which were thrust on to the continental margins during orogenesis (Vogt *et al.* 1969, Dewey and Bird 1970, Cann 1970, Smith 1971). Current views on the development and emplacement of these sequences suggest that many do not represent crust which was generated during the initial opening of an ocean. Both Smith (1971) and Dewey (1971) draw attention to the fact that in the Alps the difference between the spreading age of the ophiolite chert sequences and the time of their emplacement is not much greater than 50 million years. The same relationship is also implied for Early Ordovician ophiolite chert complexes in the Caledonoid fold mountain belt (Bird *et al.* 1971, Dewey 1971). Dewey (1971) suggests that the Early Ordovician ophiolites of the Caledonian Proto-Atlantic and the Jurassic–Cretaceous Tethyan ophiolites were generated as ocean crust in small marginal and inter-island arc ocean basins, similar to those described from the western Pacific (Karig 1970), and were emplaced as ophiolites soon after. If the analogy with the western Pacific is correct then these small basins were separated from the main Proto-Atlantic and Tethyan plates by consuming plate margins, beneath which the major oceans have vanished almost entirely.

Evidence for distinguishing two types of oceanic crust which are generated in two distinct tectonic environments is possibly provided by the structural nature of the ophiolites: (*a*) A major ocean basin environment which is represented by sheeted ophiolite complexes and their associated sediments. Complexes of this nature have been described from Newfoundland (Ordovician), Cyprus, Turkey, and Oman (Tethyan) and are interpreted as ocean crust generated about mid-ocean ridges by crustal spreading of the Vine–Matthews type (Strong 1972, Moores and Vine 1971, Cann 1970). (*b*) An inter-island arc or marginal basinal environment of which examples are represented by the Tethyan ophiolite complexes of Greece and Italy. These lack a detectable linear symmetry (i.e. dyke swarms); instead they display internal structures which are parallel to rather than perpendicular to major rock units. In this respect they are similar to the oceanic crust of the Tonga–Kermadec and Marianas arc systems which show no detectable linear magnetic symmetry (Karig 1970). Therefore it seems more likely that these ophiolites were generated in marginal and interarc basins in the manner suggested by Karig rather than about the axes of fast-spreading ridges as postulated by Moores and Vine.

The radiolarian cherts, foraminiferal nannoplankton ooze (Jurassic–Recent), and radiolarian chert black shale facies (Palaeozoic and ?Triassic) of eugeosynclines represents a third tectonic environment. These sedimentary associations probably accumulated on partially ensialic continental rise prisms (Dietz and Holden 1966) or on elevated areas on continental slopes.

Fortunately the distinction between these environments is not so important in terms of pelagic sedimentation since, with the exception of their organic diversity, the processes involved in their accumulation are the same everywhere. The apparently selective preservation of the marginal basin (Dewey 1971) and continental rise prisms during collisions between continents, microcontinents, and island arcs does, however, mean that we are dealing with a very limited sample of the ancient oceans.

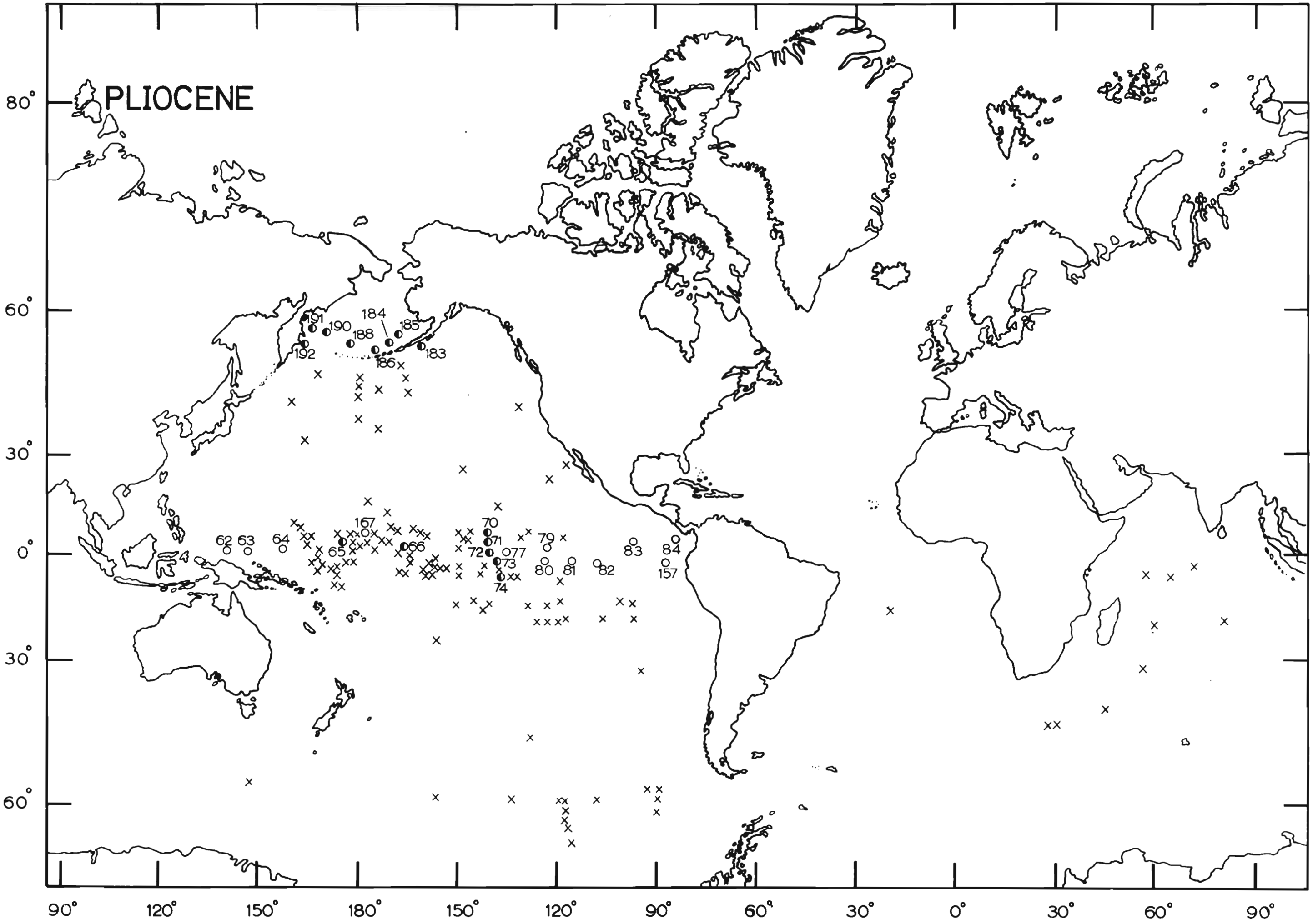
THE DISTRIBUTION OF ORGANIC OPALINE SILICA IN TERTIARY AND MESOZOIC OCEANIC SEDIMENTS

The Neogene record

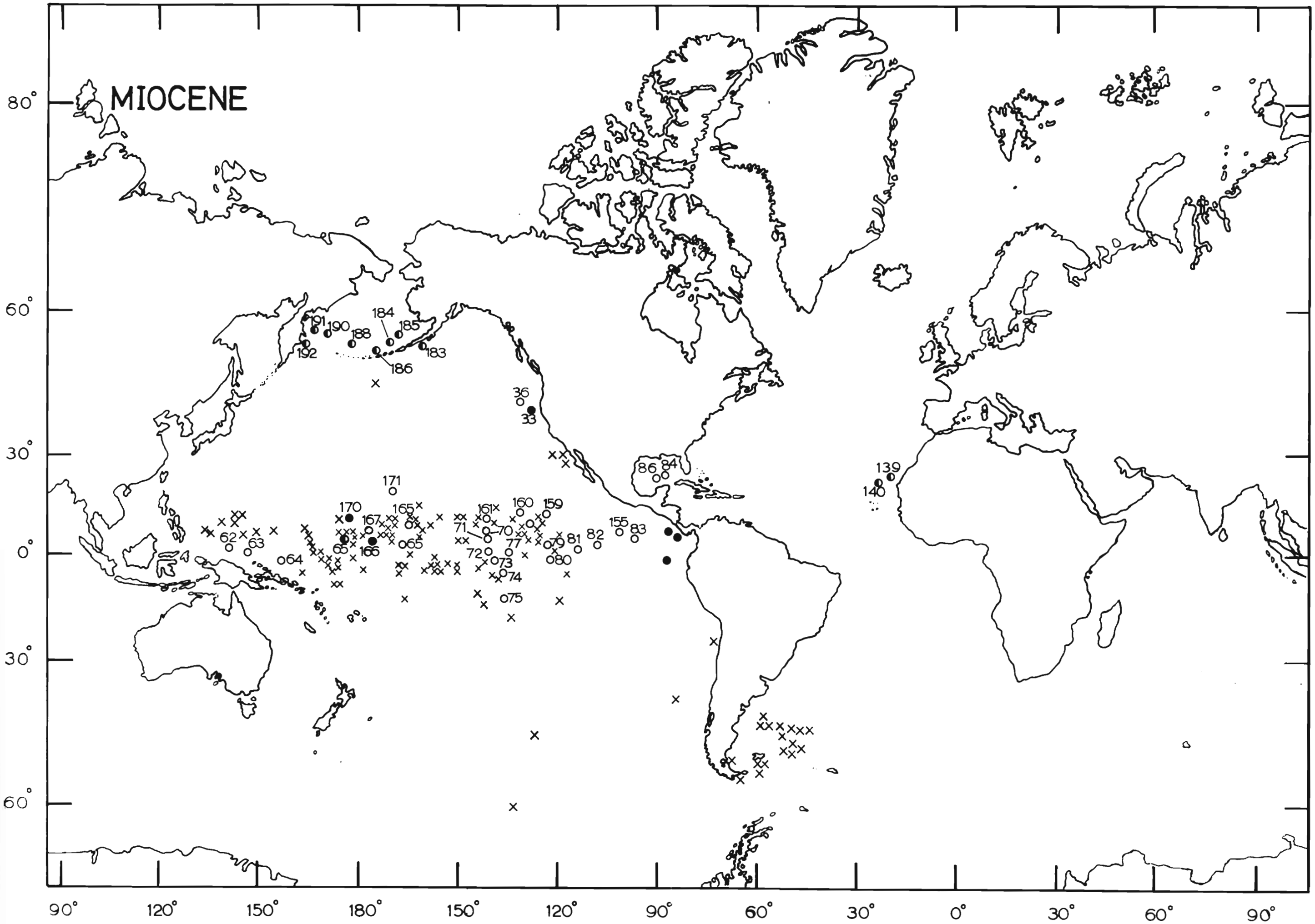
The pattern of the distribution of calcareous siliceous or siliceous oozes (including rare cherts) for the Neogene (see text-figs. 3 and 4) is similar to the modern arrangement, and it is possible to distinguish three major zones of opaline siliceous accumulation in Pliocene and Miocene sediments. Variations from the modern pattern are reflected by discrete areas of amorphous silica accumulation in Miocene sediments from the Gulf of Mexico (calcareous radiolarian ooze) and eastern Central Atlantic (diatom radiolarian ooze). These areas, however, are still regions of local divergence and high surface productivity (Bognadov *et al.* 1968, Pavlov 1968) and do not represent a fundamental departure from the Recent arrangement.

