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FOSSIL DINOPHYCEAE AND ITS USES IN PETROLEUM EXPLORATION WITH SPECIAL REFERENCE TO INDIA

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ABSTRACT

Various environmental factors responsible for the production, encystment and distribution of modern dinoflagellates are reviewed. Fossil record of dinoflagellates and acritarchs is also reviewed and indicated that their presence in the sedimens do not always represent a marine depositional environment. Acritarchs have been important in Precambrian and Palaeozoic, whereas dinoflagellates were important in Mesozoic and Cenozoic as a valuable group of fossils in biostratigraphy, palaeoecology and for the interpretation of depositional environments. It is emphasized that little work has been done in India considering the vastness of the country and utility of this group of fossil in petroleum exploration as excellent markers of various zones in the surface and subsurface sediments. The detailed study of recent dinoflagellates in the Bay of Bengal, Arabian Sea and Indian Ocean and fossil dinoflagellates of Mesozoic and Coenozoic sediments from the coastal sedimentary basins of Peninsular India would help in the understanding of evolutionary history of Dinoflagellates.

INTRODUCTION

The study of fossil dinoflagellates and acritarchs, though more than one century old, have been taken seriously as an aid in geological exploration only after 1960. At present, dinoflagellate cysts are considered important fossil group in petroleum exploration all over the world. This group displays a remarkable morphological diversity, thus can be easily identified, most of them are geologically short lived, and due to their planktonic nature, are geographically widely ditributed. These factors make them in general good index fossils. The fossil record of dinophyceae goes back to Silurian (Sarjeant, 1967), but are abundant in marine sediments only from upper Triassic onwards. These have been used in various palaeoecological and palaeoenvironmental studies (Williams and Sarjeant, 1967, Sarjeant, 1970a).

It is quite essential for palaeoecological studies based on dinoflagellates to know and understand their living present day counterparts. The difficulty of such investigation is that, dinoflagellates are represented in sediments as cysts and not as motile thecate forms. Most of the phycologists studying the living dinoflagellates are mostly concerned with morphology, taxonomy, distribution, and productivity of the living forms. The information regarding life cycle, process of encystment, cyst morphology, and modes of production is not much. Dodge (1963, 1964), Sousa e Silva (1971), and Stoch (1973) studied nuclear division in dinoflagellates. The process of encystment was demonstrated in the laboratory by Wall and Dale (1968c). It is of utmost importance for an overall understanding of dinoflagellates, that palynologists understand the works of phycologists and vice-versa. A phycologist should understand geological history and evolutionary trends in dinoflagellates, and a palynologist should understand life cycle, morphology of theca and cyst and their relationship.

In recent years there have been many studies on the distribution of dinoflagellate cysts in Recent and Quaternary, marine and non-marine sediments. This kind of study is useful in understanding of depositional environment of fossil sediments A brief survey including the many uses of dinoflagellates in petroleum exploration are discussed.

The present author has been studying this group of fossils since 1973, and has used this group of fossils for interpreting depositional environment (Kumar, 1976b), and for assigning age (Venkatachala and Kumar 1976, 1977). A detailed and systematic study of this fossil group was initiated in the subsurface sediments of Peninsular India by the author (Venkatachala and Kumar, 1976, 1977 and Kumar, 1977). The details of these studies would appear in the text.

2. DINOPHYCEAE : (a)—LIVING—AN INTRODUCTION

The division Pyrrhophyta Pascher, 1914 of plant Kingdom is divided into two classes, Desmophyceae and Dinophyceae. The Desmophyceae is characterized by the lack of plates on the cell wall, two anteriorly placed flagella, a single longitudinal groove that divides the theca into two unequal division of the cell by an anteriorly developed transverse girdle. This class has only two Upper Jurassic genera i.e. *Nannoceratopsis* Deflandre, 1938, and *Palhistiodinia* Deflandre, 1938 recorded. According to Lister (1970) many acritarch genera belong to this class.

The class Dinophyceae are of great importance as fossils. The two orders of this class Gymnodiniales Lindemann 1928 and Peridiniales (Schutt) Lindemann 1928 are recorded as fossils also. They are characterized by two flagella arising from the ventral surface and a single transverse furrow that divides the cell into two halves. The distinction between the two orders of class Dinophyceae is the lack of well defined cell wall in Gymnodiniales. The members of Dinophyceae occur in fresh, brackish, and marine waters. The presence of cellulose wall and chlorophyl places this group in plant Kingdom (Harland, 1972).

2-(b) FACTORS RESPONSIBLE FOR THEIR DISTRIBUTION AND PRODUCTION

Sarjeant (1974) in his book entitled, "Fossil and Living Dinoflagellates" has a detailed discussion of this subject in his first chapter on Ecology. A breif account is discussed here. Williams (1971, a) has discussed the following important points affecting the distribution and production of phytoplankton in general. I think these points hold good also for Dinophyceae in particular. These points are :

(1) Incident Radiation
(2) Effective Radiation
(3) Temperature
(4) Major Nutrients
(5) Minor Nutrients
(6) Hydrodynamic and other physical controls.

