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TENTH SILVER JUBILEE COMMEMORATION LECTURE

PALYNOLOGY IN OIL EXPLORATION

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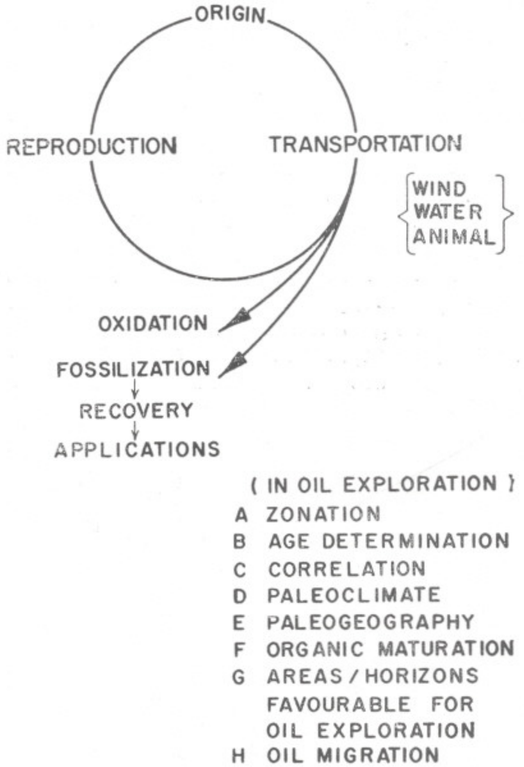
INTRODUCTION

THE Birbal Sahni Institute of Palaeobotany is the premier research organization of its kind in India. A great scientist, whose name the institute bears, was its founder, and it was to him that an oil company turned thirty-four years' ago, to solve problems of stratigraphy in oil-bearing strata of Upper Assam, which had no diagnostic marine fossils. The association between palaeobotany and oil exploration in India, which began then, has broadened in subsequent years. Therefore, when the present Director of Birbal Sahni Institute of Palaeobotany approached me, earlier in the year, to deliver the Tenth Silver Jubilee Commemoration Lecture here, it was a debt the discharge of which could not be refused, however, unworthy I may be to represent petroleum exploration in this distinguished gathering, and undeserving of the honour of delivering this lecture.

I think that it will be appropriate for me to speak about the role of palynology in oil exploration, for this is the topic which provides the connecting link between the Birbal Sahni Institute of Palaeobotany and the Institute of Petroleum Exploration.

There are four main areas in oil exploration, where the role of palynology is very significant (Text-fig. 1). These are: (i) stratigraphy, (ii) palaeogeographic reconstruction, (iii) study of oil source rocks, and (iv) maturation.



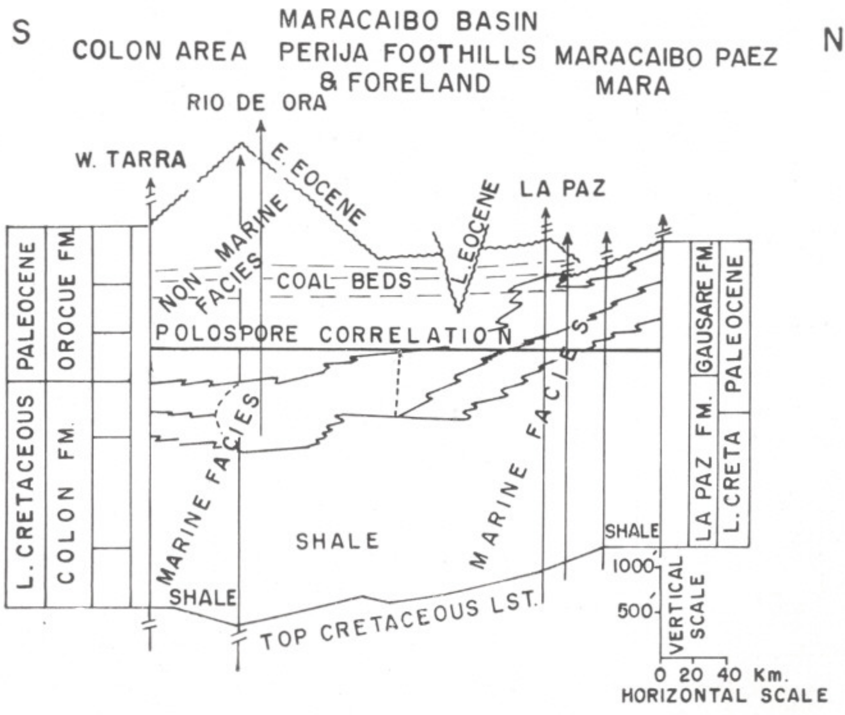
TEXT-FIG. 1 — Role of palynology in oil exploration (modified after Gutjahr, 1960).

ROLE OF PALYNOLOGY IN STRATIGRAPHY

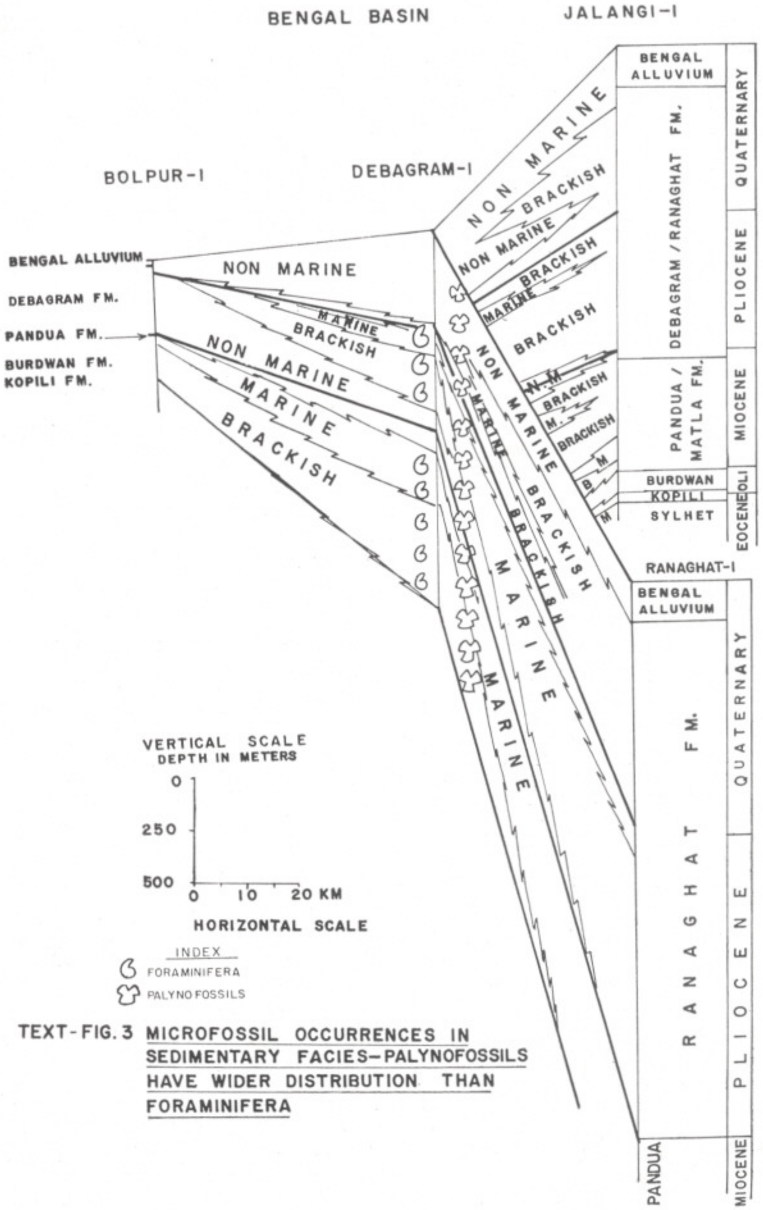
In oil exploration, the main application of geology is in the domain of sediments, because oil is formed and accumulated in sedimentary rocks. Such rocks are deposited in finite negative areas of the earth's surface, which are the sedimentary basins. Most sedimentary basins tend to remain as negative areas over most of their aereal extents, through most of subsequent geologic time. This means that their stratigraphic details can only be obtained from the subsurface, principally by drilling wells for oil and gas exploration — you cannot send a geologist to collect samples from the subcrop for stratigraphic studies. The volume of rock obtained as a sample in a drill hole is small, therefore that sample must contain the indicative fossil or mineral which can be used in stratigraphic correlation, Thus, *Gangamopteris cyclopteroides* var. *major* may be the index fossil for the Karharbari Stage of the Damuda Group of the Lower Gondwana " Series ", but if the drill hole passes at 2000 m depth through a patch of Karharbari shale without *Gangamopteris cyclopteroides* var. *major* leaf impression, we shall not know its stratigraphic position to be Karharbari. Nor will it be possible to drill a large number of wells, each costing more than one crore of rupees, in the hope that one of them will supply us with a diagnostic megafossil when passing through Karharbari shales. The form or population with the identifiable stratigraphic attribute must be ubiquitous enough to be present in a drill hole sample.