The Palaeogene record

There are no available data concerning the nature of Oligocene oceanic sediments from the high northern and southern latitudes of the Pacific and Atlantic oceans (see



TEXT-FIG. 3. The distribution of organic siliceous sediments of Pliocene age. Based on data contained in Hays (1970), Hays and Berggren (1971), Riedel (1971), Winterer *et al.* (1969), Tracey *et al.* (1970), Hays *et al.* (1970), van Andel *et al.* (1971), Scholl *et al.* (1971). Numbered circles represent JOIDES cores; open circles represent calcareous ooze, half-filled circles represent calcareous siliceous or unconsolidated siliceous ooze. Samples obtained prior to JOIDES are indicated by an X.



TEXT-FIG. 4. The distribution of organic siliceous sediments of Miocene age. Based on data contained in Riedel (1971), Saito and Funnell (1971), Winterer *et al.* (1969), Tracey *et al.* (1970), Hays *et al.* (1970), Worzel *et al.* (1970), Hayes *et al.* (1971), van Andel *et al.* (1971), Winterer *et al.* (1969), Winterer *et al.* (1971), Scholl *et al.* (1971). Numbered circles represent JOIDES cores; open circles represent calcareous ooze, half-filled circles represent siliceous ooze or unconsolidated siliceous ooze, filled circles represent cherts. Samples obtained prior to JOIDES are indicated by an X.

text-fig. 5). On the basis of data presented here together with information published by Saito and Funnell (1971), however, the pattern of sedimentation within the equatorial high productivity belt appears to have been similar to that of the Neogene and Recent, with the deposition of siliceous ooze in the Pacific and calcareous ooze in the Atlantic.

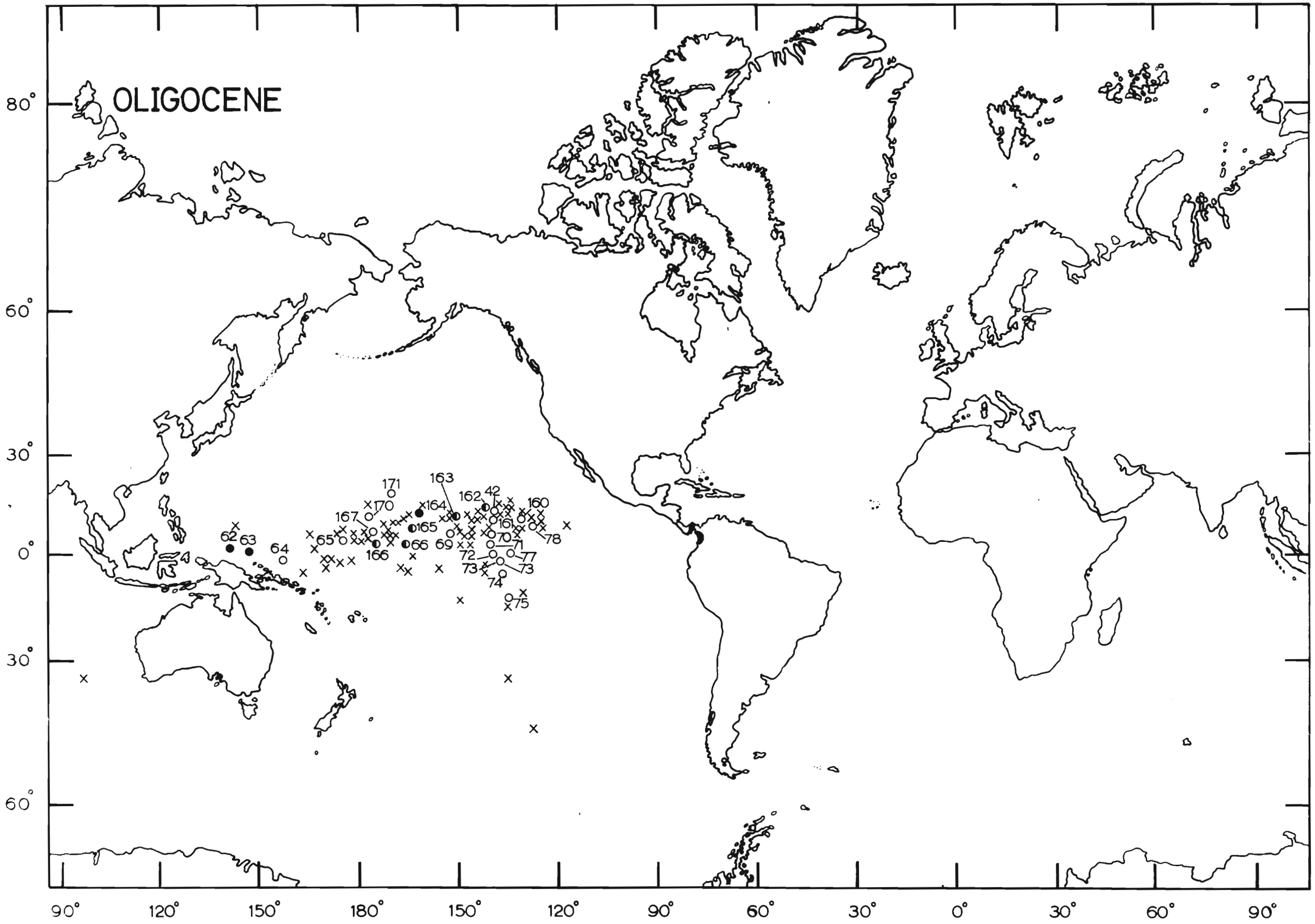
Text-fig. 6 shows the distribution of Eocene and Palaeocene localities from which opaline siliceous sediments are recorded. When these data are transferred on to the symposium reconstruction for this epoch (see text-fig. 7) two regions of organic siliceous sedimentation are defined: a distinct equatorial belt, and part of a southern belt which is represented by a number of localities situated along the margin of the Argentine basin.

The occurrence of an equatorial belt of opaline siliceous sediments in the Early Palaeogene Atlantic and Caribbean clearly represents a fundamental departure from the modern pattern of biogenic siliceous accumulation. Since the occurrence of this belt cannot be reconciled with the present hydrography, biology, and productivity of these areas, it is necessary to consider the possibility of a different deep or surface circulation pattern for the Caribbean and Atlantic, which would provide these areas with a source of nutrient-rich water.

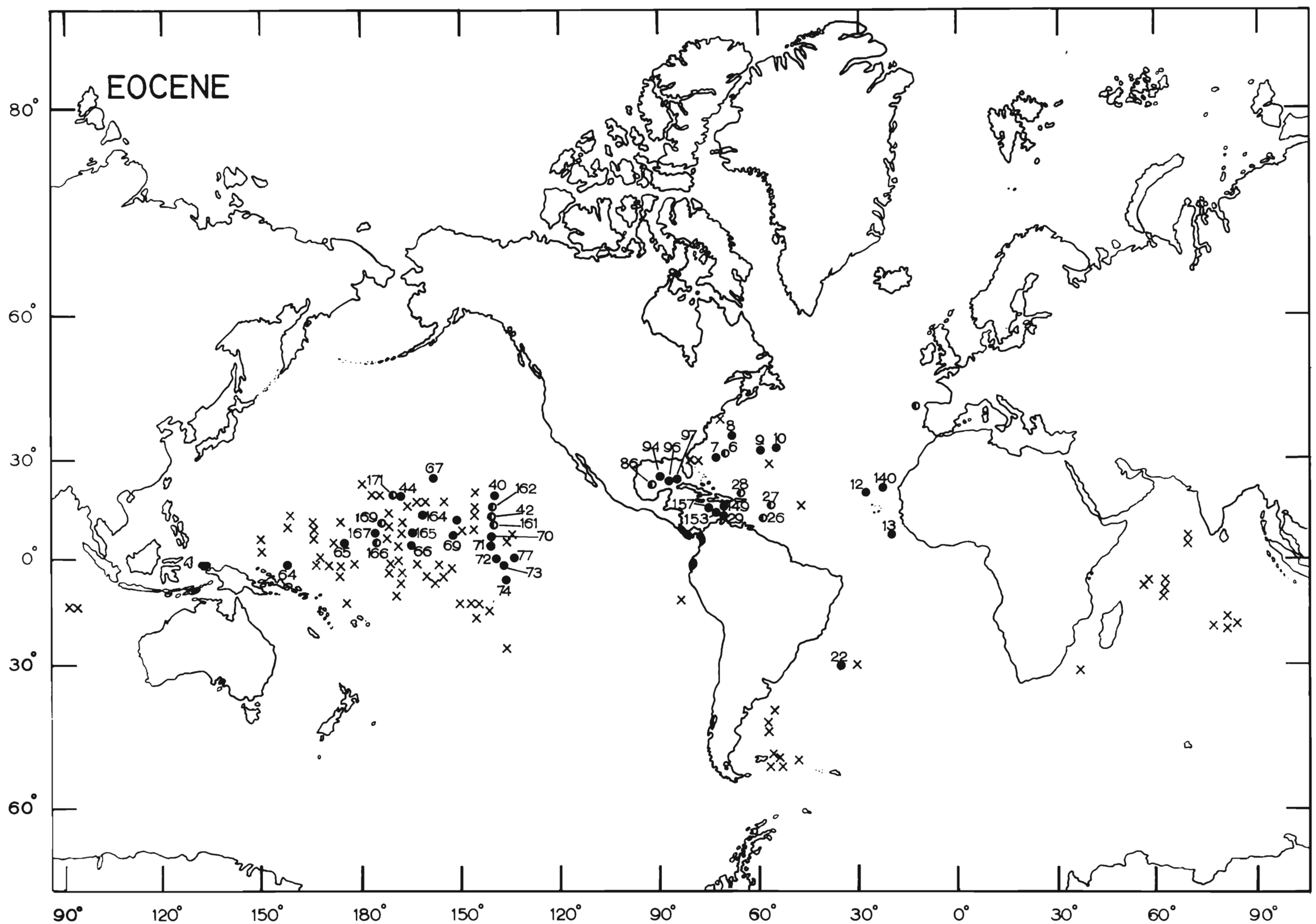
Dietz and Holden (1970) postulate that the productivity of the Middle Eocene North Atlantic increased due to the change in circulation which resulted from an interchange of cold polar water via the connection established between the North Atlantic and Polar basins on the total separation of Greenland and Europe. They also suggest that increased productivity was accompanied by the deposition of opaline siliceous sediments and that these, or their digenetic derivative chert, gave rise to the widespread seismic reflector Horizon A. These authors, however, incorrectly imply that high productivity together with the deposition of these sediments was confined to the Middle Eocene. Opaline siliceous sediments, including cherts, are recorded at various intervals in the Palaeogene and are also widespread in the Upper Cretaceous (Cenomanian to Campanian).

The only indication of the ancient pattern of deep water circulation in the Atlantic is contained in its sedimentary record. So far interpretations of this record suggest that the deep water circulation of the North and Western Atlantic has remained constant since the early Cretaceous. Jones *et al.* (1970) describe a series of seismic reflection profiles in the Labrador Sea and northernmost Atlantic, and argue cogently for the existence of the Western Boundary Current through much of the Tertiary. Ewing *et al.* (1970) in their interpretation of JOIDES (Leg 11) data suggest that the influence of this current can be traced back to the Albian.