Most of the members of Dinophyceae are autotrophic, thus the amount of energy received from radiation is important for Photosynthesis. This is a function of time of the year, and location of a place. The effective radiation is the lower limit of the photic zone or the compensation depth. This is the depth at which phytoplankton cannot produce enough Oxygen in Photosynthesis to compensate for the use of normal respiration. This is deepest at mid-day and nil during nights. The amount of radiation is important for different species, because they keep fluctuating up and down with the effective radiation. The compensation depth is effected by the presence of particulate matter, dissolved salts and organisms themselves. In the regions of higher productivity thickness of photic-zone is least. A species will not inhabit waters whose depth is insufficient to allow it to undertake the diurnal mirgation necessary to maintain the light conditions it favours

The incident radiation and movement of cold and warm water currents in the ocean are responsible for the temperature distribution in the ocean. The regions of highest productivity are found in high latitudes but extreme cold conditions will inhibit growth. This is because this region is rich in nutrients. According to Williams (1971 a) temprature has little effect on phytoplankton productivity, but it might influence the distribution of individual species. The toleration limit of Dinophycae range from 1°C to 25°C with an optimum for most species in the range from 18°C to 25°C (Harland, 1972). Salinity does not seem to effect dinoflagellate productivity.

Oxygen, Carbon dioxide, Carbon, Nitrogen, Phosphorus and Silicon are major nutrients, trace elements and vitamins are considered as minor nutrients. Nitrogen is needed for protein synthesis, phosphorus and nitrogen for energy transformation and carbon dioxide and water for carbohydrate synthesis. The nitrogen and phosphorus concentrations are the limiting factors for productivity. Minor nutrients effect the distribution of species and control general fertility in water. Redfield (1963) has discussed in detail the nutrient cycle in the sea.

The hydrodynamic effects of circulation causing mixing of deep waters with surface waters are the regions of high productivity. This is because of nutrient enrichment of the surface water by the subsurface waters. Like wise regions of divergence due to wind action are also regions of high productivity, simply because subsurface water mixes with the surface waters to maintain the hydrostatic balance. According to Sarjeant (1974) the maximum abundance of dinoflagellates is at relatively shallow depths between 18 and 90 metres under normal photic conditions. They never live at a depth greater than 200 metres, and they show a distinct depth stratification. Some species are confined to shallow waters eg. *Peridinium* and certain species of *Ceratium* while others never range up into the surface layers, eg. crtain species of *Ceratium*, *Heterodinium* and *Triposolenia*.

2—(c) REPRODUCTION

The vegetative reproduction in dinoflagellates is common. Sexual and asexual reproduction are exception. Sousa e Silva (1973) examined in detail the cell division among dinoflagellates, but has never seen anything suggesting meiosis. But Stoch (1973) observed some "small forms" budding off larger cells and considered "small forms" as male cells in the process of copulation. There is not yet definite evidence of sexual reproduction in those marine genera that are known to be represented by their cysts in fossil record (Sarjeant, 1974). However, Shyam and Sarma (1975) have demonstrated asexual reproduction through zoospore formation and sexual reproduction through planozygotes in *Woloszynskia stoschii*, a fresh water dinoflagellate from north India. Dodge (1963, 1964) has discussed the nuclear division in dinophyceae.

2-(d) ENCYSTMENT

Wall and Dale (1968-c) state that cyst production, except where occurring as a prelude to cell division or indirect by consequent upon the onset of adverse environmental conditions, resulting either from changes in the physico-chemical environment, such as falling temperature or (perhaps) changes in salinity, or resulting from population pressure. Encystment occurs at various times of the year, but primarily in association with dinoflagellate booms and towards the end of or after a period of exponential growth, encystment occurs rarely or not at all under stable environmental conditions. It is a phenomenon characteristic of neretic species especially those inhabiting temperate waters. Some of the oceanic species inhabiting warm waters are not known to encyst at all. Those marine genera which encyst for reproductive purposes apparently do neither form non-reproductive resting cysts, nor are resting cysts formed by symbiosis of parasitic dinoflagellates.

Many species of dinoflagellates, both fresh water and marine are known to encyst as a part of their life history. Wall (1965b) Wall and Dale (1967, 1968a, b, and 1969), Wall *et al.* (1967), Evitt, (1967,) Evitt and Wall (1968), Evitt and Davidson (1964), Rahat (1968), Eren (1969) and Bibby and Dodge (1972) are some of the encystment studies in dinoflagellates and their importance in the study of fossil dinoflagellate cysts. It is normally observed that cysts are smaller than the motile thecate forms, and are also seen intact inside the thecae. Cridland (1958) observed the cysts being a little larger than theca in *Gymnodinium hippocastanum* and this phenomenon was later confirmed by Mapletoft *et al.*; (1966).