It is in this respect that palynology has become increasingly important in oil exploration, because the content of polospores in rocks is much higher than other populations of chronologic significance. This is why palynology attracted the attention of oil exploring organisations, ever since 1936, when the Royal-Dutch/Shell Group studied polospore successions to solve the problem of correlation of Tertiary lignites and lignitic clays in Mexico. In India, Burmah Oil Company encountered similar problems in Assam, and in 1947, they requested Prof. Birbal Sahni to study core samples of Barail, Surma, Tipam and Dhekiajuli formations for establishing palynofossil successions, which could be used for stratigraphic analysis of these immensely thick clastic sequences.

Palynology has a definite advantage over other subsurface correlation methods, and this is the only practical method known so far by which non-marine sediments can be correlated with marine sediments (Text-figs 2, 3). Much has been made of the triumphs of micropalaeontology in stratigraphy. A great deal of information has been accumulated on these very small marine animals found in sediments, and a lot of standard chrono- and bio-zones have been erected on the basis of sequences of microforaminifera. Nevertheless, it should be remembered that, of the different types of foraminifera, it is only the calcareous forams, and among these, only those of



TEXT-FIG. 2 — Section showing facies relations and time stratigraphic correlations by polospores (after Kuyl, Muller & Waterbolk, 1955).



TEXT-FIG. 3 — Microfossil occurrence in sedimentary facies — Palynofossils have wider distribution than foraminifera.

planktonic habit, which are widely distributed and have evolved rapidly enough in certain periods of Phanerozoic time, for use in correlation. They occur only in open marine conditions. With reduced salinity, they are replaced by arenaceous foraminifera, which evolved much more slowly through time, and are therefore not of much use in correlation. Even the more rapidly evolving planktonic calcareous foraminifera are really of high correlation value only when, as in the Gulf of Mexico deltaic sequences, they are associated with marine transgressions, which punctuate the general prograding, by delta out-building, that occurred in this area, from the Jurassic onwards. When these transgressive tongues, each with a particular species of foraminifera, have been followed down the palaeoslope, they have expanded and gradually merged with the sequences above and below in holo-marine areas, as we would expect them to do. Thus the zonal boundaries defined by planktonic foraminifera become less distinct in areas of holo-marine deposition than they are in areas of intertonguing of marine and non-marine sediments. From the point of view of oil exploration, areas of holo-marine deposition over extended periods of time are not the best locales for looking for substantial reserves of oil and natural gas. The occurrence of oil seems to be associated with the transition, from the marine to the non-marine environment of deposition in a sedimentary basin at any particular point of time. This is because it is at this transition that the optimum association between source rocks (largely marine) and reservoir rocks (marine to non-marine) occurs. Here detailed correlation across the facies interfaces by means of microforaminifera is not successful at all. It is because of this limitation that oil companies, who were pioneers in the use of forams in stratigraphy, have gone in for the study of spores and pollen for stratigraphic zonation. Although spores and pollen originate largely in terrestrial plants, their easy transportability ensures that they are widely distributed, both in marine as well as in non-marine depositional environments. In Oil and Natural Gas Commission, the problem of correlation of strata associated with oil reservoirs with no marine fossils in them, also made us turn very early to palynology for solution.

In palynofossils we generally include spores, pollen grains, nannoplanktons, silicoflagellates, diatoms, dinoflagellates, acritarchs, algae, and plant remains such as cuticles, exines, tissue fragments, etc. (Pl. 1, figs 1-10).

According to Talukdar (1980) the advantages of correlation by palynology are as follows:

1. The relatively indestructible nature of the pollen. Even Pre-Cambrian metamorphosed sediments contain identifiable palynofossils.

2. Their relative abundance, particularly in sub-surface samples. This allows the use of quantitative methods in their study.

3. Their susceptibility to long distance transport.

4. Their occurrence in both fresh water and marine environments enables us to correlate standard marine sequences with non-marine sequences.

5. Their colouration indicates the highest temperature to which the host rock was subjected subsequent to its formation.

6. They are good indicators of the ecological habitat of source, and are thus of great importance in the study of periods of rapid climatic change, such as the Pleistocene and Holocene.

The disadvantages are:

1. Small size of spores and pollen make them particularly susceptible to the removal by waters circulating through strata. An outcrop may be barren, whilst subcrops have prolific spores and pollen content. A buried unconformity may, for the same reason, give rise to poor yield of spores and pollen in the stratum below the unconformity.

2. For the same reason, and because of their resistance to mechanical erosion, the older forms are easily re-incorporated in younger deposits, complicating stratigraphic interpretation.

3. Disaggregation of spores and pollen from host rock is not easy, and the yield is strongly influenced by the method of separation. Spore-pollen colouration is also affected by some of the chemicals used in laboratory separation processes.

4. Since the land habitat is much more diverse as compared to the marine habitat, the separation of the source factor from the age factor of polospore populations is not easy. While this is an advantage in palaeogeographic work, it is a distinct disadvantage in stratigraphy.

5. Some of the economically most important sediments, such as evaporites and carbonates, do not contain significant amounts of spores and pollen.

6. In older strata, it is difficult to relate spores and pollen with the plants and trees which gave rise to them.

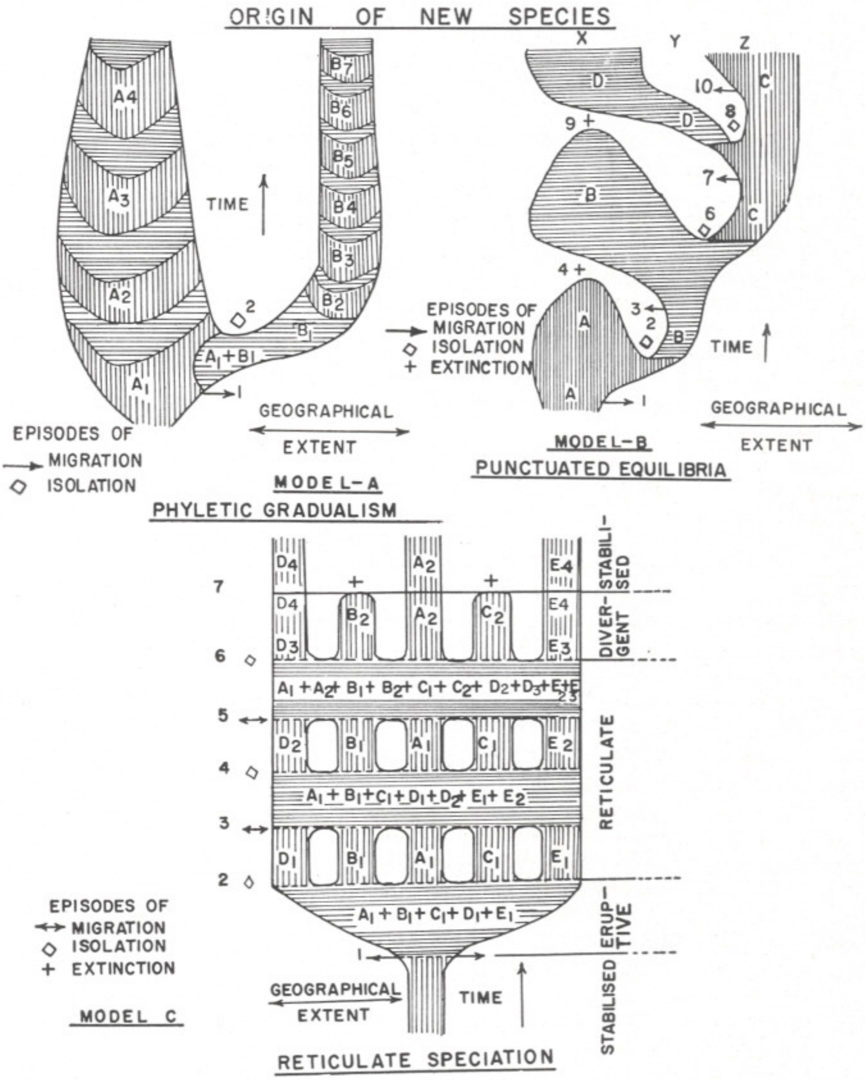
7. Taxonomy of spores and pollen is based entirely on morphology, and lineages based on genetic linkage are only inferred. Yet all stratigraphic and palaeogeographic

conclusions are based on the assumption that the evolutionary sequence of polospores can be inferred from their morphological-linkages. This is, of course, a problem which is common to all fossils.

A distinguished gathering of scientists, such as this, will be interested in the theoretical basis of palynostratigraphy, which is as follows.

The theoretical basis of palynostratigraphy is the change with time of populations and species of spores and pollen. New species may arise in a number of ways, of which the three more important are (Text-fig. 4) : (i) speciation by phyletic gradualism (i.e. Darwinian classical model), (ii) by punctuated equilibria (Eldredge, 1971), and (iii) reticulate speciation (Sylvester-Bradley, 1977).