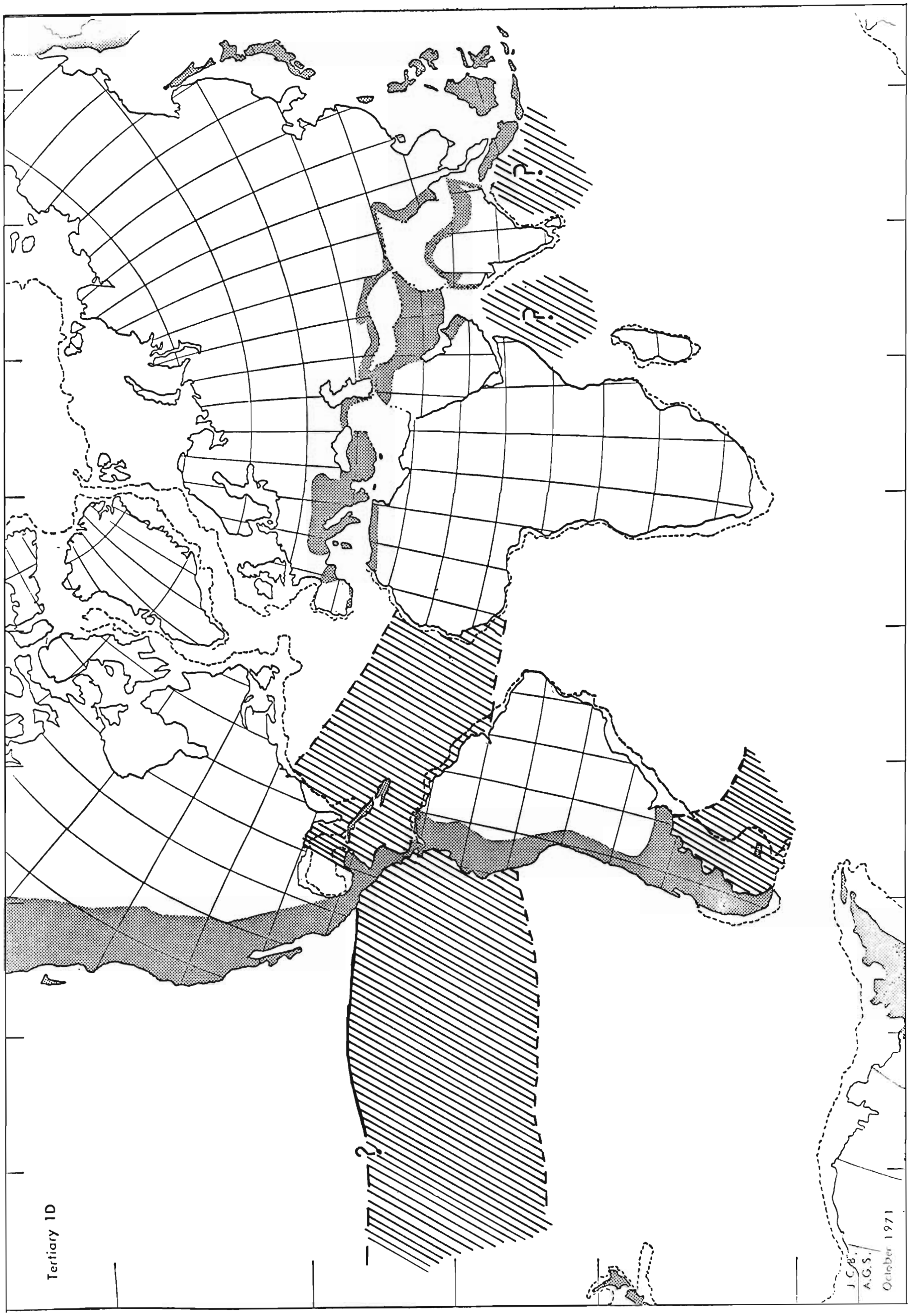
Text-fig. 8 represents an attempt to express a model of deep water circulation in the Eocene Atlantic in terms of a model of its palaeobathymetry. In the bathymetric model the reconstructed vertical relief is based on two assumptions; first that the elevation width and slope of the Eocene and modern mid-Atlantic ridges are similar, secondly that with the exception of younger areas of the Atlantic (i.e. north of 50° N.) there have been no major vertical movements at the periphery of this ocean since the Mesozoic. The first assumption is reasoned on the grounds that currently available data (Vogt *et al.* 1969, Williams and McKenzie 1971, Maxwell *et al.* 1970) show that the Palaeogene ridge like its modern counterpart was the product of a slow spreading



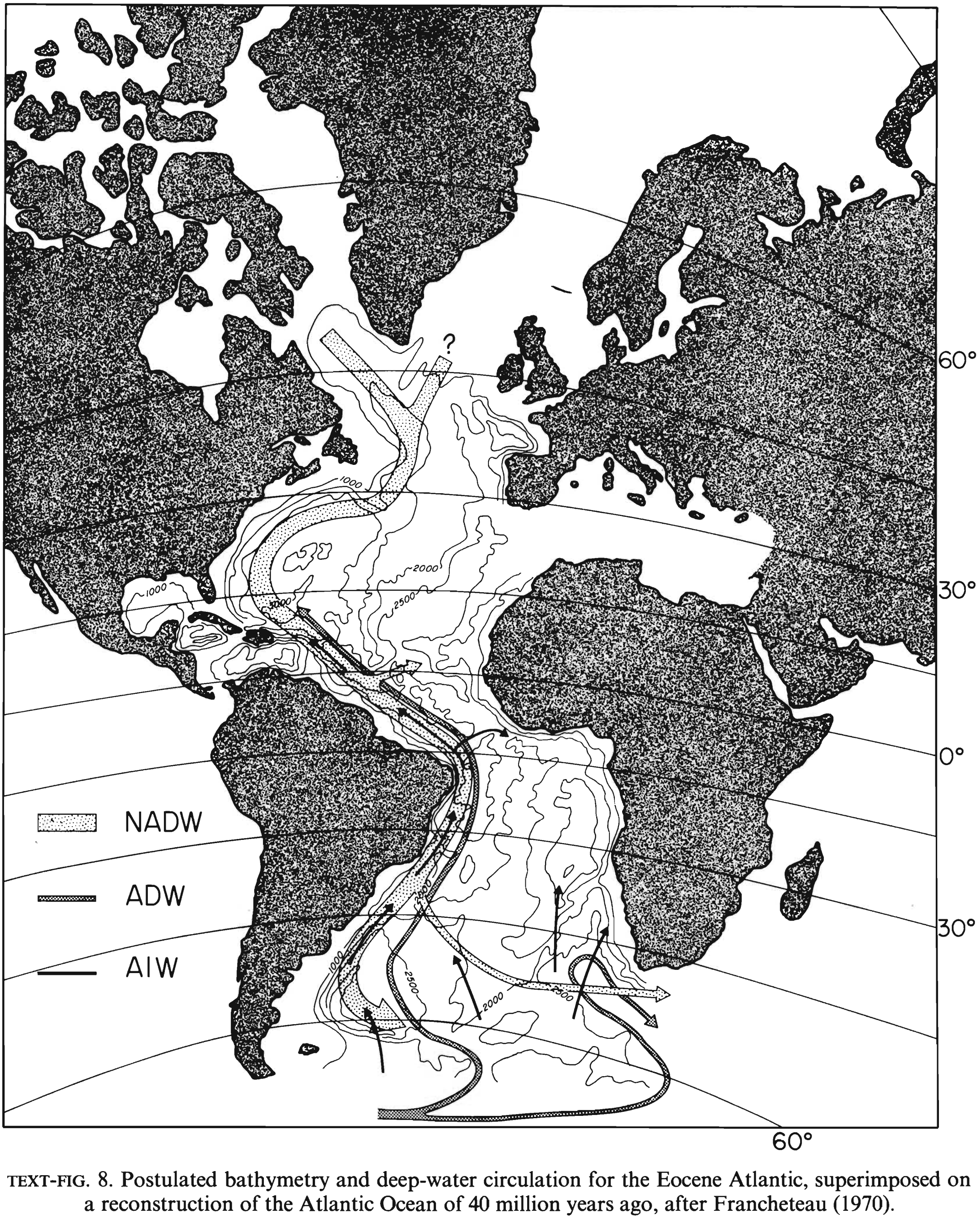
TEXT-FIG. 5. The distribution of organic siliceous sediments of Oligocene age. Based on data published by Riedel (1971), Winterer *et al.* (1969), van Andel *et al.* (1971), Winterer *et al.* (1971), Grunau (1965). Numbered circles represent JOIDES cores; open circles represent calcareous ooze, half-filled circles represent calcareous siliceous ooze or unconsolidated siliceous ooze, filled circles represent cherts. Samples obtained prior to JOIDES are indicated by an X.



TEXT-FIG. 6. The distribution of organic siliceous sediments of Eocene and Palaeocene ages. Based on data published by Riedel (1971), Saito and Funnell (1971), Ramsay (1971*a*), Bandy (1970), Grunau (1965), Fischer *et al.* (1969), McManus *et al.* (1969), Winterer *et al.* (1969), Tracey *et al.* (1970), Worzel *et al.* (1970), Hayes *et al.* (1971), Edgar *et al.* (1971), van Andel *et al.* (1971), Winterer *et al.* (1971). Numbered circles represent JOIDES cores; open circles represent calcareous ooze, half-filled circles represent calcareous siliceous ooze or unconsolidated siliceous ooze, filled circles represent cherts. Samples obtained prior to JOIDES are indicated by an X.



TEXT-FIG. 7. Postulated silica belts for the Eocene oceans based on data from text-fig. 6.



TEXT-FIG. 8. Postulated bathymetry and deep-water circulation for the Eocene Atlantic, superimposed on a reconstruction of the Atlantic Ocean of 40 million years ago, after Francheteau (1970).

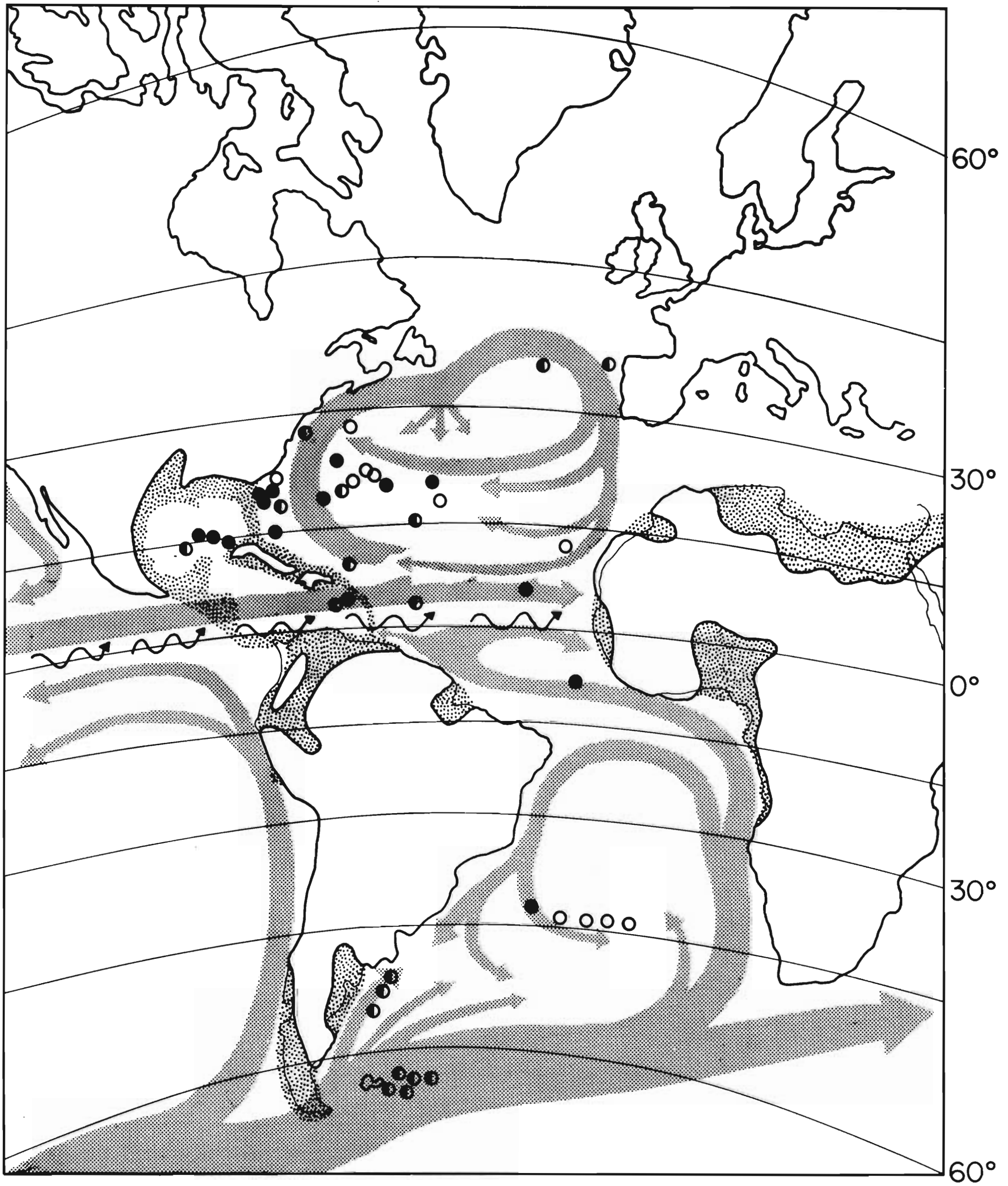
rate (i.e. 1–2 cm/yr^{-1}). Various authors (Vogt and Ostenso 1967, Menard 1967, Le Pichon and Langseth 1969) have demonstrated a causal relationship between the width, local topography, and spreading rate of Recent mid-ocean ridges. There is no conclusive evidence either for or against the second assumption. If, however, the results obtained at the margins of the North Atlantic by Leg 12 of the Deep Sea Drilling Project (Laughton *et al.* 1970) are typical, then one may postulate that vertical movements occur at the periphery of an ocean during the initial 40 to 50 million years of its formation as an isostatic response to opening.