2-(e) DINOPHYCEAE IN INDIAN WATERS

The distribution of dinoflagellates in the Bay of Bengal, Arabian Sea, and northern waters of Indian Ocean are considered for discussion. The occurrences of fresh water dinoflagellates from India are not discussed. Subrahmanyan (1958, 1968, 1971) has done an extensive work on the distribution of dinoflagellates in Bay of Bengal and Arabian Sea. Prakash and Sarma (1964) reported the Red Water eight miles northwest of Cochin harbour in November, 1963. They found out this phenomenon to be due to the bloom in *Gonyaulax polygramma* Stein, which is a common tropical and subtropical dinoflagellate. *G. polygramma* accounted for 99% of the total cell count per litre of sample of "Red Water". Durairatnam (1964) studied the vertical distribution of some dinoflagellates near Cocos-Keeling Island in Indian Ocean. Most of the dinoflagellates and diatoms are confined to the top 50 metre zone, but in the zones 50-100 metres and 100-200 metres dinoflagellates were much more than diatoms. He also gave the vartical distribution of various species of *Dinophysis*, *Amphisolemia*, *Ornithoceras*, *Phosphacus*, *Peridinium*, *Gonyaulax* and *Ceratium*. In another paper, Durairatnam (1963) discussed the seasonal cycles of sea surface temperature, salinities and their effect on dinoflagellate production in Puttalam Lagoon, Dutch Bay and Portugal Bay along the west coast of Ceylon. Wood (1963) gave a check list of dinoflagellates recorded from Indian Ocean.

3. FOSSIL RECORD OF DINOPHYCEAE

3-(a) DINOFLAGELLATE CYSTS

The earliest record of undisputed dinoflagellate goes back to Upper Triassic. Calandra (1964) reported *Arpylorus antiquus* a supposed to be dinoflagellate from Silurian of Tunisia, and two Permian reports are by Jansonius (1962) from Peace River area of Western Canada and Tasch (1963) from Kansas. These reports are controversial and most palynologists have their own reservations about accepting them as dinoflagellates. The American Association of Stratigrathic Palynologists (AASP) contribution series Number 4 (1975) contains the stratigraphic range charts of selected fossil dinoflagellates. Recently, Thusu (1977) published the geological ranges of selected dinoflagellate taxa mainly from Europe.

3-(b) ACRITARCHS

These are group of fossils found mainly in the sediments ranging in age from Early Proterozoic to Coenozoic and possibly in Recent marine sediments, but are mostly abundant in Palaeozoic sediments. These are supposed to be having algal affinity and could very well be a polyphyletic group. Evitt (1963) proposed the term "Acritarch" and separated them with dinoflagellate cysts by a remark "lacked the minimum of morphological features—required for recognition". Sarjeant (1967) observed that the decline of acritarchs coincides with increase in dinoflagellate cysts and thought that many of the acritarchs are dinoflagellate cysts. Some of the Palaeozoic acritarchs like *Lophodiacrodium, Cymatogalia, Priscogalea, Hystrichosphaeridium buecospinosumv* could be morphologically interpreted to be dinoflagellate cysts. Lister (1970) has attemptal to relate Palaeozoic acritarchs to dinoflagellate cysts. His attempts to relate *Cymbosphaeridium* and *Dilatisphera* to dinoflagellate are the same kind of attempt as of Evitt (1963) who demonstrated the affinity of "Hystrichospheres" to dinoflagellates as their cysts. Diez and Cramer (1974, 1977) has given an extensive stratigraphic range chart of acritarchs for lower Palaeozoic.

3-(c) REPORT FROM CONTINENTAL DEPOSITS

There are very few reports of fossil dinoflagellate cysts from the non-marine sedimentary deposits. But there are many reports of modern non-marine dinoflagellates and their cysts, Huber-Pestalozzi (1950) and Preseott, (1962). The presence of dinoflagellate cyst in sediments is generally considered by palynologist as indicative of marine environment. Such conclusion should be substantiated with other kinds of information also. Generally dinoflagellates are most diverse in marine sediments and were considered to be absent or scarce in brackish or non-marine sediments (Williams and Sarjeant, 1967). A general history of study of fresh water dinoflagellates is given by Harland and Sarjeant (1970).

Recently Jain and Maheshwari[1] (1978) reported the occurrence of non-marine dinoflagellates from the sediments of Jabalpur Group (Upper Mesozoic). They recorded *Kalyptea indica*, *Necropsroomea*, *Canningia* and *Tenua*. The detailed report is not yet published. The oldest undisputed record is from Palaeocene of Queensland, Australia (Harris, 1973) and Eocene Brown Coal in Germany (Krutzsch, 1962). Traverse (1955) reported *Peridinium hansonianum* from Oligocene Brandon Lignite of Vermont, U.S.A. Evitt (1974) restudied the brandon fossil in detail morphology and reassigned it to *Palaeoperidinium hansonianum*. The other reports are from Holocene peats of north western Australia by Churchill and Sarjeant (1962, 1963), Sub Recent lake muds of Minnesota by Eisenack and Fries (1965) which was revised later by Evitt and Wall (1968) and established the Minnesota fossils are cysts and not thecate forms as indicated by Eisenack and Fries. Other Holocene reports are Lake Hertel near Montreal (Lasalle, 1966) Cape Cod, Massachusetts (Evitt and Wall 1968), Norris and Mc Andrews (1970) also studied post glacial muds of lake Glatsch in Minnesota. They very keenly observed the morphology of these fresh waters cysts and its implications to the palaeoecology. Wall, Dale and Harada (1963) described a few new fresh water-brackish water dinoflagellate cysts from Late Quaternary of the Black Sea. Sarjeant and Strachen (1968) reported fresh water acritarchs from pleistocene peats of Staffordshire, England. Downie and Singh (1969) reported dinoflagellate cysts from estuarine and raised beach deposits from Northern Ireland.