In phyletic gradualism, both phylogenesis (i.e. origin of new species, by modifications, arising in course of geological time, in a single phyletic line) and cladogenesis (origin of new species by the splitting of the phyletic line) occur. This involves the episodes of migration and isolation. In



TEXT-FIG. 4 — Three different ways of evolution of species (after Sylvester-Bradley, 1977).

the punctuated equilibria model, new species arise abruptly. This involves episodes of migration, isolation and extinction. In reticulate speciation, new species arise in course of expanding migration, with hybridization between geographical races. It combines the features of phyletic gradualism and punctuated equilibria, although punctuated equilibria are antithetic to gradualism. Sylvester-Bradley (1977) claims that phyletic gradualism provides a tool that can be coupled with statistical evaluation of any population to give a precise point on a curve, correlating evolutionary modifications with stratigraphic position. The model of punctuated equilibria provides, on the other hand, a series of index fossils, each of which characterises one of a series of consecutive zones.

The three phylogenetic patterns have been described to have quite different functions in biostratigraphy :

1. There is sufficient danger of error in using a polytypic complex, with its associated geographical sub-species, and changing morphology in different directions with time and space, for correlation purposes. This danger becomes still greater if the species also exhibits ecotypic variation, where the modification is caused by the same environment at different times. Such a species can be used for stratigraphic purposes, only after studying the variations over the entire provenance of species.

2. In case of polymorphic species, discontinuous speciation showing punctuated equilibria, we get the results which are more helpful in defining the zonal boundaries. Thus, one zone is abruptly replaced by another, and is easy to recognize.

3. In phyletic gradualism, in order to determine the accurate stage of evolution in the lineage, besides the knowledge of taxonomy of the group, it is necessary to study a very large population and carry out statistical analysis of variance. Such statistical analysis of a lineage representing phyletic gradualism gives a more reliable stratigraphic picture. However, phylogeny is rarely gradual, and more often discontinuous. Therefore, one cannot assume that new species evolve in one particular manner only. Punctuation in biostratigraphy does exist and is helpful in finding the zonal limits.

Palynozones in a sedimentary sequence are generally deciphered on the basis of four criteria : (i) establishment of an evolutionary series, ii) first appearance, maximum development and extinction tops of groups, genera and species, (iii) general assemblage of palynofossils and their ratio, and (iv) increase and decrease in quantity of palynofossils.

In our own work in the Oil and Natural Gas Commission, palynology has given us information on stratigraphic position of otherwise unfossiliferous sequences when other information was lacking. Drilling in Gangetic plains had confirmed the occurrence of two sequences, an upper unfolded one thickening northwards, and a lower sequence with major folds and faults. Both are devoid of microfauna. However, spores and pollen were recovered, and it was evident that the upper sequence is of Siwalik age (Upper Miocene to Pleistocene), whereas the lower sequence is of Upper Proterozoic to Lower Cambrian age, equivalent to Vindhyans exposed to the south of Gangetic plains, in the area to the WNW of the Patna-Saharsa subsurface high. To its east, the folded sequence below the Neogene is of Gondwana age, and it is possible to establish, on the basis of polospores, the boundary between the Permian and the Triassic in the subsurface near Purnea (Venkatachala & Rawat, 1979). Similarly, it was only possible to fix the stratigraphic position of the 4000 m thick Dharmsala sequence of the foothills of north-western Himalayas on the basis of palynoflora. This thick sequence of sandstones and red clays ranges in age from Oligocene to Lower Miocene (Mathur, 1979). The overlying Siwalik sequence, known the world over for its vertebrate fossils, was examined by the ONGC in great detail in outcrops as well as in drilled wells. We found that fossil vertebrate occurrences are extremely rare, and totally absent in drilled wells. Heavy minerals did allow some correlation between blocks, but heavy mineral populations were provincial, and heavy minerals could not be used for widespread correlation. However, palynoflora does occur, not in as much abundance as we had hoped, and from the palynoflora Lower, Middle and Upper Siwalik subgroups (total thickness in excess of 6000 m) could be tied into the standard Tertiary time sequences (Mathur, 1979). Such work also showed the strong time-transgressive nature of the lithologic zones.

To the north-west of this belt, in Ladakh, the age of the youngest sedimentary sequence (the Ladakh Molasse) was established as ranging from Palaeocene to Miocene (Bhandari *et al.*, 1977). Palynoflora recorded from the tuffs associated with the Dras Volcanics suggests that the volcanic episode here is contemporaneous with that of Deccan (Mathur & Jain, 1980). This has obvious implications in regard to the tectonic history of the Indian plate in terms of the plate tectonics hypothesis.

In what is essentially a continuation of the Assam-Arakan fold belt, the Andaman and Nicobar islands, workers in the Institute of Petroleum Exploration have identified palynofossils typical of the Barails of Upper Assam and thus established a basis for long distance correlation between widely separated areas. The palynoflora of the lowermost part of Port Blair Formation of Middle Andaman Island is also similar to that found in Burdwan Formation of Bengal Basin (Mathur & Mathur, 1980).

In Bengal Basin, a large part of the sequence can only be classified on the basis of palynostratigraphy. Established palynostratigraphic zones can be recognized throughout the basin (Text-fig. 5).

At the other end of India, Muller (1974) indicated a close similarity between the Albian-Senonian palynoflora of Kachchh and that of Borneo and Australia, which provides some interesting contrasts to the affinities of the Mesozoic Cephalopod fauna of Kachchh with those of Madagascar. Subsurface material obtained by drilling of deep wells by ONGC in the Banni of Kachchh and studied in our Laboratory has clearly indicated the beginning of sedimentation in the Rhaetic-Liassic times, somewhat earlier than obtainable from surface evidence (Koshal, 1975). In the Tertiary of Kachchh, we could erect 16 palynozones and correlate them with standard planktonic foraminiferal zones.

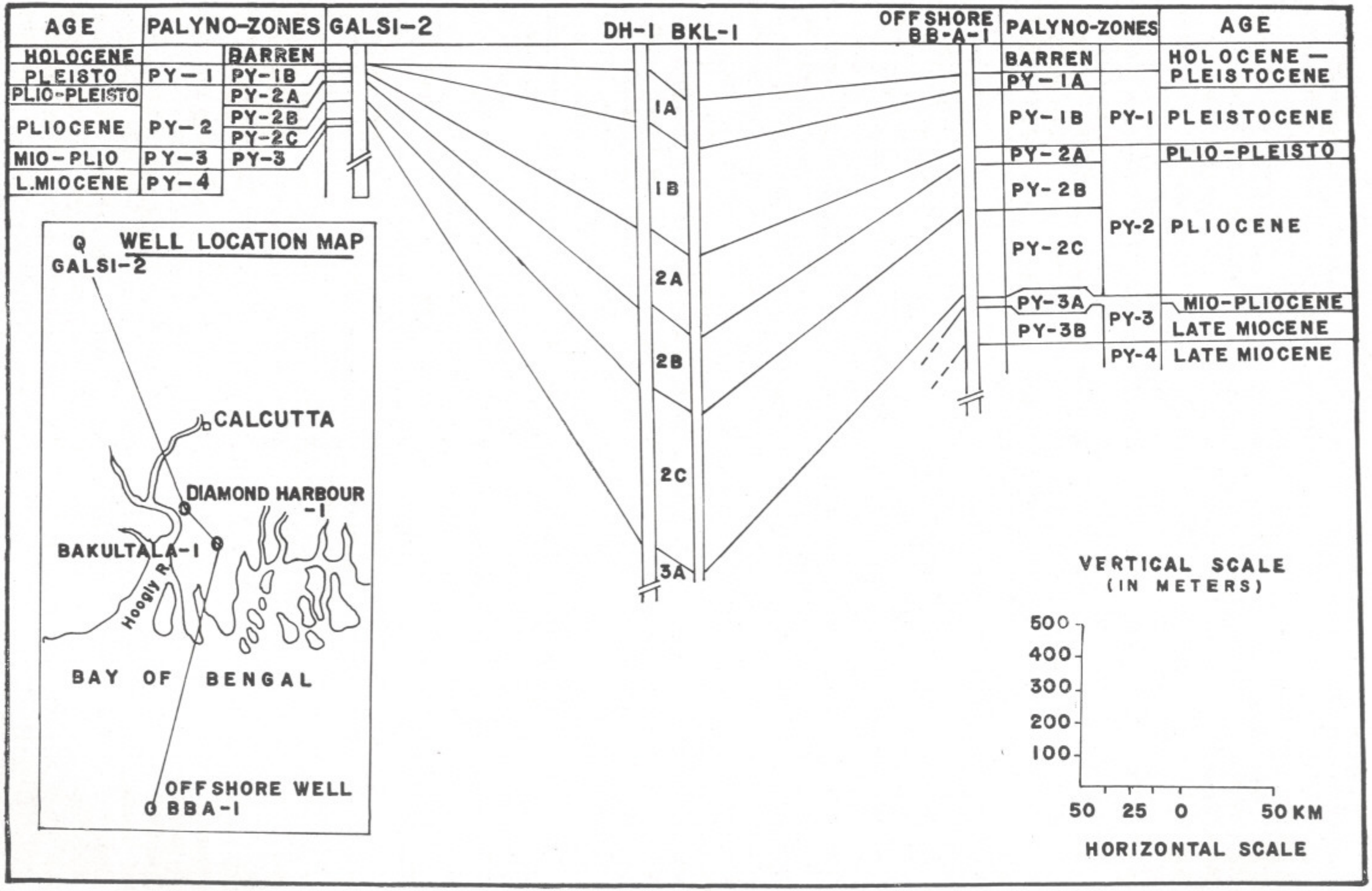
In the course of oil exploration in the other shelf of Indus Basin, Rajasthan, the ONGC found it necessary to establish a palynology laboratory at Jodhpur for solving problems of stratigraphic correlation of sequences met with during drilling. With the help of palynoflora, 18 palynozones could be established in the Mesozoic. In the Jurassic-Lower Cretaceous transition, which is totally devoid of fossil fauna, the boundary could only be obtained from polospore data (Mathur & Mathur, 1976). Permian and Triassic sediments were also recorded from palynological studies (Tikku *et al.*, 1976). All this stratigraphic information, useful for detailed analysis as well as for intra-basinal correlation, could not have been obtained by any other means.

