Diatom Analysis.
Introduction to Methods and Applications

INTRODUCTION

Diatoms, unicellular micro-algae, have cell walls (frustules) of biogenic silica. Their ingenious and beautiful constructions show a great abundance of forms and structural patterns (Fig. 1). Due to the resistance and specific construction of frustules it is sometimes possible to carry out identifications of small diatom fragments with characteristic fine structures (Fig. 2).

Most diatoms live in water. The composition of a diatom flora is dependent on the environmental and hydrographical conditions including the water chemistry. Living (recent) diatoms are important in limnological and marine biological studies. The succession of fossil floras in sediments reflects the changes of the sedimentary environment of the basin (lake, sea shore, deep sea, tidal zone). In this way analysis of fossil diatoms is an excellent method for geologists to use when reconstructing palaeoenvironmental and palaeohydrological conditions. This is done by means of stratigraphical diatom records which indicate the environmental origin of the strata, e.g. marine/salt water, brackish water, brackish lagoon and slightly brackish water, limnic/lacustrine/freshwater, oligotrophic, eutrophic, polluted, eolian, redeposited, contaminated etc. (M.-B. Florin, 1944, 1946, 1984; Miller, 1979, 1981, 1987).

Diatom analysis is usually applied to studies of environmental changes in sedimentary basins such as sea-level changes, shoreline displacement, land uplift, eutrophication and acidification (Miller, 1981). Diatom analysis and stratigraphy are also valuable tools in connection with oil and gas prospecting, geotechnical and agricultural problems connected with «quick» clays and gyttja soils (organic mud, sapropel). In favourable aquatic environments such as those rich in silica, diatoms may occur in masses resulting in deposition of diatom gyttja. Diatoms are important oil producing microorganisms and good stratigraphic indicators. Diatomite (consolidated diatomaceous gyttja) is a mineral resource with many practical fields of technical application. Diatomite has a high porosity and is used as insulating material for high temperature ovens, as filter material and filling in bank-safe doors. It has also been used for nitroglycerin absorption in dynamite production and due to its low density, as building-material, mainly as bricks.

The history of diatom research is connected with the invention of the microscope in the end of the 18th century and the development and improvement of microscopical techniques during the 19th century (Ehrenberg, 1854; Van Heurck, 1880-85; Cleve, 1894-95). The real break through of the diatom research however came in the 20th century (Hustedt, 1927-66, 1930; Cleve-Euler, 1951-55).