Thus the presence of dinoflagellate cysts in the sediment may not necessarily indicate a marine environment. Varma (1964) has cautioned and stressed the careful interpretation of marine versus non-marine environment based on dinoflagellate cysts. According to Wall (1970) the known Quaternary fresh water and marine dinoflagellate cysts are morphologically distinct enough to be identified and can be used to indicate fresh water or marine environment. Evitt (1974) considered Dinophyceae originally was a marine group, he states "Fresh water environment has served as a Cenozoic asylum for certain dinoflagellate lineages that in earlier time (but no longer) were represented by widespread and characteristic marine species". The precise time of such migration is still uncertain, and may perhaps be difficult to establish (Norris and Hedlund, 1972). At least migration did occur in Eocene as it is evident from the work of Krutzsch (1962).

1This note is present in the abstracts of 2nd Indian Geophytological conference held at Birbal Sahni Institute of Palaeobotany, Lucknow 11-12 March 1978. This paper was not presented at the conference.

3-(d) REPORTS FROM INDIAN DEPOSITS

There are many scattered reports of dinoflagellates from Indian sediments. Jain (1974) has reviewed and listed all such occurrences. The important dinoflagellate studies of Indian sediments include : Varma and Dangwal (1964), Sah, Kar and Singh (1970), Jain and Tougourdeau Lantz (1973), Jain, Sah and Singh (1975) and Venkatachala and Kumar (1976, 1977). The first catalogue of fossil dinoflagellate cysts in India was prepared by the author from the Dalmiapuram Gray Shale in which 26 genera and 69 species were identified. There are many new taxa added to Indian flora (Venkatachal and Kumar, 1977). A similar catalogue has been prepared from the Late Jurassic-Early Cretaceous subsurface sediments of Krishana-Godavari basin (Kumar, 1977).

Dinoflagellates in India have been used for dating the sediments (Jain and Tougourdeau Lantz, 1973, and Venkatachala and Kumar (1976), and defining stratigraphic boundaries (Jain, Sah, and Singh 1975). In addition, in almost all the palaeoecological and palaeonvironmental interpretations based on palynological studies, dinoflagellates have offered valuable information.

Acritarchs have been extensively used for precise dating of the so-called Precambrian sediments of peninsular India. Gowda and Sreenivas (1969) reported acritarch assemblage from Chitaldurg Schist Belt of Archaean Complex. The important taxa reported are *Protoleiosphaeridium, Leiosphaeridium Leiofusa, Deunffia* and/or *Bacisphaeridium*. This assemblage belongs to the age group of 2000—1400 m. yrs. Venkatachala and Rawat (1974) also reported 13 genera and 21 species along with algal filaments, organic plates and some doubtful trilete bearing spores from Dharwar Shimoga schist belt. The acritarch assemblage from Kaladgi basin is also reported by Venkatachala and Rawat (1973) and Viswanathiah *et al.*, (1975). A Precambrian-Cambrian age is assigned to these sediments. A detailed study by Viswanathiah *et al.*, (1976a) of Lokpur Formation of Kaladgi group reported 100 species belonging to 69 genera. They interpreted Lokpur Formation to have been deposited in shallow marine waters.

Salujha *et al.*, (1972) described an acritarch assemblage from Kurnool sediments. They assigned Late Precambrian- Cambrian age to these sediments and established equivalence to Lower Vindhyans of Son Valley. The sediments of Bhima series were studied by Salujha *et al.*, (1970) and Venkatachala and Rawat (1972). The recorded acritarchs from Bhimas are *Leiosphaeridia*, *Lophotriletes*, *Lophosphaeridium*, *Protoleiosphaeridium*, *Schismatosphaeridium.* Venkatachala and Rawat (1972) assigned a Late Cambrian age to these sediments. Viswanathiah *et al.*, (1976 b) listed the acritarchs and scolecodonts from Temple Quartzites of Badami Group and assigned an Ordovician age. The palynomorphs of Vindhyan System are most extensively studied. The systematic description of microplankton are reported by Maithy (1969), Salujah *et al.*, (1971a, b) from Rajasthan and Son valley. The most significant use of acritarchs has been in assigning age to the subsurface sediments of Ujhani and Tilhar wells below alluvium and Siwalik sediments in Bihar. The sediments below the Siwalik unconformity were studied by Salujha *et al.*, (1967) who assigned an early Palaeozoic (Cambrian) age. A restudy by Sastri and Venkatachala (1968) assigned Carboniferous or Precarboniferous age for the rocks immediately below the Siwalik unconformity and considered them to be equivalent to outcropping Vindhyan sediments. Venkatachala and Rawat (1972) assigned Late Precambrian-Cambrian age to Vindhyan sediments and pre Ordovician age to the subsurface sediments occurring below Siwalik uncomformity in Ganga basin after the reassessment of data.