In addition to establishing the age of a stratum or sequence, of course, palynology gives us a great deal of information on the palaeogeography.

PALYNOLOGY IN PALAEOGEOGRAPHIC RECONSTRUCTION

The geologist who is engaged in oil exploration very soon realises that where the volume of rocks in a sedimentary basin containing commercial deposits of oil and gas is very large, measurable in hundred of thousands or millions of cubic kilometres, the fraction of interest for oil exploration is a very small percentage of the total rock volume. For example, the Gujarat petroliferous basin has about 100,000 cubic kilometers of sediments. The total oil reserves of this basin, which supplies 30% of India's indigenous production, occupies a rock volume of only 5 cubic kilometer. Source rocks and reservoir rocks each, are deposited in particular physico-chemical environments, and so are cap rocks. These environments are inter-related in space and time with each other, and therefore the different source and depositional environments existing in a particular interval of time can be mapped, the areas of interest from the point of view of oil exploration in a basin where sedimentary rocks were deposited during that period of time, can be demarcated, and exploratory activities concentrated there.

Both source rocks and cap rocks share one property — they are fine grained. However, whereas all fine-grained rocks are good cap rocks; all are not good source rocks. It is necessary that source rocks should be fine grained. because only in low depositional energy environments does organic matter get preserved. However, it is also necessary that the palaeoenvironment should be such that a significant



TEXT-FIG. 5 — Palynostratigraphic correlation of Plio-Pleistocene strata in Bengal onland and offshore wells.

quantity of organic matter could form and enable itself to be transported to the depositional area, without too much destruction. Such formation and deposition is restricted to particular environments, such as silled basins, or pro-deltas and interdistributary swamps in rapidly prograding sequences.

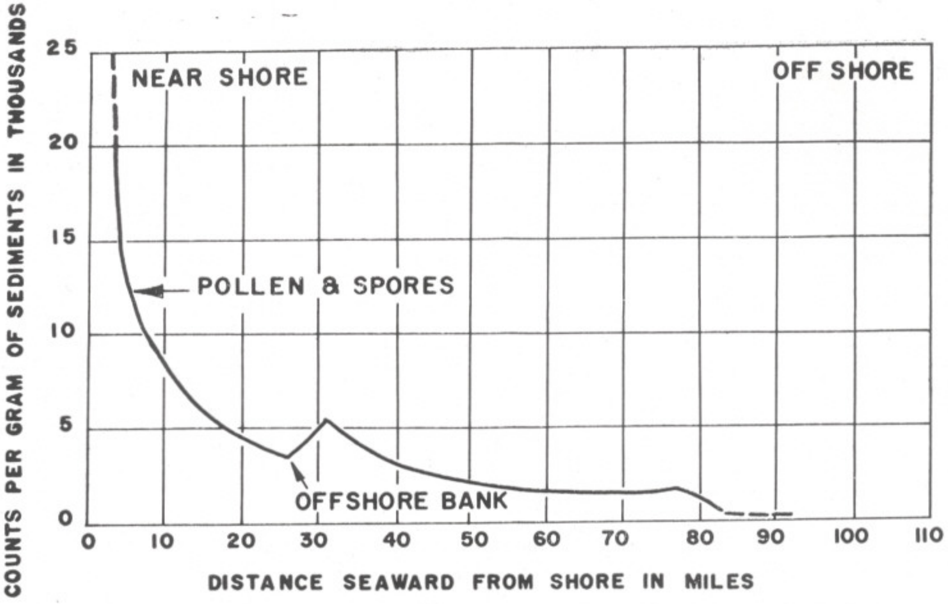
Reservoir rocks, on the other hand, should have primary and/or secondary porosity development. Primary porosity development requires a high energy depositional locale, where sorting of grains ensures that the larger and better rounded fragments are concentrated and finer fractions of the sediment winnowed out. Secondary porosity development is the result of diagenetic changes subsequent to deposition, as well as of tectonism after the sediment is consolidated. Ultimately, therefore, secondary porosity development is the result of endogenetic forces directed outwards. Source rocks maturation, on the other hand, is caused by movements in the reverse direction, i.e. towards greater depths and higher temperature associated with greater depths.

Nevertheless, for oil to concentrate into economically exploitable deposits, the source rocks, reservoir rocks and cap rocks, deposited in dissimilar palaeoenvironmental situations, must be connected up during the time of migration of the oil from the source rock. There must be a migration path or conduit between the source and reservoir, and the potential energy difference should be adequate to ensure that the oil does in fact migrate from the source to the reservoir along the conduit. After migrating to the reservoir, there must be a permeability barrier to further migration, in order to ensure the retention of the oil in the deposit. The key to understand these occurrences in a sedimentary basin is the palaeogeography during deposition and thereafter.

For these reasons, in oil exploration, geologists make a great deal of efforts on obtaining the palaeogeographic information on the sequences in a sedimentary basin. It is here that palynology is becoming increasingly important. Land plants are sensitive indicators of the environment, and it is the spores, pollen and other parts of such plants which are transported and deposited, together with the enclosing sediments in the basin. Fossilized remains of land plants should therefore indicate the climate of the source area of the sediments. Since spores and pollen are easily transported by wind, their concentration in a sedimentary sequence should also be related to the distance travelled. Remains of marine plants, on the other hand, are not transported to the same extent as those of land plants, since they occur in the depositional basin itself. Marine habitats are also not so sharply differentiated as land habitats. Temperature, salinity, amount of light available, exposure to atmosphere in inter-tidal zones, etc. are the deciding factors.

Thus, the quantity of spores and pollen of shoreline land plants in a marine sedimentary deposit indicates proximity to shore line (Text-fig. 6), as does the ratio between spores and pollen of land origin to phytoplankton of marine origin. Where the marine phytoplanktons are absent, it will be safe to conclude that the deposition was in fresh water or sub-aerial. Where the marine organisms are present, and are not, the result of redeposition, the conclusion that sedimentation was in a marine environment is inescapable.