In the reconstructed Atlantic the western gap on the Rio Grande Rise is already developed. This observation is reasonable in the light of palaeomagnetic (Dickson *et al.* 1968) and geological data (Maxwell *et al.* 1970) for the age of the ocean floor to the east of the gap. Thus the Rio Grande Rise would not have impeded deep-water circulation in the Eocene Atlantic. The Walvis Ridge, on the other hand, would have formed as effective a barrier to deep-water circulation as it does at present.

The model of deep-water circulation on text-fig. 8 is based on the data published by Jones *et al.* 1970 and Ewing *et al.* 1970 for the North Atlantic and on theoretical considerations of wind-driven circulation in the South Atlantic. The North Atlantic Deep Water (Western Boundary Current) was presumably generated by the cooling and vertical mixing of waters of different densities in the northernmost Atlantic and embryonic Norwegian and Greenland seas, probably in a similar manner to the Recent (Reid and Lynn 1971). If one accepts that the major features of global atmospheric circulation have remained constant then surface circulation in the South Atlantic has always been characterized by an anticyclonic subtropical gyre and a cyclonic West Wind Drift (see text-figs. 1 and 9), with the production of Antarctic Intermediate Water by sinking at the convergence between these water masses in the manner suggested by Stommel (1957). This circulation would have developed even in the event of the establishment of a complete meridional barrier between the Antarctic Peninsula and South America (see Stommel 1957, fig. 26b). The production of Antarctic Deep Water during the Early Palaeogene is postulated on the basis of recently published data (Geitzenauer *et al.* 1968, Margolis and Kennet 1971) which suggest that the Antarctic was glaciated during the Eocene.

Clearly the model outlined above is speculative. If it is correct, however, it implies that the present pattern of deep-water circulation was already established in the Early Palaeogene Atlantic, and that this ocean, like its modern counterpart, was deprived of nutrients (phosphates, nitrates, and silica) by the same flushing mechanism which operates in the modern Atlantic.

Ramsay (1971*b*) suggested that nutrient-rich water was derived from an influx of surface and subsurface equatorial Pacific water into the Caribbean and Atlantic across an open Isthmus of Panama. This flow was achieved by the eastward flowing equatorial surface countercurrent and subsurface Cromwell current (text-fig. 9). As the continuity of the present countercurrents is seasonal in either ocean (Knauss 1963), the bulk of the flow was probably contained in the Cromwell current. This current, which has a total volume transport of 40×16^6 M^3 S^{-1} (Neumann 1968), is 300 km wide, occupies depths between 50 and 200 m and is symmetrical about the equator (Knauss 1963, Neumann 1968). A depth greater than 200 m was therefore necessary to facilitate the passage of this current across the Isthmus of Panama during the Early Palaeogene.



TEXT-FIG. 9. Proposed circulation patterns for the Eocene Atlantic. The broad arrows represent surface currents, the sinuous arrow the Cromwell current. The stippled regions on the continent represent shelf areas.

The Cretaceous record

Records of organic siliceous sedimentation during the Cretaceous are contained in sediments from the deep-sea and in Alpine ophiolite chert sequences (text-figs. 10 and 11). On the basis of these data it is possible to distinguish an equatorial and part of a southern belt of organic siliceous sediments (text-fig. 10). Tethyan pelagic sequences are preserved in the ophiolite chert sequences of mid-ocean ridges and marginal or interarc basins which were thrust on to the continental margins during a compressional phase in the closure of the Tethys.

The continuation of the equatorial belt of Upper Cretaceous siliceous deposits into the Caribbean and Atlantic (text-fig. 10) suggests a similar pattern of surface and subsurface circulation to that outlined above for the Early Palaeogene. In my opinion the South Atlantic was wider in the Cretaceous than is suggested in the symposium reconstruction. Ramsay (1971*c*) suggests that the separation of South America and South Africa began in the Late Jurassic, approximately 138 million years ago, and that this basin was approximately 800 km wide at the latitude of the Brazil and Gabon basins by Aptian times. Francheteau (1970) also considers that the South Atlantic was open by this time.

The Jurassic record

Unfortunately there are too few data from the oceans to define belts of high productivity and siliceous sedimentation in the Jurassic (text-figs. 12 and 13).

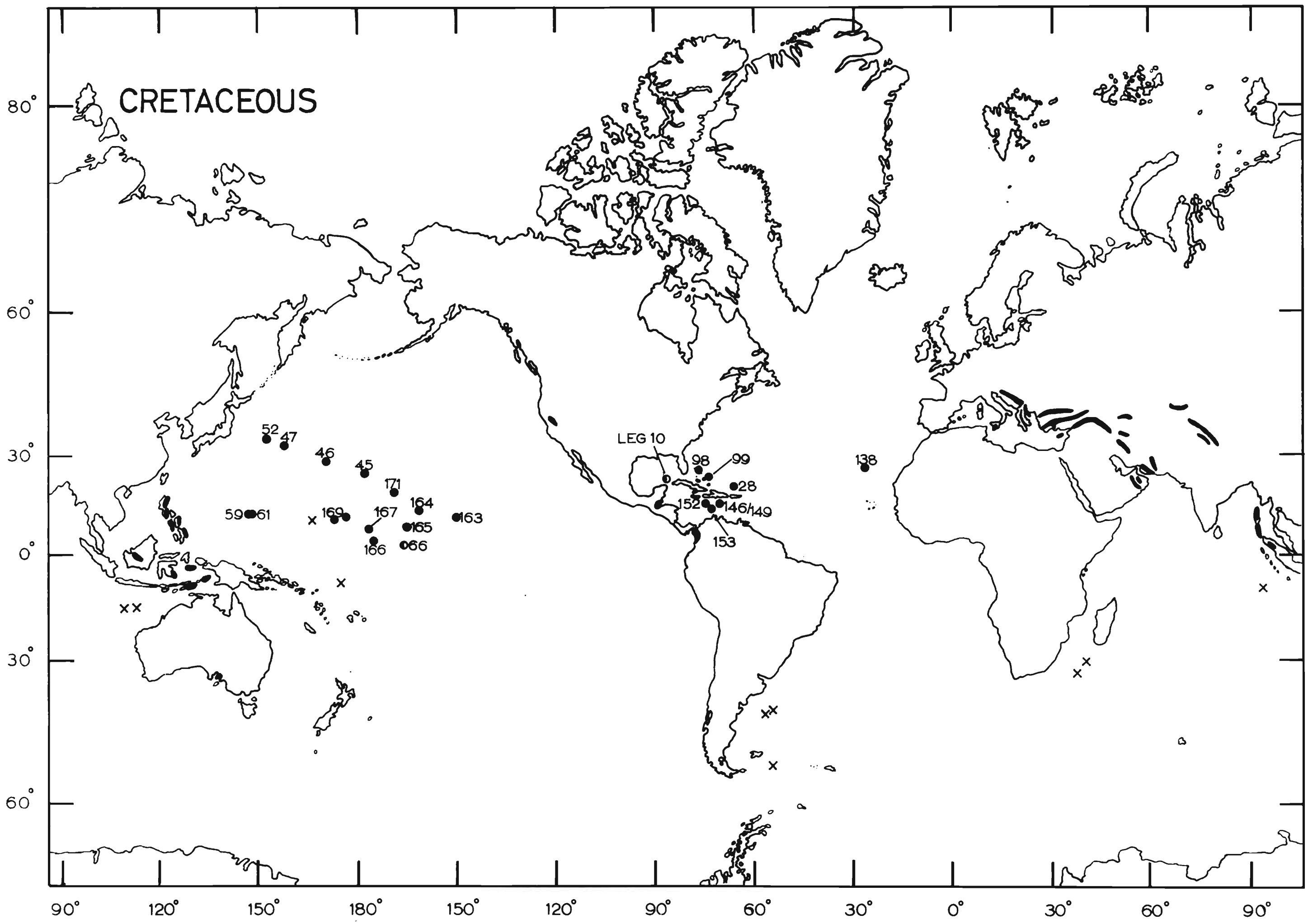
Cherts contained in the ophiolite sequences of the Philippines, Borneo, Celebes, Iran and the Western Mediterranean, and California, together with siliceous ooze from the Cape Verde Islands, however, are possible remnants of an equatorial belt of opaline silica accumulation. While eugeosynclinal cherts from Japan and Alaska may represent sediments which were deposited in a northern belt (text-fig. 13).