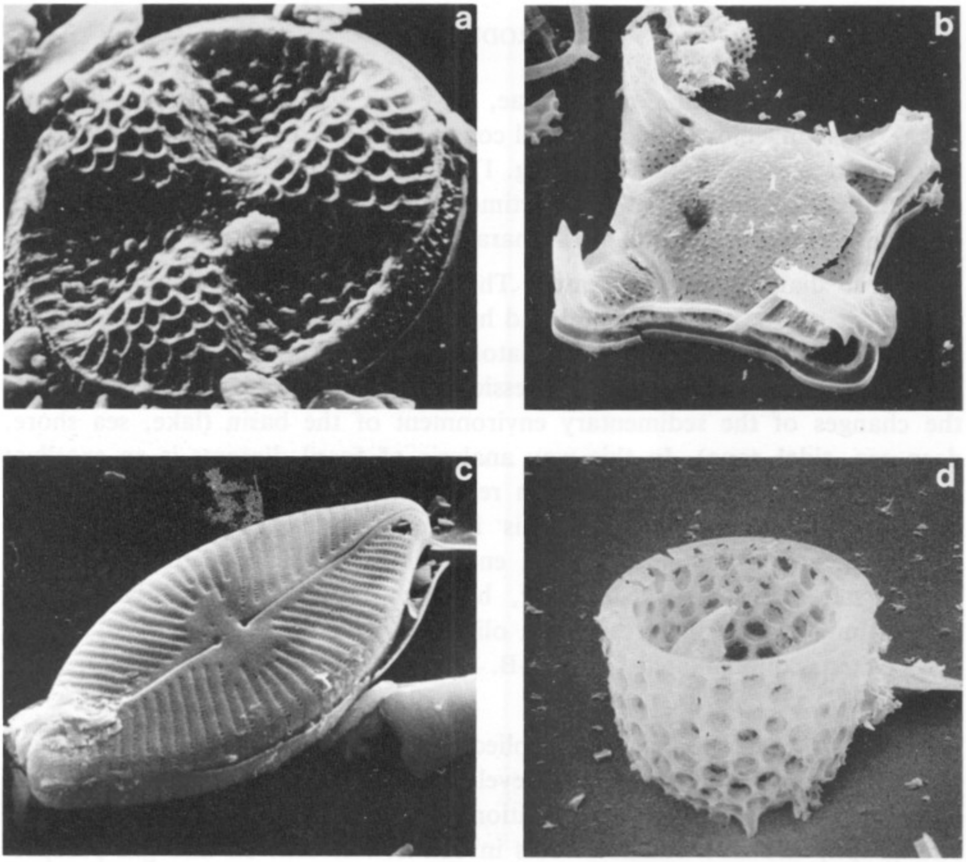


Fig. 1. Diatom frustules show a great abundance of forms and structural patterns which facilitate their way of living and functioning as perfect water-filters. Illustrated here by the diatom genera Actinoptychus (a), Triceratium (b), Navicula (c) *and* Stephanopyxis (d). *Scanning electron microscope (SEM). Magnification x 1,000-2,000.*