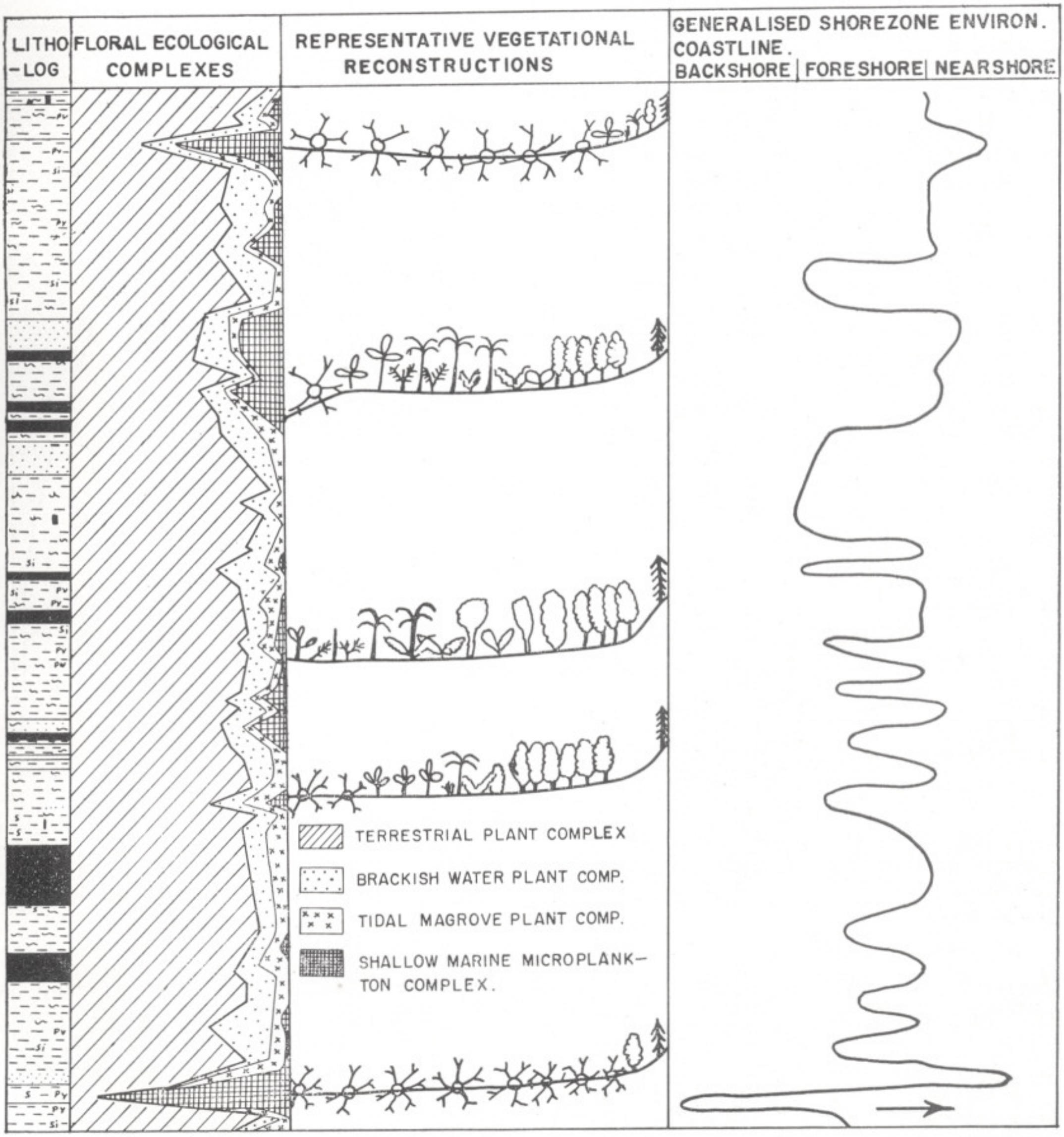
In 1958, Ghosh found spores and pollen in Lower Siwalik sediments of Jawalamukhi suggestive of warm and humid climate in close proximity to the sea. Until then, the prevailing idea was that the Lower Siwalik is entirely fresh-water in deposition, the Upper Miocene sea occurring much further to the south-west of the north-west Himalayan foot-hills area. The rich vertebrate fauna of the Kamlial and Chinji " Stages " of Potwar Plateau, 4000 km to the west of Jawalamukhi, the total absence of marine megafossils (indeed the total absence of microfauna), the red colour of Lower Siwalik clays, and the cross-bedded nature of Lower Siwalik sandstones, were all held to indicate fresh-water and sub-aerial deposition. Yet there were many saline springs in areas of outcropping Lower Siwaliks of Jammu and Kangra, and very high salinity of connate waters of Lower Siwalik sandstones in drilled wells in the plains at locations as far apart as Adampur (near Jullundur), Puranpur (in Pilibhit District, U.P.) and Raxaul (on the Nepal border of Champaran District, Bihar), suggested that the palaeogeographic conclusions from the spores and pollen in Lower Siwalik strata need not be brushed aside, although they were in opposition to the views held by such pioneer workers as Pilgrim and Wadia.



TEXT-FIG. 6 — Pollen and spore density in recent sediments from the Gulf of Mexico (after Woods, 1955).

Recently, we have obtained some microfossils of undoubted marine origin in Lower Siwalik sediments, and are trying to ascertain whether they are reworked forms, or are indigenous to the host sediments. I need hardly emphasize that possible palaeogeographic implications are tremendous. Similarly, our palynologists have recorded marine forms in the Talchir shales of the Palar basin, to the north of Madras. These are, of course, uppermost Carboniferous to Lower Permian in age.

Palaeoshoreline delineation by mapping the palynofloral density as well as by the ratio between land and marine forms, as already mentioned, is an important activity in basin studies conducted by oil exploration organizations. This is because in any one geologic interval, oil accumulation is concentrated in areas on both sides of the palaeoshoreline, where the maximum contact occurs between source and reservoir rocks. Oil fair-ways migrate with the strandline migration in time, as demonstrated many years ago by Rainwater in the deltaic sequences bordering the Gulf of Mexico. It was in shoreline delineation that palynology first proved its utility in palaeogeographic reconstruction. Hoffmeister (1954), in his classic work on the determination of ancient shorelines by means of polospores, used the technique of drawing " isobotanical lines " through points with the same microfossil population or the same type of microfossils. His opinion was that the shoreline was indicated when the density of spores and pollen decreased to below 7500 per gram of sediment. Subsequently in 1960, he utilized palaeoshoreline maps prepared on the basis of polospore density to demarcate areas favourable for oil occurrence, in the Seminole-Oklahoma City region. Mathur and Chowdhury (1977) have used palynological studies for interpreting the palaeogeography and shoreline changes in detail in the northern part of Cambay basin during the deposition of Kalol Formation (Middle Eocene). They grouped various palynofossils into 13 ecological complexes and traced their vertical and lateral distribution in time and space. Fifteen shoreline fluctuation cycles were recognized (Text-fig. 7) and generalised palaeogeographic maps for the Sertha (Text-fig. 8) and Wavel (Text-fig. 9) members of the Kalol Formation were prepared. Earlier, Mathur *et al.* (1973, 1974) interpreted certain areas and horizons of the Kalol Formation as being

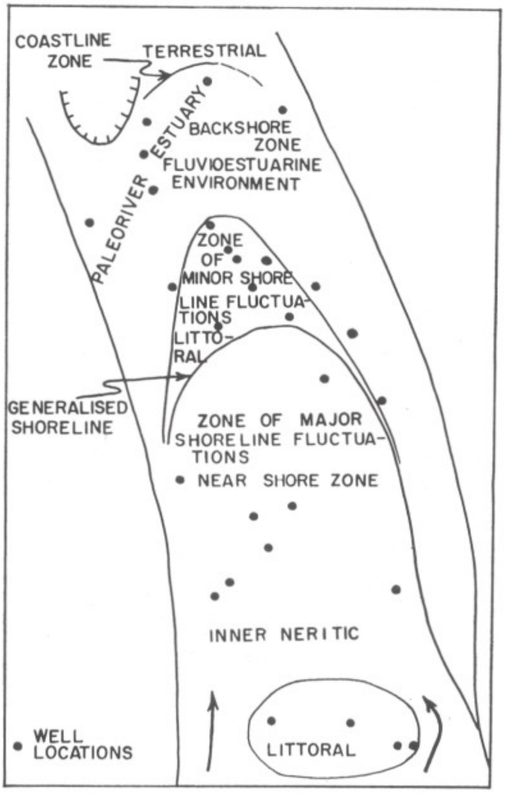


TEXT-FIG. 7 — Floral complexes distribution in Kalol Formation of Kalol Well no. 109 showing shoreline fluctuation and vegetational reconstructions (after Mathur & Chowdhury, 1977).

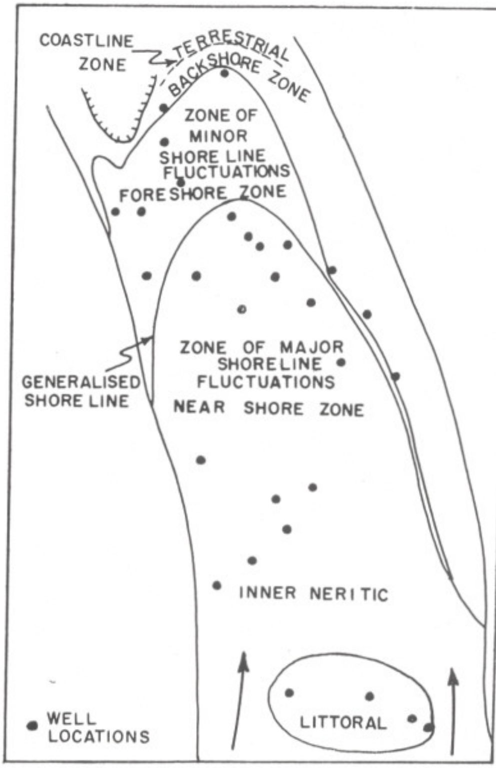
favourable for oil exploration on the basis of their study of palynoflora of the area (Text-fig. 10). Parameters taken into account were general palaeogeography of the basin during the time intervals, shoreline changes, concentration of palynoflora, polo-spores and dinoflagellate ratios, and distribution of lipid-rich organic matter in the sediments. In some parts of the area interpreted to be favourable, oil accumulations have subsequently been discovered.

ROLE OF PLANTS IN PROVIDING SOURCE MATERIAL FOR HYDROCARBONS

The organic origin of oil and gas is now almost universally accepted. The organic matter is incorporated in the sediments



TEXT-FIG. 8 — Palaeoecogeographic map of North Cambay Basin during the deposition of Sertha Member, Kalol Formation (after Mathur & Chowdhury, 1977).