The Triassic record

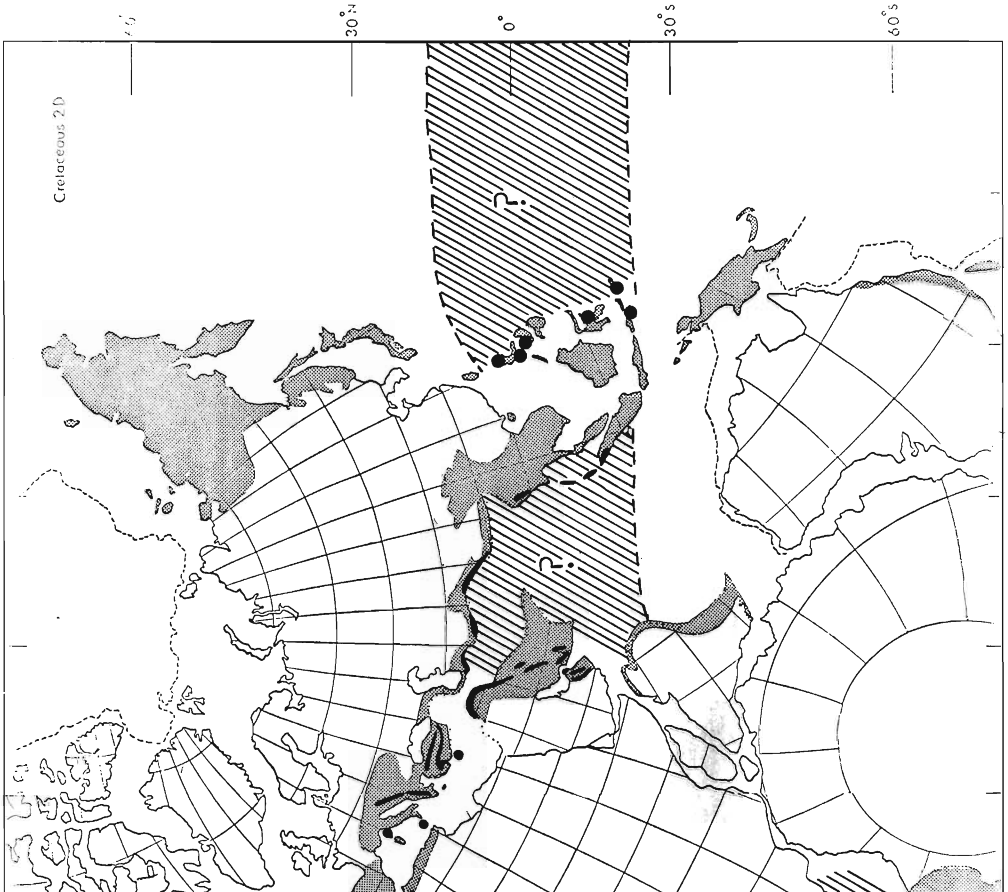
Despite a paucity of data the distribution of Tethyan Triassic ophiolite chert complexes, together with eugeosynclinal cherts from Japan, is not very different to that for the Jurassic. Again these sediments may be remnants of northern and equatorial belts of organic siliceous deposition (text-fig. 14).

ORGANIC SILICEOUS SEDIMENTATION: EVIDENCE FOR MAJOR CHANGES IN OCEANIC CIRCULATION DURING THE MESOZOIC AND CENOZOIC

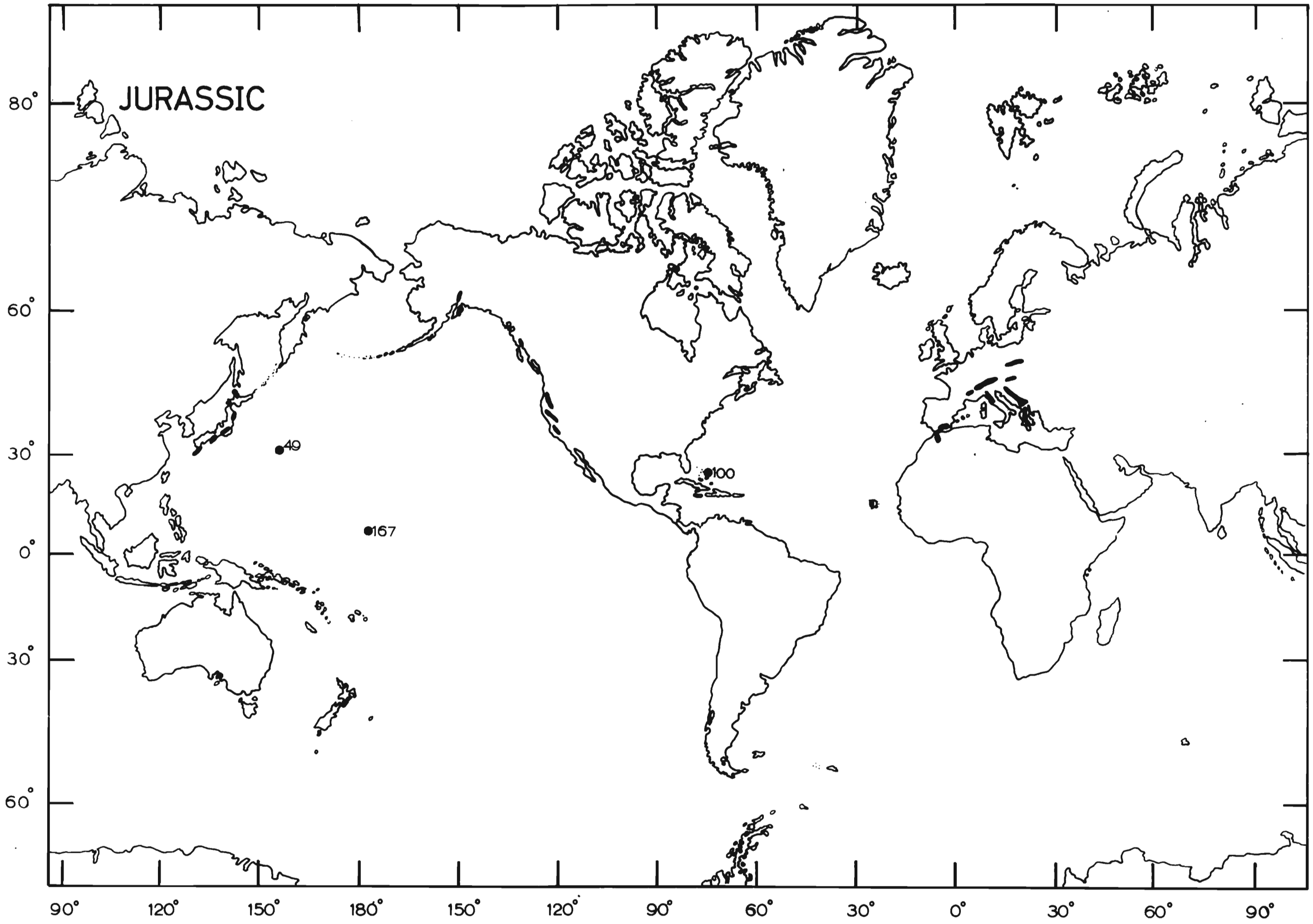
The opening of the Atlantic and the initiation of a pattern of deep-water circulation similar to the Recent in the embryonic Atlantic ocean may not have had a profound effect on the distribution of dissolved products of weathering, e.g. silica, carbonate, and other elements in the Late Mesozoic and Tertiary oceans. Although river discharge supplies more products of weathering to the modern North Atlantic than any other ocean basin (Olausson 1971), and although some of these are carried in solution into the Indian and Pacific oceans, via the North Atlantic Deep Water, it is



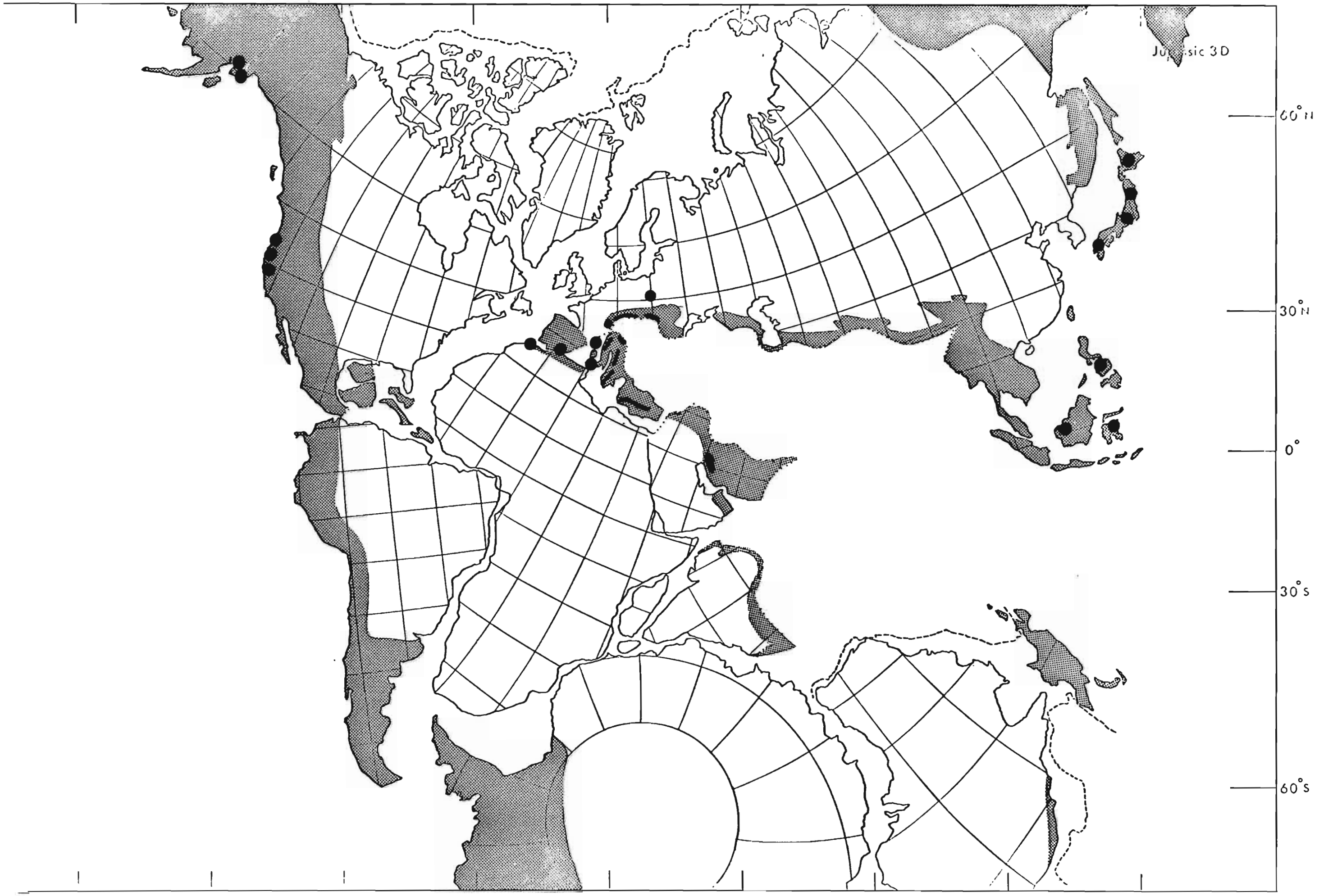
TEXT-FIG. 10. The distribution of organic siliceous sediments of Cretaceous age. Based on data published by Riedel (1971), Saito and Funnell (1971), Ewing, J. I. *et al.* (1970), Peterson *et al.* (1970), Worzel *et al.* (1970), Ewing, M. *et al.* (1970), Fischer *et al.* (1969), Winterer *et al.* (1969), Hayes *et al.* (1971), Edgar *et al.* (1971), van Andel *et al.* (1971), Winterer *et al.* (1971), Bandy (1970), Grunau (1965). Numbered circles represent JOIDES cores; all contain cherts.