4. THE DISTRIBUTION OF DINOFLAGELLATE CYSTS IN RECENT SEDIMENTS

There are many studies of marine palynology in various parts of the world. Most of such studies are mainly about the lateral distribution of polynomorphs. The following workers have studied the distribution of dinoflagellate cysts. The earliest of such study was in Orinoco delta, Gulf of Paria and continental shelf area north of Trinidad by Muller (1959). Mckee *et al.* (1959) studied Pacific Attol in the Caroline Islands, Rossignol (1961, 1962, 1964) studied south eastern Mediterranean sea, Wall (1965b) studied Woodshole region, Massachusetts, Cross and Shaffer (1965) and Cross, Thomson and Zaitzeff (1966) studied gulf of California, Mexico, Traverse and Ginsburg (1966) studied Bahama platform, Williams (1971 a, b) studied North Atlantic Ocean, Davey (1971) and Davey and Rogers (1975) studied Western coast of South Africa and most recently Wall *et al.* (1977) studied the north and south Atlantic Oceans and adjacent seas. All such studies till 1966 demonstrated, (*a*) the distribution of dinoflagellate cysts in the various sedimentary facies of marine realm and (*b*) various physical factors responsible for their distribution.

Williams (1971, a) is probably the first detailed analysis of biogeographical distribution of dinoflagellate cysts in North Atlantic Ocean. Most of the species he found were described by Rossignol (1962, 1964) and Wall (1967), and found that they are distributed uniformly throughout. A good pattern of distribution was shown when a biofacies map was prepared by treating the statistically ideal samples to factor analysis. This report contained the distribution of cyst assemblages as well as distribution of individual species also. Davey and Rogers (1975) is also a similar attempt in which the distribution of individual species as well as cyst assemblages are discussed on the western continental shelf of South Africa. Wall *et al.*, (1977) is an excellent contribution to such an study. They have shown the changes in cyst depositional environments, and latitudinal variation considering climatic changes. The cyst compositions of both the trends are statistically defined.

4-(a) FACTORS CONTROLLING THEIR DISTRIBUTION

According to Davey (1971), the distribution of dinoflagellates appears to be governed mainly by temperature, although salinity, nutrients, turbulence and water depths are also important factors. The surface environments are most important factors for the distribution of dinoflagellate cysts in marine sediments. The absolute frequency of cysts per unit weight in sediment is probably related to the conditions controlling total productivity at the surface, the seasonal stability to the surface environment and the relative rate of sediment accumulation (Williams, 1971a). Dinoflagellate cysts are found in lower frequencies in sediments from tropical regions. The relative frequencies are related more closely to the surface currents than to any other factor (Williams, 1971 a). The following points are summarized by Davey (1971) and Davey and Rogers (1975).

(1) The presence and abundance of palynomorphs in the sediments are governed primarily by water turbulence at the site of deposition.

(2) The distance of depositional site from shore effects the palynologic content of the sediment. Beyond the inner shelf, water depth in itself does not appear to be significant.

(3) The ratio of sporomorphs (land derived palynomorphs) to dinoflagellate cysts within the sediment normally decreases oceanwards.

(4) Fine grained, near shore, marine sediments may be devoid of dinoflagellate cysts but may contain abundant land drived palynomorphs. This is particularly evident in the vicinity of a river effluence and is due to the paucity of cysts-forming individuals in low salinity waters and to the movement of water-bodies oceanwards from the river mouth.

(5) The percentage abundances of palynomorphs species in sediments vary across the continental shelf and from one region to another.

(6) Ocean and warmer-water dinocysts tend to have longer and more delicate processes than near shore forms. This variation could occur within

cysts of a single dinoflagellate species depending upon where encystment takes place.

(7) A pre-Recent sediment rich in dinoflagellate cysts but of only one or two species normally indicates that deposition took place in an unfavourable environment, such as that of low salinity. In the present study (southwest African coast) the strong upwelling, and its consequences, constitute the unfavourable elements.

(8) In the present region, offshore southwest Africa, dinoflagellate cysts are numerically most abundant in the vicinity of upwelling and where terrigenous detritus is a minor constituent (less than 25%). The number of species present is greater in slope sediments where deposition was slowest and a greater period of time is represented in a sediment sample.

(9) It appears that it is possible for one motile dinoflagellate to produce several morphologically distinct cysts ; conversely it is likely that individual cysts attributed to one cyst species could excyst to give more than one motile species.

Wall *et al.*, (1977) is the most extensive discussion of environmental and climatic distribution of dinoflagellate cysts in the Recent sediments of north and south Atlantic Oceans and adjacent seas. They demonstrated that individual taxa, species associations as well as species diversity have a definite inshore-offshore trend. *Spiniferites*, *Lingulodinium*, *Hemicystodinimm* and *Tuberculodinium* are most abundant close to shore in estuarine environments, *Operculodinium* and *Peridinium* tend to be most abundant in continental slope and rise sediment below the transitional and neretic-oceanic hydrographic zone and *Leptodinium* is limited to and most abundant within pelagic sediments which occur near the outer continental shelf and beyond it. Species diversity also tend to increase seawards partly because the oceanic suits of species (*Leptodinium*) is added to other assemblages from continental slope, and many abyssal zone sediments. This rise in species diversity is also due to the presence of allochthonous estuarine, neretic modern species and many cysts which occur on continental slope or rise zone are probably not of recent age. Cyst value per gram of sediment also tend to increase offshore, primarily because of sedimentological factors rather than biological factors like more fine grained sediments, lower rates of sedimentation, and presence of recycled material are important factors.