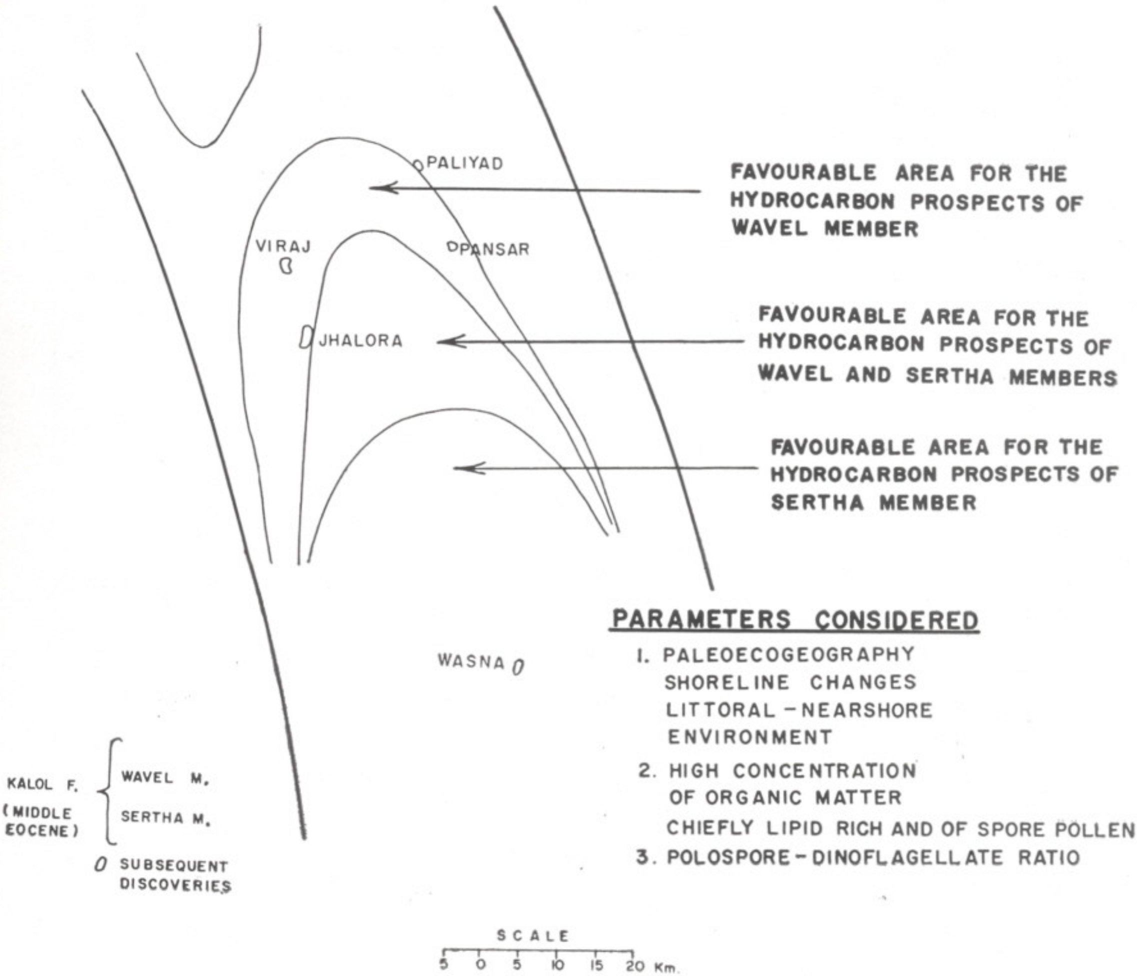


TEXT-FIG. 9 — Palaeoecogeographic map of North Cambay Basin during the deposition of Wavel Member, Kalol Formation (after Mathur & Chowdhury, 1977).

deposited and altered — at the surface by biogenic agents, and when deeply buried, in a subsiding basin receiving sediments by thermo-chemical means.

What is this organic matter ? Earlier, it was believed that only large animals contributed organic matter for transformation to oil and gas. Later on, this role was ascribed to small animals. But now it is realized from biochemistry that it is plant life, including microorganisms such as bacteria, which not only form the beginning of the food chain of the biosphere, but also contribute the largest volume of organic matter to source rocks of petroleum. This is the result of intensive work on the biological and chemical nature of the organic remains in sediments, carried out in the last decade in the laboratories of oil companies and institutes. It involves collaborative studies between petroleum geochemists and palynologists, the latter being largely concerned with the study of the alteration of plant remains by different agencies, from the time of their deposition to their complete transformation into source material, commonly known as kerogen.

Land plants and marine phytoplankton convert CO_2 by photosynthesis into cellular tissue of fatty substances, or lipids, carbohydrates and proteins. Thereafter, the plants may die and be altered, or they may provide food for animals at the beginning of the food chain. In the latter case, plants provide the material for cells of the living animal, as well as faecal matter which are enriched in lipids. On death, the animal cells are also broken down, and either returned to the atmosphere, or incorporated as organic matter in sediments. Only the

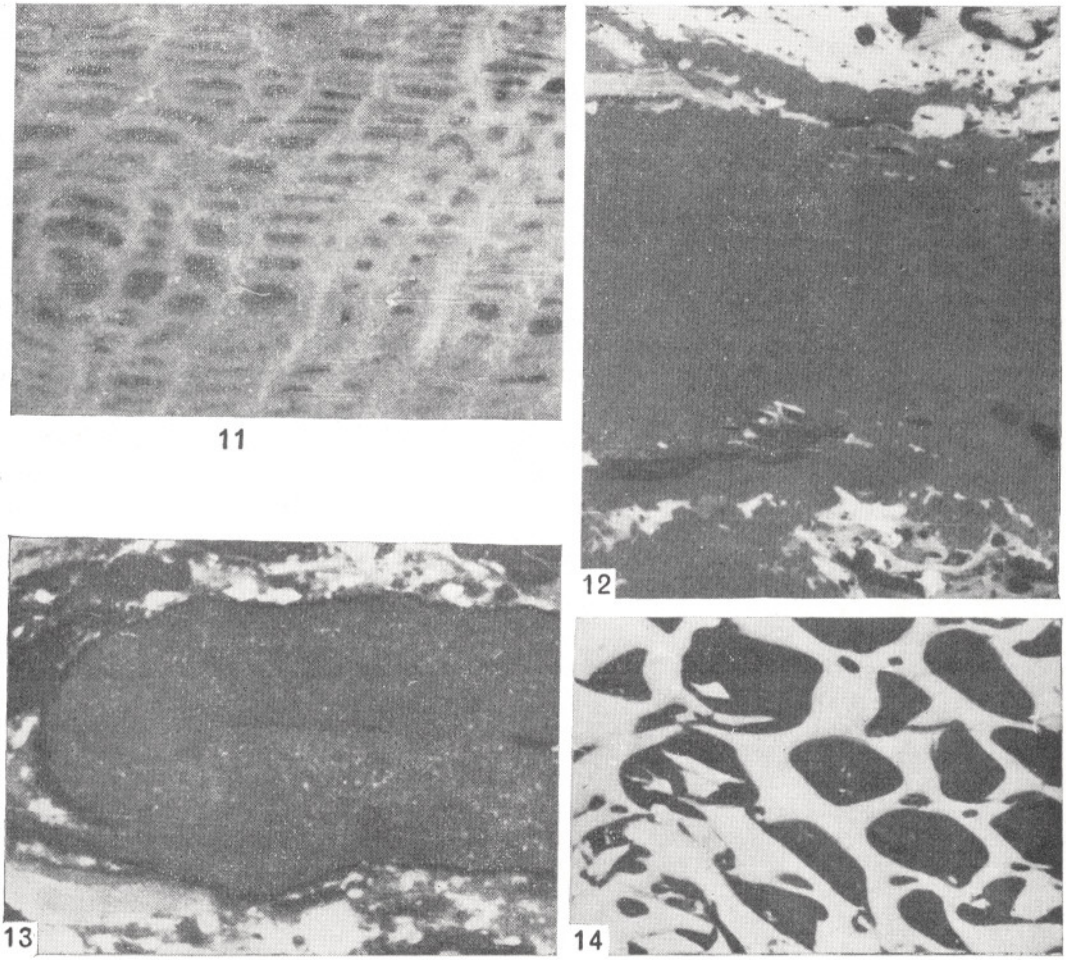


TEXT-FIG. 10 — Map of North Cambay Basin showing areas and members of the Kalol Formation predicted to be hydrocarbon bearing on palynological methods and subsequent discoveries (modified after Mathur *et al.*, 1974).

most resistant parts of organic matter remain; they consist essentially of humic and lipid matter.

Plants contain carbohydrates, such as cellulose and starch, strengthened by lignin. The leaves are protected by cuticle, which is impregnated with wax. The plants may also secrete resins, and they produce spores and pollen grains which are transported. When the plants die, they are biodegraded by means of the soil microfauna, fungi and bacteria. The carbohydrates are consumed, and humic acid is produced by the micro-organisms. When plant remains are abundant and the debris water logged, oxygen supply is rapidly depleted, and the humic acid forms a gelatinous solution permeating the woody skeleton, consisting mainly of lignin. The humified wood becomes *Telinite* (Text-fig. 11) and the humic acid gel becomes *Collenite* (Text-fig. 12), two principal constituents of *Vitrinite*. With higher oxygen supply, the microbial degradation of organic matter is increased and the humic acids and humified woody skeletons become altered to mineral charcoal or *Fusinite* (Text-fig. 13). The spores, pollen, wax coated cuticle and resins together form *Exinites*.