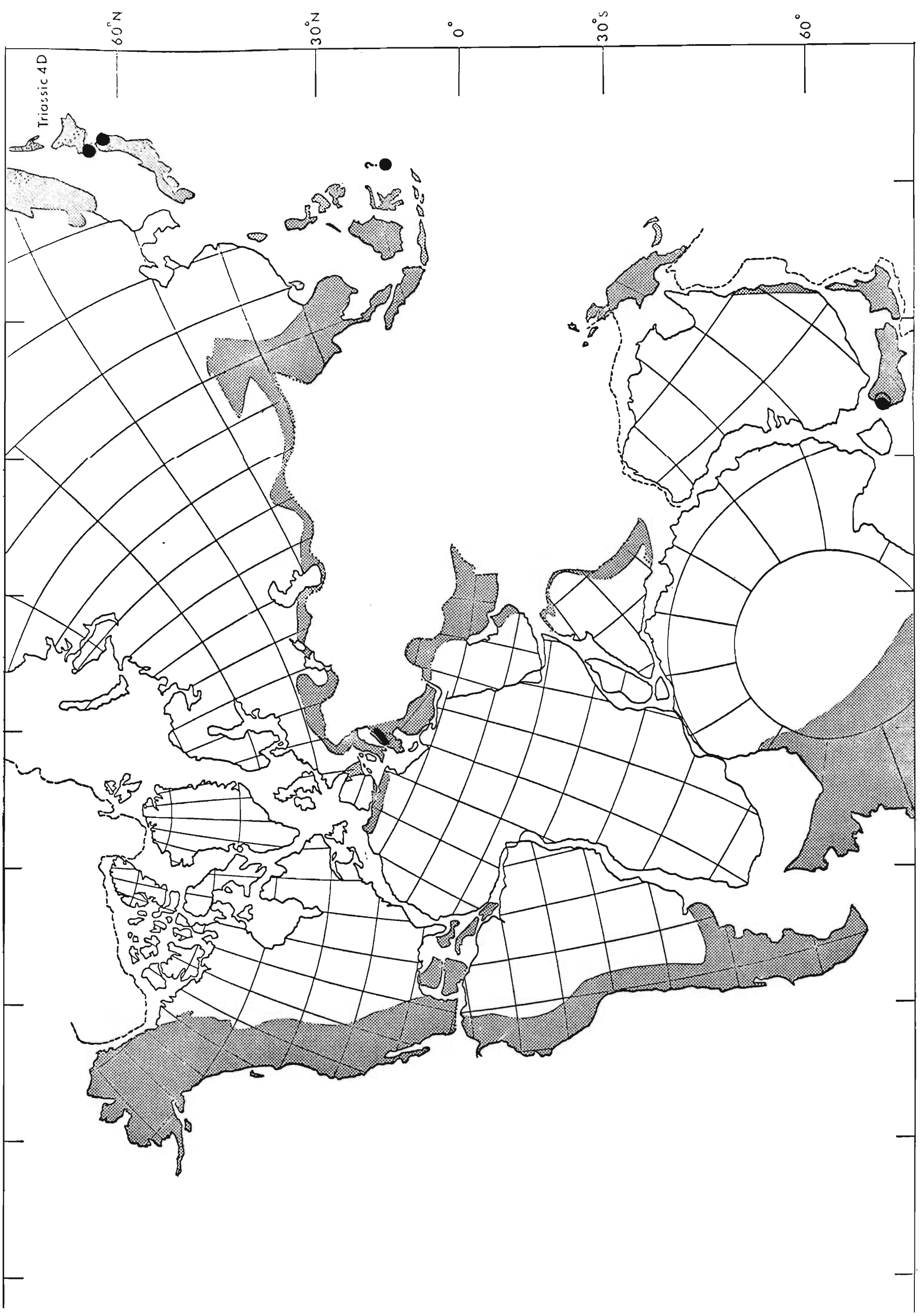
TEXT-FIG. 11. Postulated silica belts for the Cretaceous based on data from text-fig. 10.



TEXT-FIG. 12. The distribution of organic siliceous sediments of Jurassic age. Based on Funnell (1971), Fischer *et al.* (1969), Winterer *et al.* (1971), and Grunau (1965). Numbered circles represent JOIDES cores; all contain cherts.



TEXT-FIG. 13. The distribution of organic siliceous sediments expressed on the symposium reconstruction for the Jurassic. Data based on text-fig. 12.



TEXT-FIG. 14. The distribution of Triassic organic siliceous sediments based on data published by Grunau (1965) and Dietz and Holden (1966).

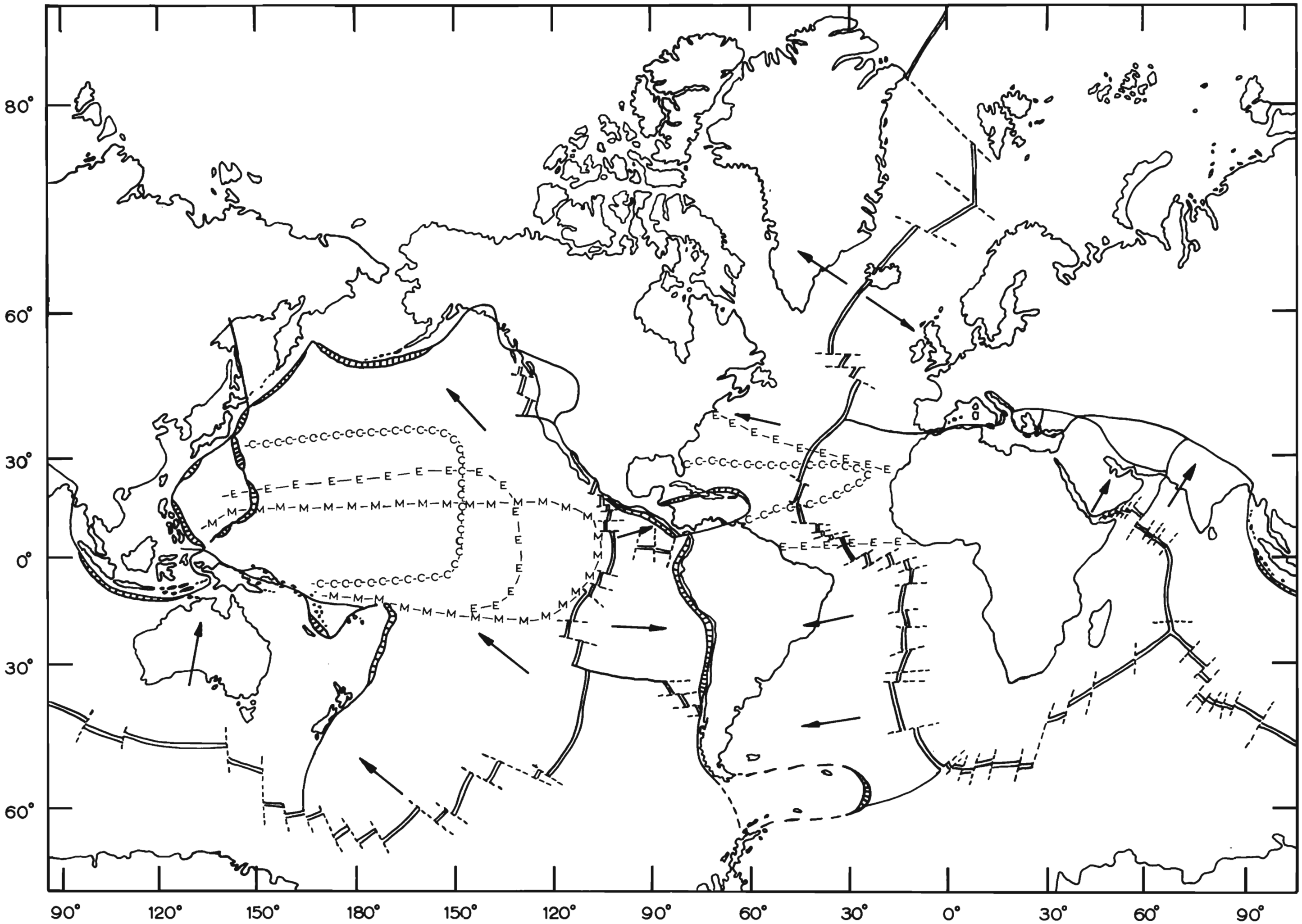
probable that the Tethys was an equal recipient of weathered products during the Late Palaeozoic and Early Mesozoic. Consequently this basin fulfilled the function of an oceanic source area for dissolved inorganic nutrients for the Late Palaeozoic and Early Mesozoic oceans.

The increased productivity of the Caribbean basin and equatorial Atlantic during the Cretaceous and Palaeogene evidently reflects a different pattern of oceanic circulation to the Recent. This may have been produced by the uninterrupted flow of equatorial Pacific water into these areas during Late Cretaceous and Early Palaeogene times. Changes in the northerly extent of the northern boundary of the Pacific equatorial belt which have been quoted as evidence for a shift in the equatorial water mass during the Tertiary (Riedel and Funnell 1964) are also reflected by Cretaceous sediments (text-fig. 15). This shift in the position of this boundary is evidently related to the north-west component of motion of the Pacific plate. The westward shift in the eastern boundary of the silica belt clearly demonstrates the western component of motion of this plate away from the East Pacific Rise.

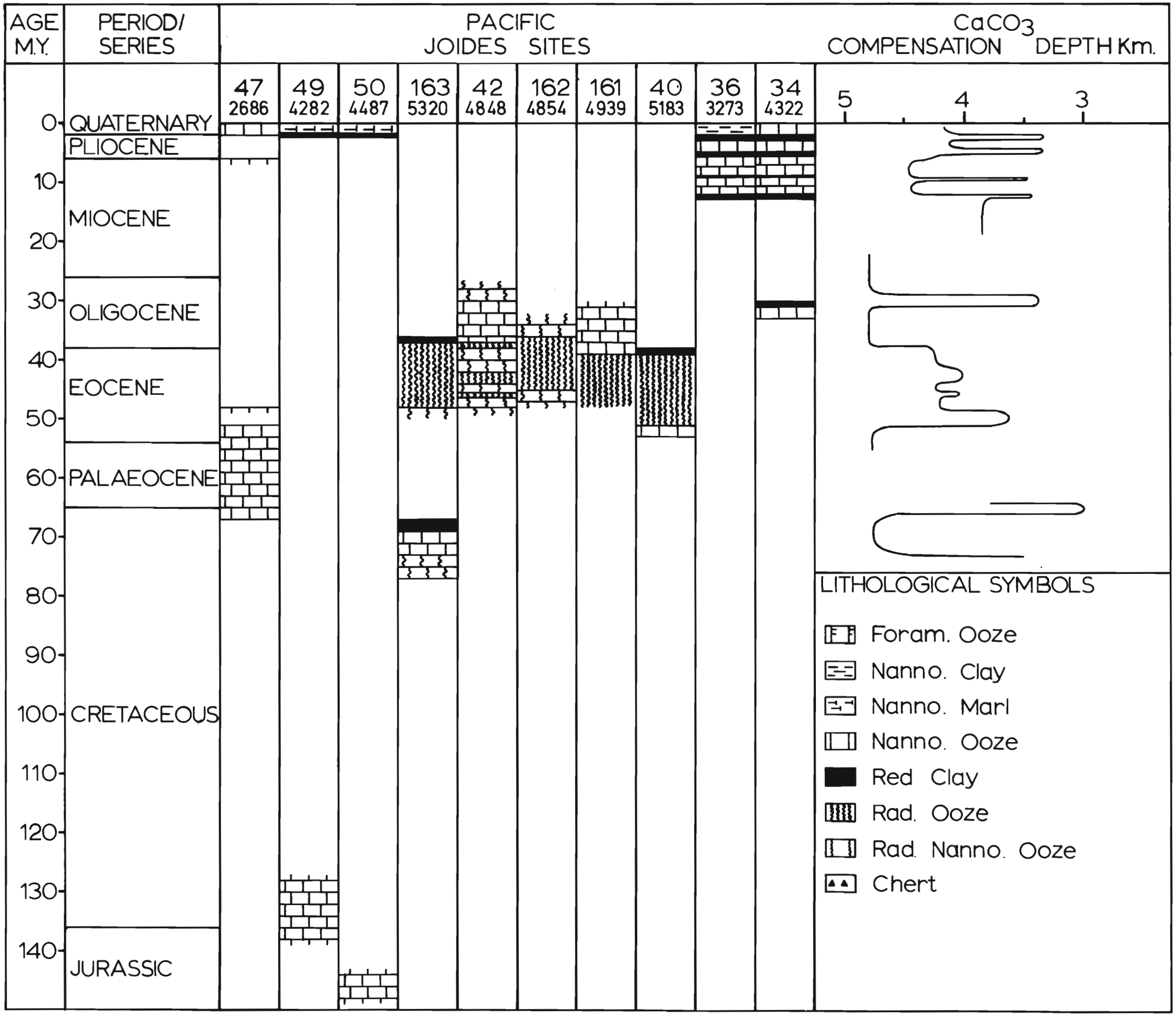
Winterer *et al.* (1971) on the basis of results from JOIDES Leg 17, and earlier JOIDES Legs, postulate that the slow rate of accumulation of Early Tertiary sediments recorded for the Pacific and Atlantic could be related to a major environmental change of global extent; possibly a change in circulation patterns. This interpretation of the Early Palaeogene sequences is directly relevant to the present discussion for it is precisely in these sequences that we find the widespread chert horizons of the Atlantic and Pacific.