The climatic or latitudinal variations are best seen in nearshore sediments. *Hemicystodinium zoharyi*, *Tuberculodinium vancampoae*, *Operculodinium israelianum* are found to be restricted in tropical to subtropical regions, *Spiniferites elongatus*, *Bitectacodinium* and a rare taxa *Planinosphaeridium choanum* are restricted to cool to warm temperate regions. Species assoications are also defined on the basis of climatic zones. Species diversity tends to increase towards low latitudes and thus parellels the situation with the living dinoflagellate concentration in oceanic waters. This is because of higher primary productivity in cooler climatic zones.

The most important factors of distribution of cysts in sediments are the hydrodynamic motions and biologic and ecologic properties of the water. There are certain species which are adapted selectively to relatively stable sectors of marine environment and such species are very useful for palaeoecological and palaeoenvironmental purposes.

4—(b) SIGNIFICANCE OF THEIR STUDIES IN RECENT SEDIMENTS

Dinoflagellate cysts and acritarchs have been extensively used for exploration purposes and for the better understanding of the Earth's geobiologic past. Palaeoecological interpretations and the interpretation of depositional environments of various kinds of sediments have been undertaken without proper understanding of the ecological distribution of living dinoflagellates. A palaeontologist studies thanatocoenosis, and makes interpretations about the biocoenosis. It is of utmost importance to understand the physical, chemical and climatic factors controlling the biogeography and life history of individual organism, and also various groups of organisms. It is again important to know the factors responsible for the distribution, settling and transportation and fossilization after the death of an organism or groups or organisms.

The studies on dinoflagellate life history, encystment, distribution in modern waters and in recent sediments have helped in their better understanding to geologist and biologists both. A palynologist is particularly benefited by such studies and he can more confidently use dinoflagellate cysts for palaeoecological and palaeoenvironmental and up to certain extent, palaeoclimatological interpretations.

5. USES IN PETROLEUM EXPLORATION

The establishment and identification of zones in subsurface sediments for correlation purposes, and palaeoecology and depositional environment of various sediments are of utmost use to a geologist exploring for petroleum. In addition to such information, changing palaeogeography of a sedimentary basin, age determination of a particular stratigraphic unit are also important. Hoffmeister (1960) and Evitt (1964) have given a general account of dinoflagellate cysts and acritarichs and their use in petroleum exploration.

5. (a) AGE INDICATORS

Fossil dinoflagellates are used for dating purposes of sediments as old as upper Triassic. There are some doubtful older records of dinoflagellates, but they can not be used for dating purposes. There are some index fossils and various genera discussed by Sarjeant (1974), which are restricted to only certain geological time interval are used for age determination. Fossil assemblages are more reliable in dating the sediments. The geological range charts of dinoflagellate cysts are published by Downie and Sarjeant (1964), American Association of Stratigraphic Palynologist (AASP) contribution series No. 4 (1975), Sarjeant (1967, 1968) Riley and Sarjeant (1972) and Thusu (1977).

Acritarchs have been mainly used for such a purpose only in Late Precambrian and Palaeozoic sediments. Diez and Cramer (1974, 1975) have published geological range charts for acritarchs of Lower Palaeozoic. These range charts are very useful in assigning age to sediments.

5 (b) HELPFUL IN ZONING THE SEDIMENTS

The precise biozonation of fossil sediments helps in the identification of a rock unit in trems of time. Clarke and Verdier (1967) proposed zones and subzones of Chalk (Cenomanian-Senonian) of Isle of Wight and named them after the predominant dinoflagellate. Sarjeant (1974) questioned such a practice and considered it to create more confusion rather than helping a geologist. He suggested that it is enough to describe the dinoflagellate assemblage of already established and named zones based on another group of fossil, instead of naming dinoflagellate zones on the basis of predominant dinoflagellate.

Zaitseff and Cross (1970) have successfully demonstrated the use of dinoflagellate cysts and acritarchs in zonation and correlation of the Navarro Group (Maestrichtian) of Texas. Wray (1964) used Palaeozoic acritarchs in zoning and correlating the subsurface sediments in Lybia. Eaton (1971) zoned two sections of Eocene of Isle of Wight, England, where invertebrate fossils actually failed. Evitt (1964) has discussed stratigraphic applications, and noted the following characters of dinoflagellates which make them good index fossils (*a*) wide geographical distribution (*b*) limited stratigraphic range, (*c*) independence from bottom conditions, and (*d*) morphological diversity sufficient to recognize numerous genera and species. There are numerous publications in which dinoflagellates have been used for zoning the stratigraphic column, the important new publications are, Stover (1973) in Victorian coastal and offshore basins in Australia, McIntyre (1973, 1974) in North Western Territory in Canada, Norvick and Burger (1976) Australia, Botlenhagen (1977) in Gabon, Africa and Brideau (1975) in Arctic Canada.