These, then, are the components of land plants which are deposited in sediments.



TEXT-FIGS 11-14 — Organic macerals. **11**, Tellinite; **12**, Collenite; **13**, Semifusinite; and **14**, Exinite.

In the sea, the lipid-rich phytoplanktons, partially digested by the zooplankton, are acted on by bottom dwellers and bacteria. Eventually, the residual components of the micro-algae and bacteria are disseminated through the sediment as it is buried; sometimes as actual cell walls which are termed *Alginites* and *Sporinites* (Text-fig. 14), but more often as a very fine-grained and amorphous film, clinging to inorganic particles. This organic matter is termed *Amorphous* sapropel. Where the concentration of organic matter is high enough, the enclosing rock is termed as the *source rock*. It is the thermo-chemical metamorphism which, this material undergoes due to burial, gives rise to economic deposits of combustible minerals. When the proportion of lignin is large, thermo-chemical metamorphism converts the organic material to coal and dry gas. Where the other material is preponderant, we get wet gases and oils. Historically, the insoluble organic matter remaining in a rock after extraction with solvents has been named as *Kerogen*. Kerogen on distillation yields hydrocarbons, and most authorities believe that kerogen is the source of petroleum. Most sedimentary kerogens are mixtures of organic matter derived from land plants rich in humic matter and marine plants rich in lipids.

Palynologists study the progressive alteration of plant material, from source area to mature source rock, as a part of the process of understanding how petroleum is formed. I have already mentioned the earlier stages of the process, i.e. biodegradation. The other facet of study is the *typing* of organic matter. The hydrocarbons produced by the source rock depend upon the percentages of different types of material in the kerogen, and thus we are getting near to being able to predict what kinds of oils and gas will be produced from a particular type of kerogen.

Besides the composition of the Kerogen, the other parameter in the composition of the resulting combustible mineral, i.e. coal or oil, is, of course, the degree of thermo-chemical alteration of the source material, due to increasing pressure and temperature, as the material is progressively buried. Here too, palynology has provided us the tools for estimating the degree of maturation of the source rock.

MATURITY OF SOURCE ROCKS FROM PALYNOLOGICAL STUDIES

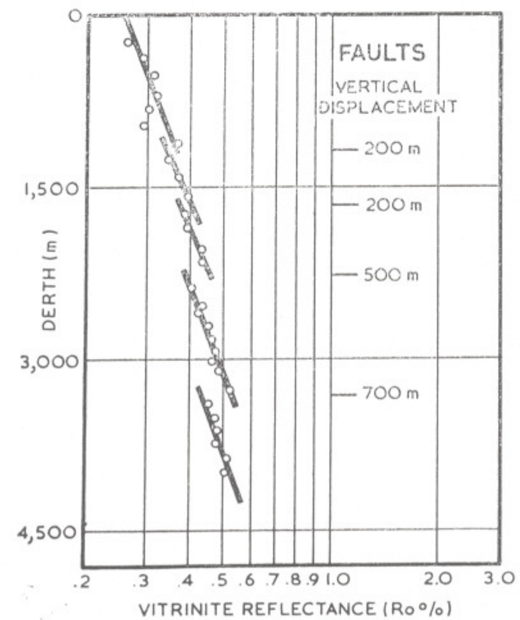
Organic matter in source rocks, as mentioned earlier, consists chiefly of remains of land and marine plants, which responds to increasing heat by physical changes, reflecting decrease in content of volatiles and concomitant enrichment in carbon. These changes are of four kinds, viz., (i) darker colouration of organic matter, (ii) increase in refractive index, (iii) increase in reflectivity, and (iv) loss of structural detail on particulate organic material and decrease in light transmission of particles.

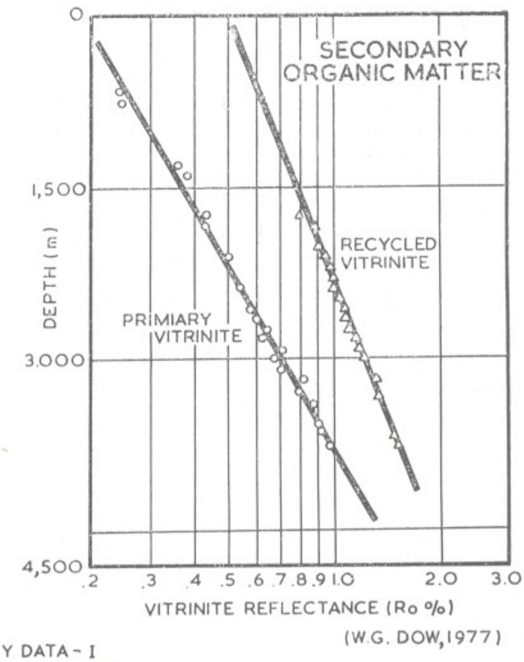
The changes can be quantified. Colour change of plant remains is the easiest to use and the least expensive method of estimating the maturity of the source rock. However, different organic material alter or mature at different rates. A scale of progressive alteration that uses colour changes must be based on similar material. It is usual to study colour change in spores and pollen which lack ornamentation as a guide to the maturity of the organic matter. Cuticles and epidermis could also be used, in the absence of spores and pollen, or as supplementary material. Care has to be taken in such work to eliminate older spores and pollen, redeposited with material appropriate to the age of the sediment being studied.

There are several scales for measuring the degree of thermal alteration. The 1-5 scale proposed by Staplin is the one which is generally used. The number assigned to a particular sample is designated as its Thermal Alteration Index or TAI. Higher numbers reflect progressively increasing temperature to which the sediments have been exposed. TAI 1 is ascribed to fresh material, and an index of 5 to thoroughly metamorphosed material. An index of 3·5 corresponds to the disappearance from both source and reservoir of all light oil producible components, except dry gas. At this index, plant cuticles and spores and pollen are dark brown in colour. The principal oil generation phase is at TAI 2·5-3·0

Of the other techniques, increase in vitrinite reflectivity is widely used, and is in many ways the most suitable, because it is quantitative, discriminatory, accounts for both time and temperature, is useful over the entire maturity range, and can be applied to most sedimentary rock types. In this type of work, too, it is necessary to identify the indigenous or autochthonous vitrinite. The results are plotted as reflectograms, i.e. histograms of frequency 1/2 V stages (0·05% vitrinite reflectivity intervals), and notes are made on organic petrography. When all the results are plotted, the indigenous vitrinite reflectance has to be selected, and the vitrinite reflectance vs. depth plot made. Vitrinite reflectivity provides a direct guide to thermal maturity of gas prone organic matter (humic material), and an indirect guide to the thermal maturity of oil prone organic matter (sapropelic material).

Discontinuities in the reflectivity — depth plot give important geological information. Normal faults are indicated by abrupt increase in reflectivity gradient, whereas reversed faults show abrupt decrease (Text-fig. 15). Reworked vitrinite may show a persistent trend (Text-fig. 16) indicating persistence through time of a particular source. Unconformities are marked by an abrupt increase in reflectivity, and often, from the change in the gradient, the thickness of the eroded strata can be calculated (Text-fig. 17). Igneous intrusions (Text-fig. 18), sills and dykes cause a rapid increase in reflectivity (Dow, 1977).