Analyses of the record (obtained by JOIDES) of pelagic sedimentation in the Pacific, Caribbean, and Atlantic basins for the past 65 million years by Hay (1970, Atlantic and Caribbean) and Ramsay (1971*d*, Atlantic, Caribbean, and Pacific) indicate that the calcium carbonate compensation level in the oceans (and consequently the rate of pelagic sedimentation) has fluctuated considerably through the Tertiary (text-figs. 16 and 17). The changes in this level, which are expressed by the alternation of calcareous ooze with organic siliceous ooze in the equatorial high productivity belt, and with red clay in less productive regions, are broadly synchronous for all three basins.

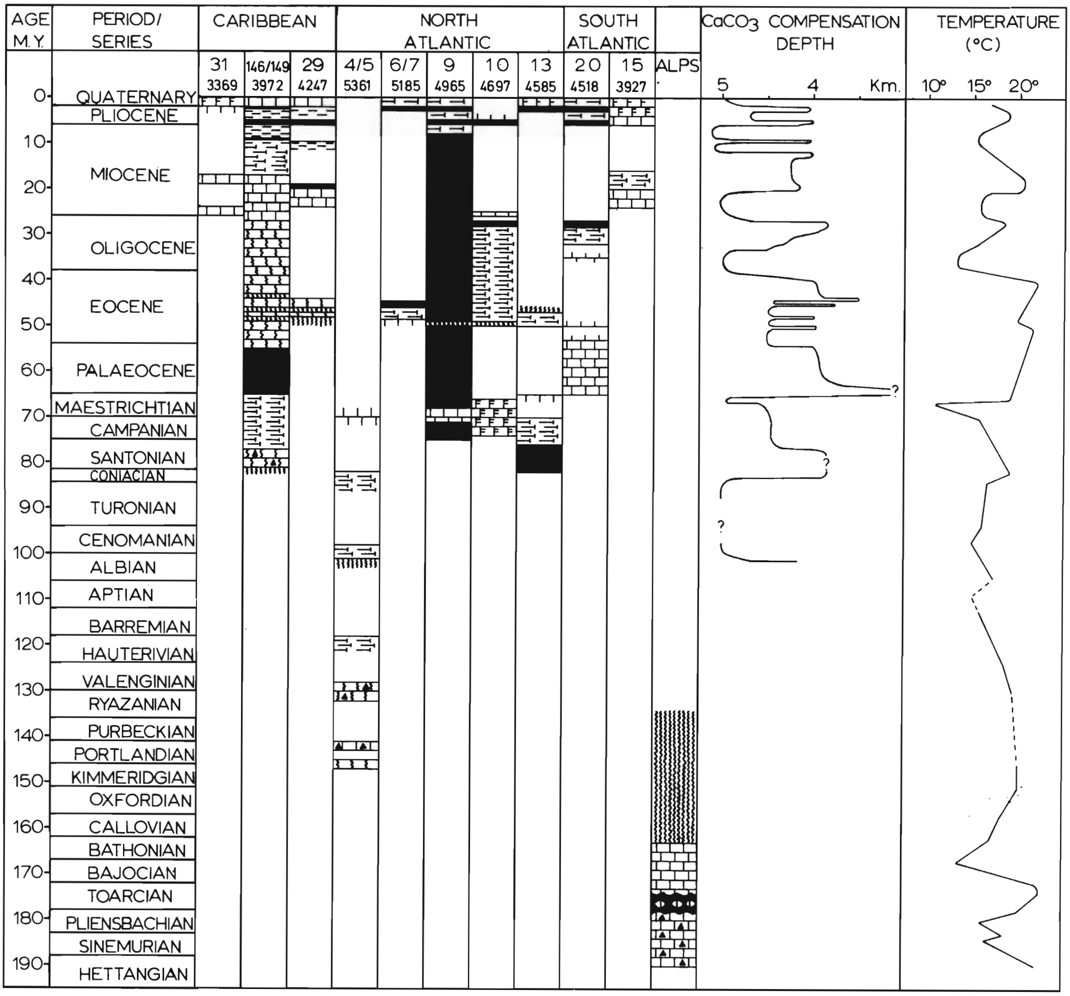
The broad correlation between the fluctuations in the Tertiary compensation level and the temperature-related oxygen isotope curves for this period (compare text-figs. 16 and 17) suggests that the fluctuation may be caused by changes in temperature. It is possible that the increased productivity of carbonate producing organisms at the surface during warm periods may upset the delicate balance between the input of $CaCO_3$ to the oceans and its loss to pelagic sediments. Since this balance is maintained by the solution of carbonates in the deep sea (Li *et al.* 1969), changes in the surface productivity would lead to fluctuations in the calcium carbonate compensation depth. These fluctuations would be expressed by an elevated compensation level during warm intervals and a depressed level during cooler intervals. Broecker (1970, 1971) demonstrates that, in the Quaternary, high carbonate sedimentation corresponds with a depressed compensation level during glacial periods, and low carbonate accumulation to an elevated compensation level during interglacial periods. He also suggests changes in surface productivity as a possible mechanism for these fluctuations.



TEXT-FIG. 15. Displacement of Mesozoic and Cenozoic northern and western boundaries of the silica belt, due to movement of the Pacific Plate. C–C = Cretaceous boundary; E–E = Eocene boundary; M–M = Miocene boundary.



TEXT-FIG. 16. An interpretation of the record of fluctuations in the calcium carbonate compensation depth for the Pacific, plotted against time. Time-scale after Berggren (in Maxwell *et al.* 1970) and Harland *et al.* (1964).



TEXT-FIG. 17. An interpretation of the record of fluctuations in the carbonate compensation depth for the Atlantic and Caribbean plotted against time and compared with a palaeotemperature graph for the Jurassic to Recent. Time-scale after Berggren (in Maxwell *et al.* 1970) and Harland *et al.* (1964). A detailed discussion of these diagrams is contained in Ramsay (1971*d*).

Fluctuations in the compensation level produce a rather bizarre situation in deep-sea pelagic sedimentation, in that maximum rates of sedimentation occur in cool less productive periods and minimum rates in warm highly productive periods. On the continental shelves this situation is of course reversed for carbonate sedimentation. Apart from producing attenuated Early Tertiary sequences, however, the fluctuations in the compensation level produced an alternating series of siliceous oozes and carbonates which are potentially an ideal environment for chert formation since they would produce interstitial solutions of different alkalinities. Opaline silica would be dissolved in a high pH environment and reprecipitated in one characterized by a lower pH.

It is interesting to note the similarity between Eocene and Quaternary equatorial pelagic sequences. Both appear to have been deposited under fluctuating climatic conditions, and both contain alternating sequences of calcareous and siliceous ooze. One may speculate that with continued deposition through changing climatic conditions, the Quaternary, Recent, and future sediments will eventually give rise to widespread chert horizons in the oceans of 50 to 70 million years hence.

OPALINE SILICEOUS SEDIMENTATION DURING THE PALAEOZOIC

As one would expect from the ages derived for oceanic basement in the modern basins, all Palaeozoic oceanic sediments are now represented by slivers of ophiolite chert sequences or eugeosynclinal black shales and cherts which have been incorporated in the fold mountain belts.

The Permian record. Permian cherts are recorded from two localities (text-fig. 18), one in Japan and the other in Timor, and one must await further data before making any pronouncement on the Permian record of organic siliceous sediments.

The Carboniferous record. Remnants of a possible equatorial belt of opaline silica are preserved in the radiolarian cherts and shales of Borneo, Malaya, the Caucasus, southern England, and Nevada. Similar eugeosynclinal sediments from Japan may represent sediments which were deposited in the northern belt (text-fig. 19).

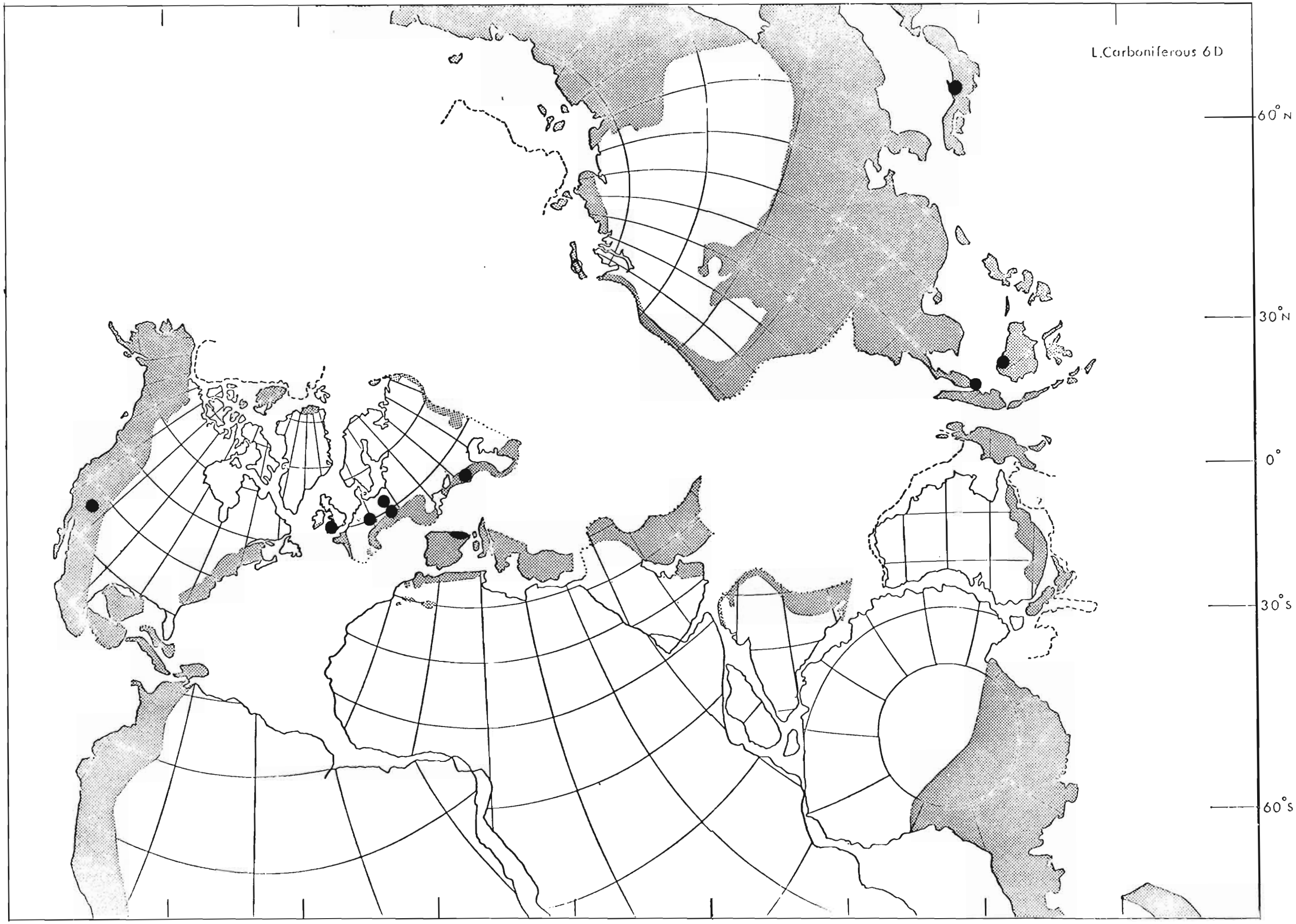
The Devonian and Silurian record. Devonian and Silurian radiolarian cherts and shales, recorded from Australia, the Urals, North America, and western Europe, have probably accumulated in the equatorial belt (text-fig. 20). The Siluro-Devonian Caballos Novaculates from the Marathon basin of Texas are situated at a latitude which is approximately synchronous with the modern southern silica belt. Thompson (1964) presents a very convincing argument for the deep-sea origin for this formation, and if his interpretation is correct this formation contains a record of Silurian and Devonian pelagic sediments.