5—(c) FOR INTERBASINAL, INTRABASINAL AND INTERCONTINENTAL CORRELATION

The identification of a stratigraphic unit and its recognition in other places in the basin of exploration is very important. Wray (1964), Zaitzeff and Cross (1971) and many others are good examples of uses of dinoflagellate cysts and acritarchs for correlation purposes. Evitt (1964) stated that an assemblage reported by Deflandre in 1938 from upper Jurassic of France has been found in the Curtis Formation in Utah and also in the same stratigraphic unit in England, Germany and Austria. He has quoted another example of common upper Cretaceous dinoflagellate cyst taxa found in California, Wyoming Texas, New Jessey, Venezuela, West Africa, Paris Basin, Pakistan and Australia. Davey (1970) has described common dinoflagellate taxa in England, Northern France and North America. Venkatachala and Kumar (1977) recovered an assemblage from Dalmiapuram Gray Shale, Tamilnadu, India, which is correlatable with the assemblage recorded from the Aptian-Albian sediments in Australia and Papua, New Guinea. Dalmiapuram assemblage contains many taxa commonly reported from Early Middle cretaceous sediments in Europe and North America. Kumar (1977) has also recovered many of the Early Cretaceous dinoflagellate taxa from the subsurface bore hole core samples of Krishana-Godavary Basin in Andhra Pradesh, which are commonly found in North America, Europe and Australia.

Williams and Bujak (1977) published on the distribution pattern of North Atlantic Coenozoic dinoflagellate cysts. They concluded that some species do not have uniform world-wide ranges, but for an international correlation local biostratigraphic zonation must be established before a regional biostratigraphic zonation can be made.

5—(d) ENVIRONMENTAL INDICATORS

There are many publications demonstrating the uses of dinoflagellate cysts and acritarchs as palaeoecological and palaeoenvironmental-indicators. A few of such publications are by Hoffmeisster (1954), Sarmiento (1957) Tschudy (1961), Staplin (1961), Evitt (1964) Upshaw (1964) Vozzhennikova (1965) Wall (1965a) Cross *et al.*, (1966) Scull *et al.*, (1966), Williams and Sarjeant (1967) Smith and Saunders (1970) Downie *et al.*, (1971), Sarjeant (1974) Kumar (1976 a, b) and Williams and Bujak (1977). The following points are discussed in detail.

1—*Finding Ancient Shorelines* : Most palynological slide preparations contain dinoflagellate and acritarchs along with pollen and spores. An idea of the distance of depositional site from the shoreline can be estimated by calculating the ratio of allochthonous land derived palynomorphs, i.e. spores and pollen with autochthonus dinoflaggllate cysts and acritarchs. This method has been used by Upshaw (1964), Sarmiento (1957), Kumar (1976 a, b) and many others. This method is actually based on the studies of the distribution of palynomorphs in recent marine and marginal sediments. It has been generally found that the ratio of pollen and spores to dinoflagellates and acritarchs decreases as one moves away from the shoreline in the sea. Such ratios in a stratigraphic column give a generalized idea of moving shoreline (transgressive and regressive) through time. This kind of interpretation could be misleading if (*a*) a dinoflagellate 'bloom' has occurred near the shore line in shallow water in past, this will show a much exaggerated proportion of dinoflagellate, and (*b*) the area where rivers meet oceans will have an exaggerated proportion of spores and pollen. Although longshore under water currents do transport the allochthonous sediments in the oceans but it is a heterogeneous distribution. It is of utmost importance that any such interpretation must be substantiated with the information obtained from Sedimentology and Micropalaeontology. Dinoflagellate cyst assemblages can be used to obtain (*a*) orientation of ancient shore lines, and (*b*) limiting marine zones and direction of sediment movement (Scull *et al.*, 1966). Brideaux (1971) noted the recurrent groupings in the late Albian of Western Canada to be in part produced by successive marine transgressions and regressions.

2—*Depth of Water Indications* : The morphological complexity of the dinoflagellate cysts and acritarchs have been indicated to represent relative depth of Ocean waters. The smooth or fine processed taxa are supposed to represent shallow near shore waters, and complex and densely processed taxa represent deeper waters. This was first demonstrated by Staplin (1961) in the upper Devonian reefs of Alberta. He found that accitarchs increase in abundance with increasing distance from reefs, and smooth, papillate or ciliate forms were distributed near as well as away from the reefs, thin and long spined forms were not found around one mile of the reef, and the polyhedral and saccate forms with processes very broad at their bases and often hollow, were not found around four miles of the reef. This clearly indicates that the acritarchs with more, long and complex processes inhabited deeper waters. Wall (1965 a) observed almost similar distribution in the lower Jurassic sediments in Baritain. The acritarch taxa with long spines favoured regions of quiet deposition, whereas those with very reduced spines were more tolerant of turbulent conditions of deposition. Vozzhennikova (1965) also suggested that variable morphology of dinoflagellate cysts might be an index to conditions of deposition. A similar distribution of forms was also noted by Scull *et al.*, (1966) in Vicksburg Formation in Taxas and by Smith and Saunders (1970) in the Silurian of East Central Pennsylvania. Williams and Sarjeant (1967) have discussed the uses of these fossils in indicating depth and ancient shore lines. Zaitzeff and Cross (1970) and Kumar (1976 a) have demonstrated the relative depth of water at which different formations of Navarro Group (Maestrichtian) of Taxas were deposited.