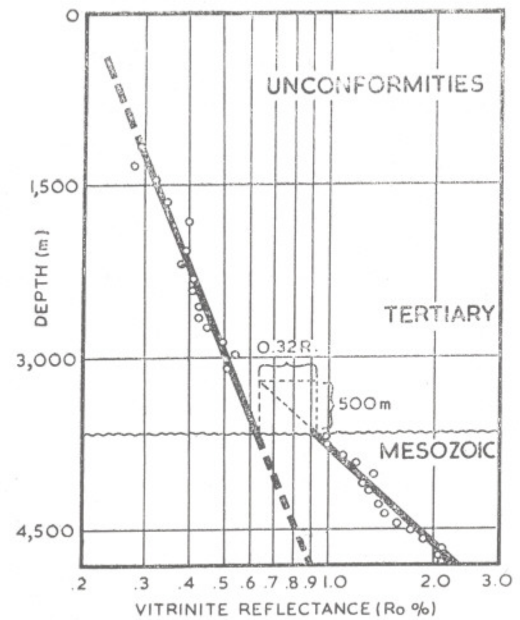


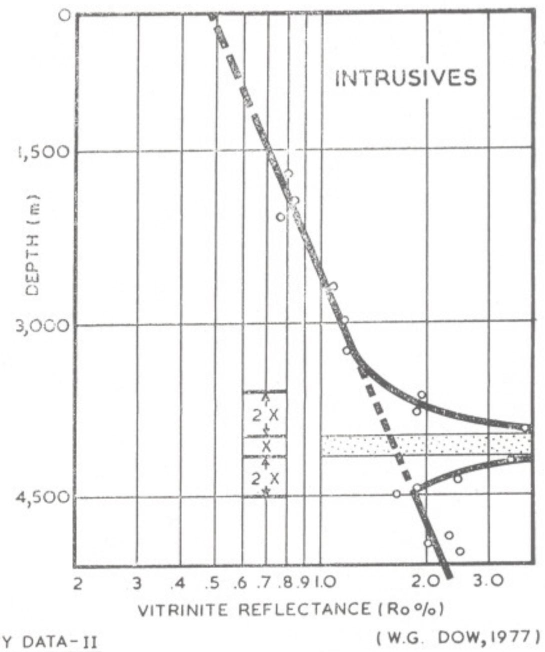


DISCONTINUITIES IN VITRINITE REFLECTIVITY DATA - I

TEXT-FIG. 15

TEXT-FIG. 16



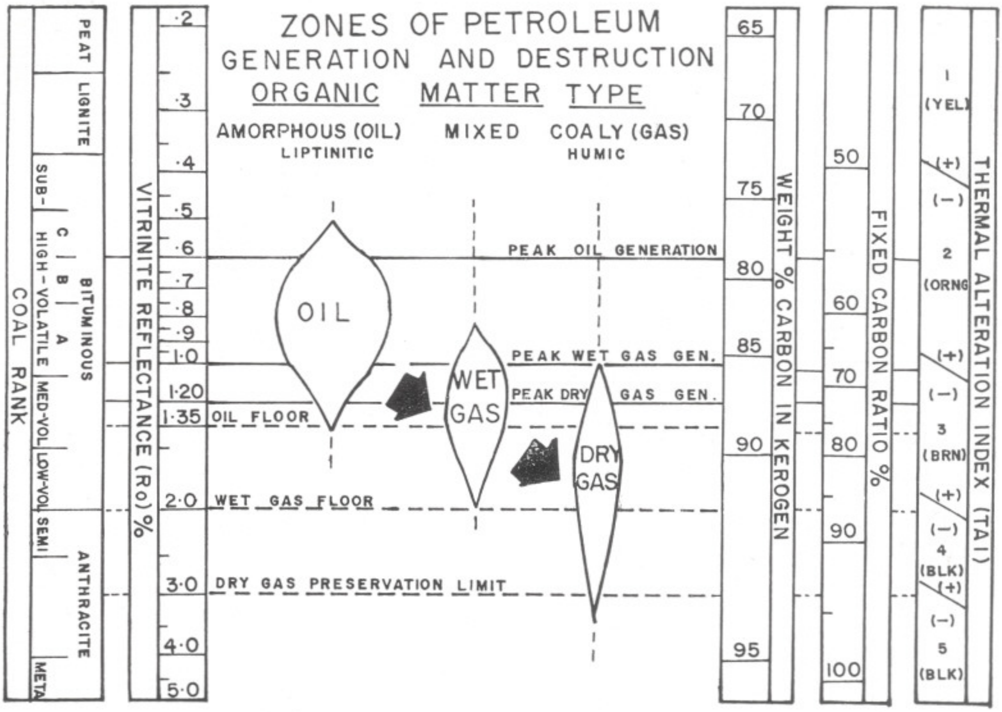


DISCONTINUITIES IN VITRINITE REFLECTIVITY DATA - II

TEXT-FIG. 17

TEXT-FIG. 18

TEXT-FIGS 15-18 — Vitrinite reflectance maturation profiles.



TEXT-FIG. 19 — Correlation of the coal rank scale with various maturation indices and the zones of petroleum generation and destruction (Dow, 1977).

The correlation of different maturation indices and the zones of petroleum generation and destruction is shown in the Text-fig. 19 (Dow, 1977).

SUMMARY

To sum up, the special nature of the habitat of oil in sedimentary sequences is such that many of the problems connected with the geological side of oil exploration can only to tackled by palynology. In stratigraphy it is only by palynological studies that fresh-water sediments can be zoned and compared with standard marine zones down the palaeoslope from the strand line, and it is around the palaeo-shorelines that most oil occurs, being the most favourable location for the intertonguing between source and reservoir rocks. If we keep in mind the evolutionary and geological processes by which floral successions are vertically stacked in a sedimentary sequence, palynostratigraphy becomes a very important tool in oil exploration. Indian examples bear out the truth of this statement. Again, because land and marine plants occupy very specific ecological habitats, their remains are of high interpretative value in palaeogeographic studies. In particular, palaeo-shorelines can be demarcated by estimating palynoflora density and ratio between land and marine palynoflora. Such studies have also been undertaken in Indian sedimentary basins. Palynology is also necessary in source rock studies, because plants contribute the largest amount of organic matter to source rocks. Different parts of plants contribute different types of organic compounds to source rocks, and form different oil and gas constituents, on the thermochemical metamorphism of the source rock. Finally, the degree of metamorphism of source rocks is best determined by studying the colouration of fossil spores and pollen and the vitrinite reflectance of plant remains. The latter study also yields other structural and stratigraphic information on a sequence, which is of importance in oil exploration.

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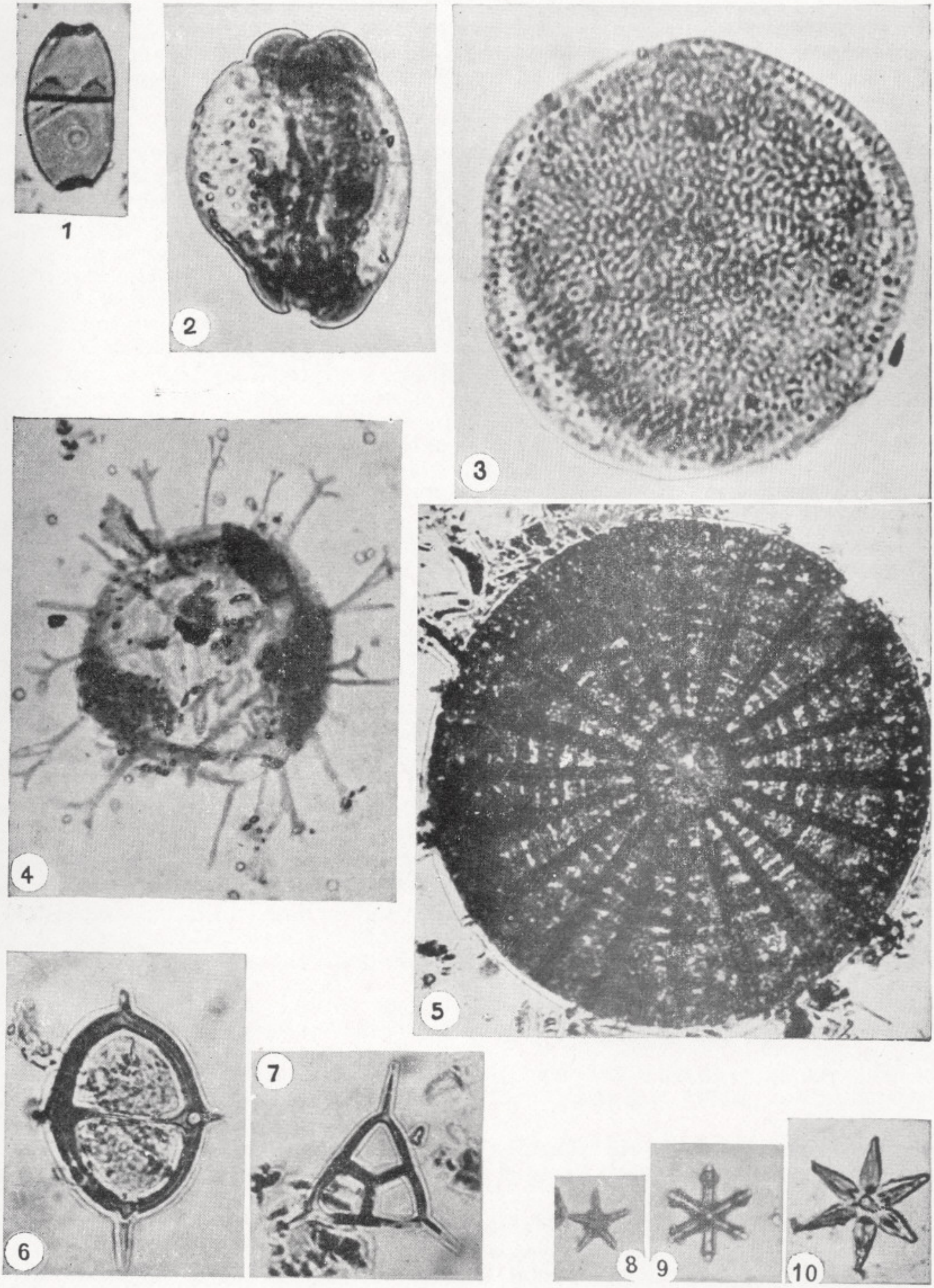

PLATE 1