The Ordovician and Cambrian record. All radiolarian cherts for these ages are contained in a broad zone (text-fig. 21) which is probably the Lower Palaeozoic equivalent of the modern equatorial silica belt. The excessive width of this belt may be due to the large interval of time represented by the sediments and the reconstruction.

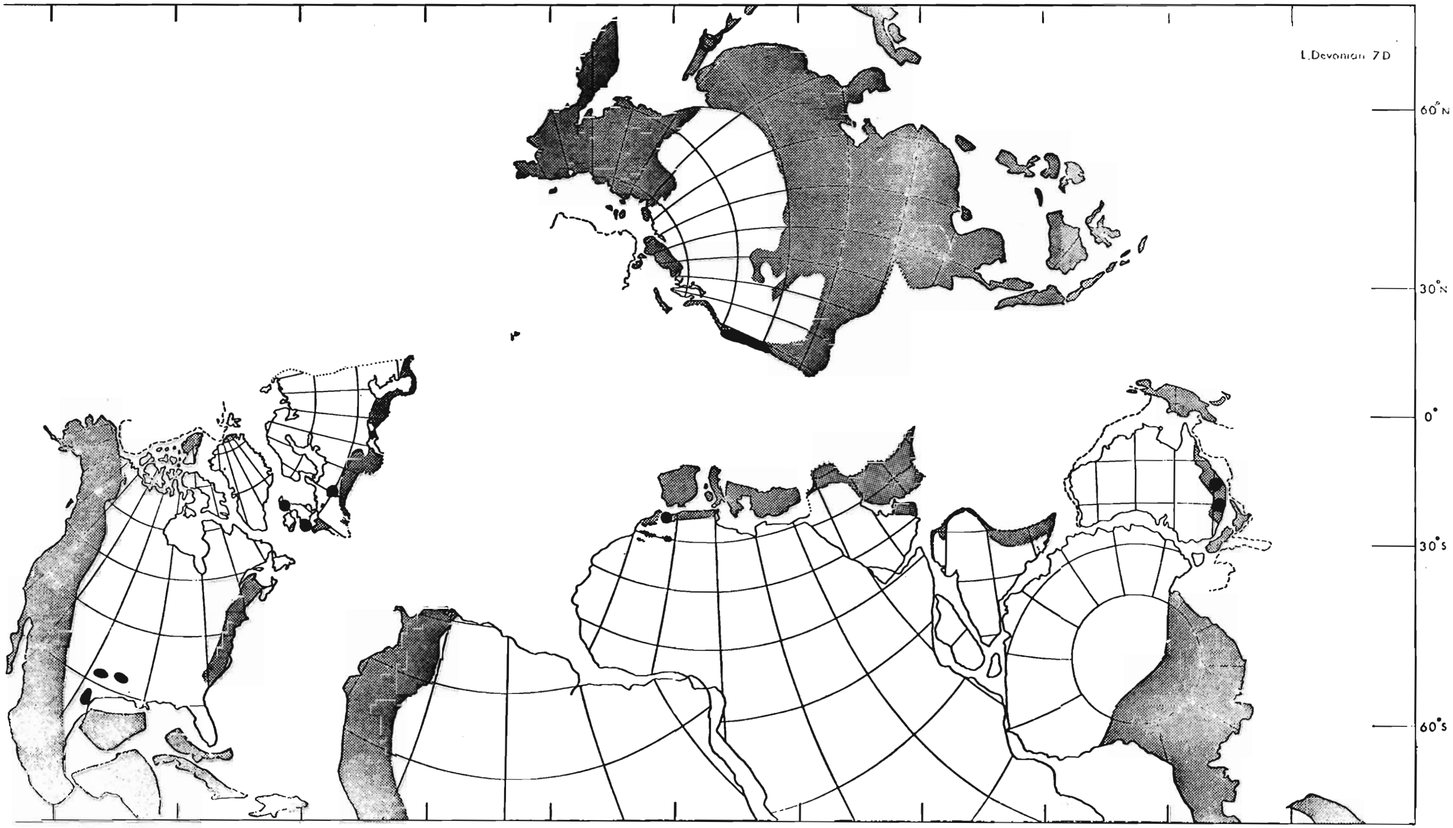
COMMENTS ON THE PALAEOZOIC RECORD OF DEEP-SEA SEDIMENTATION

Despite the rather sparse nature of the Palaeozoic record of deep-sea pelagic sediments it is still a highly interesting record and one which deserves closer attention. The absence of pelagic carbonate sedimentation during the Palaeozoic is strikingly obvious in all sequences. It appears that deposition during this large interval of time was restricted to carbonaceous black shales, radiolarian black shales, and radiolarian ooze. This sedimentary association ceased only in the Jurassic with the emergence of the calcareous coccolith-bearing algae (Black 1971), though it is likely that

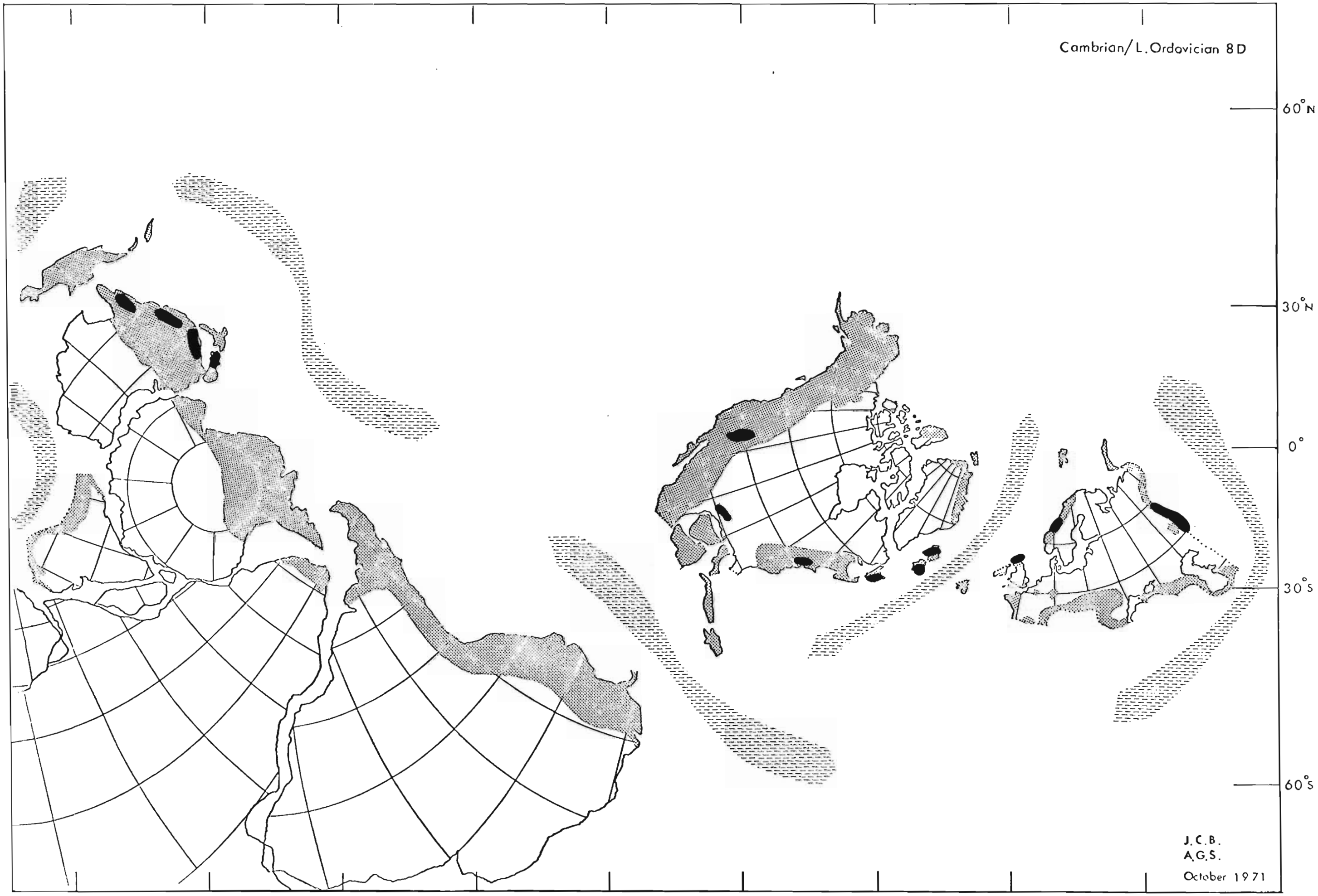
TEXT-FIG. 18. The distribution of Permian organic siliceous sediments, based on data published by Grunau (1965).



TEXT-FIG. 19. The distribution of Carboniferous organic siliceous sediments, based on information published by Grunau (1965), Dietz and Holden (1966), De Sitter (1962), Prentice (1962).



TEXT-FIG. 20. The distribution of Silurian and Devonian organic siliceous sediments based on data published by Grunau (1965) and Dietz and Holden (1966).



TEXT-FIG. 21. The distribution of Cambrian and Ordovician organic siliceous sediments, based on information published by Grunau (1965), Dietz and Holden (1966), Ketner (1969).

these were preceded by the uncalcified Haptophyceae similar to those illustrated by Black (1968).

Clearly the Palaeozoic radiolarian oozes together with their diagenetic derivative chert can be equated with similar sediments of the modern oceans, and were probably deposited beneath highly productive areas. The black shales on the other hand do not occur in modern deep-sea environments and their place may have been taken by coccolith and foraminiferal ooze. It is possible that carbonaceous black shale deposition in the Palaeozoic oceans occurred when the world's atmosphere together with the ocean bottom waters contained less oxygen than at present. This reduced level of oxidation would enhance the preservation of organic carbon in bottom sediments, and one could conceive their deposition in oceans depleted in oxygen, which were not necessarily reducing.

Quantitative faunal and floral analyses at the micro and macro levels together with determinations of the abundance of organic carbon in Palaeozoic deep-sea sediments should reveal much more about productivity and productive regions in these early oceans.

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