3—*Indicators of various nearshore, coastal, brackish water to open marine environment* : Hulbert (1963) studied the recent phytoplankton populations from Atlantic Ocean between New Zealand and Bermuda. He noted reduction in diversity of species within populations taken from estuarine and bay environments as compared with populations from the open sea, coastal and deep ocean habitats. Wall (1965 a) found members of Acanthomorphitae (*Micrhystridium* and *Baltisphaeridium*) appear to have favoured an inshore partly enclosed environment, whereas members of Polygonomorphitae (*Veryhachium*) and *Netromorphitae* (*Leiofusa*, *Metaleiofusa*, *Domasia* and *Cantulodinium*) appear to have favoured open marine environment in upper Jurassic sediments in Britain. He further noted that dinoflagellate species *Dapcodinium prescum*, *Gonyaulax rhaetica*, *Nannocaratopsis gracilis* and *Hystrichosphaeridium* spp., are restricted to dark shale facies of British Rhaetic, and concluded that all these species are facies controlled. Downie *et al.*, (1977) described four species associations in the Eocene of England and considered them to be controlled by changing environment. They suggested that associations dominated by the genera *Hystrichosphaera* (*Spiniferites*) and *Areoligera* may represent open sea conditions, a third association dominated by the acritarch genera *Micrhystridium* and *Eomasphaeridium* marked the initial and closing stages of a marine transgression, and the fourth association dominated by the cavate species *Wetzeliella* may have represented estuarine conditions. Wall and Warren (1969) recovered dinoflagellate cysts from Pleistocene and Holocene sediments from the cores of Red Sea. The cyst genus *Hemicystodinium* is known to be formed by the motile thecate species *Pyrodinium bahamence* an inhabitant of protected shallow coastal embayments. The presence and absence of *Hemicystodinium* in cores of Red Sea was interpreted to indicate changes in the Sea level during Pleistocene glaciation. Williams & Bujak (1977) stated that by integrating data of ecologically overlapping taxa, it should be possible to correlate all the marine palaeoenvironments within any climatic regime.

4—*Others* : Dinoflagellates have been used as indicators of palaeoclimate. Davey (1970) thought that the abundance of *Deflandrea* in the Cenomanian of Saskatchewan and Arctic Canada and its absence from the northwest Europe and Texas suggests that this was a boreal form. He further noted that Canadian assemblages were species poor suggesting a coldwater conditions. Wall and Dale (1968 a) identified five species associations from the Early Pleistocene of Norfolk, England.

This included cysts identified with those of some living dinoflagellates whose temperature ranges were known. Thus these species associations could be related to warm and cold Climate phases.

Dinoflagellates have also been related to indicate current circulation patterns by Davey (1971) Cross *et al.*, (1966) and Williams (1971-b).

5—(e) PRODUCTIVITY OF DINOFLAGELLATES AND THEIR ROLE IN PETROLEUM GENERATION

Most geologists and organic geochemists now-a-days believe in organic origin of petroleum. The amorphous organic matter in the marine sediments is considered to be the primary source of petroleum. Phytoplankton form the base of food chain in marine ecosystem, and the primary organic productivity in the ocean is by phytoplankton only. The average productivity of dinophyceae is estimated to be a few billion tons by weight. Dr. Aditi Pant of National Institute of Oceanography Goa, India, has kindly provided the following data on productivity of phytoplankton.

1—Bay of Bengal=0.06 to 0.25g Cm^{-2} day^{-1}.
2—Arabian Sea=0.08 to 1.55 g Cm^{-2} day^{-1}.
3—Indian Ocean :
(*a*) Within 50 metre depthzone. 2g Cm^{-2} day^{-1}.
(*b*) Pelagic. 0.1 to 0.2 g Cm^{-2} day^{-1}.
4—World Ocean :
(*a*) Riley (1945)
15.5×10^{10} tonnes per year per $361 + 10^{6}$ square kilometres.
(*b*) Schaefer (1965)—
1.9×10^{10} tonnes per year per 361×10^{6} square kilometres.
(*c*) Steemann and Jensen (1967) 1.2 to 1.5×10^{10} tonnes per year per 361×10^{6} square kilometres.

The dead phytoplankton settle at the bottom and get mixed with sediments. This organic rich sediment forms petroleum by a series of physical, chemical and bacterial changes in time.

6. CONCLUSION

Dinophyceae occupies an important group among phytoplankton. They inhabit, fresh, brackish and marine environments. There are various physical and chemical factors responsible for their distribution. Most of the species have their own ecological requirements and thus limited to certain area. Most of them are photosynthetic autotrophs and a few of them are heterotrophs. The vegetative production among dinoflagellates is common, and sexual and asexual reproduction is exception.

The production of cyst among them is common but some of the species are not known to encyst at all. There is no proof that all the dinoflagellate species throughout the geological time have encysted in the course of their life history. It has been conclusively demonstrated that fossil dinoflagellates are actually cysts of dinoflagellates and not the motile thecate forms. This has given rise to some problem of taxonomy and relationship of fossils with living forms.

The study of fossil dinoflagellates is relatively new subject of microplaeontology. This work started in Europe, but at present most of the dinoflagellate workers are in the U.S.A. Canada, Western and Northern, European countries, and Australia. In India, the study of fossil dinoflagellates is in infant stage. A few palynologists are attempting sreious systematic study of this group of fossils in India.

Fossil dinophyceae have proved its worth in petroleum exploration. This group is being used in the zonation, correlating various zones, age assignment, palaeoecological and palaeoenvironmental interpretation. This has proved one of the most important tools of micropalaeontology in petroleum exploration.

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