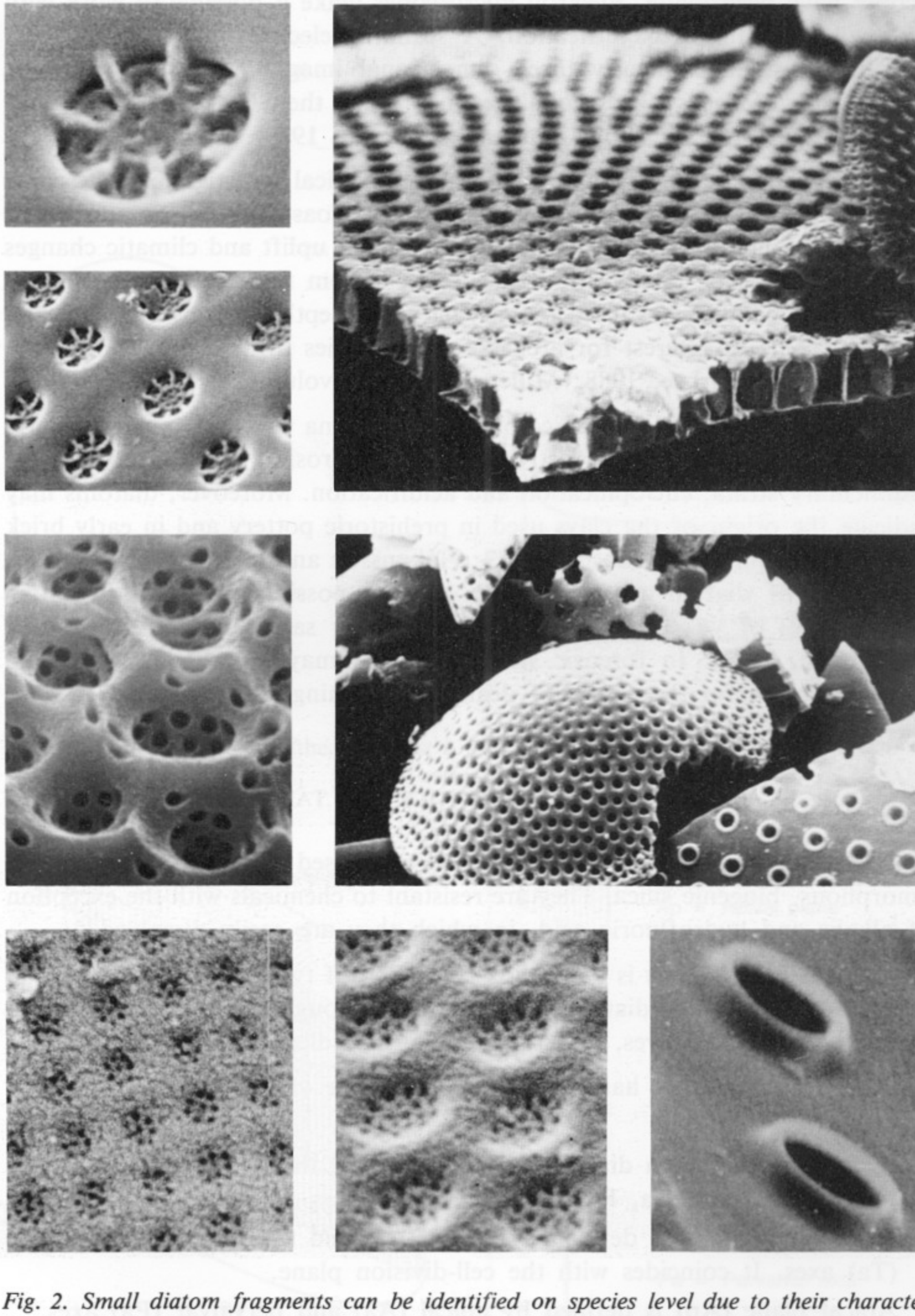


Fig. 2. Small diatom fragments can be identified on species level due to their characteristic fine structures. SEM micrographes. Magnification x 2,500-25,000.

During the last decades many new important improvements to microscopes have been made. Electron microscopes make it possible to work with up to 100,000 times magnification. A scanning electron microscope (SEM) has high resolution, nearly three dimensional image representation and a great depth of focus. These qualifications make the SEM very suitable for diatom studies (Miller, 1969; Hasle and Fryxell, 1970).

Application of diatom analysis to archaeological investigations is usually connected with shoreline displacement studies. Coastal dwellings are dependent on the interaction of sea-level changes, land uplift and climatic changes (Miller, 1982). The composition of a fossil diatom flora reflects changes in sedimentary conditions caused by varying water depth, streams and currents, which may be of interest for archaeological studies (Miller and Robertsson, 1981, 1982; Battarbee, 1988; Miller, 1989, this volume).

Diatoms are also good indicators of phenomena which may be of natural origin or caused by human activities, such as erosion and redeposition of sedimentary strata, eutrophication and acidification. Moreover, diatoms may indicate the origin of the clays used in prehistoric pottery and in early brick industry (Foged, 1968; Jansma, 1977; Håkansson and Hulthén, 1986, 1988). By means of diatom analysis it can also be possible to trace the origin (provenance) of wrecked ships and their former sailing routes (Miller and Robertsson, 1982). In forensic studies diatoms may also be of great help when searching for the causes of death by drowning (Peabody, 1977, 1980).

MORPHOLOGY, SYSTEMATICS AND TAXONOMY

The siliceous diatom frustules are composed of opaline, hydrated, amorphous, biogenic silica. They are resistant to chemicals with the exception of alkalis and hydrofluoric acid, in which they are easily dissolved.

A frustule or *theca* is like a box consisting of two halves with a bottom and a lid (The word «diatoma» means «cut throughout»). Bottom and lid surfaces are called valves, and the side walls girdles.

A diatom frustule has two views: the valve view and the girdle view (Fig. 3).

The symmetry of a diatom cell is defined by three planes: Vp, Ap, Tp and three axes: Aa, Ta, Pa (Fig. 4).

1. Valvar plane (Vp) is defined by apical (Aa) and transapical or transverse (Ta) axes. It coincides with the cell-division plane.
2. Apical plane (Ap) is defined by apical (Aa) and pervalvar (Pa) axes.
3. Transapical plane (Tp) is defined by transapical (Ta) and pervalvar (Pa) axes.

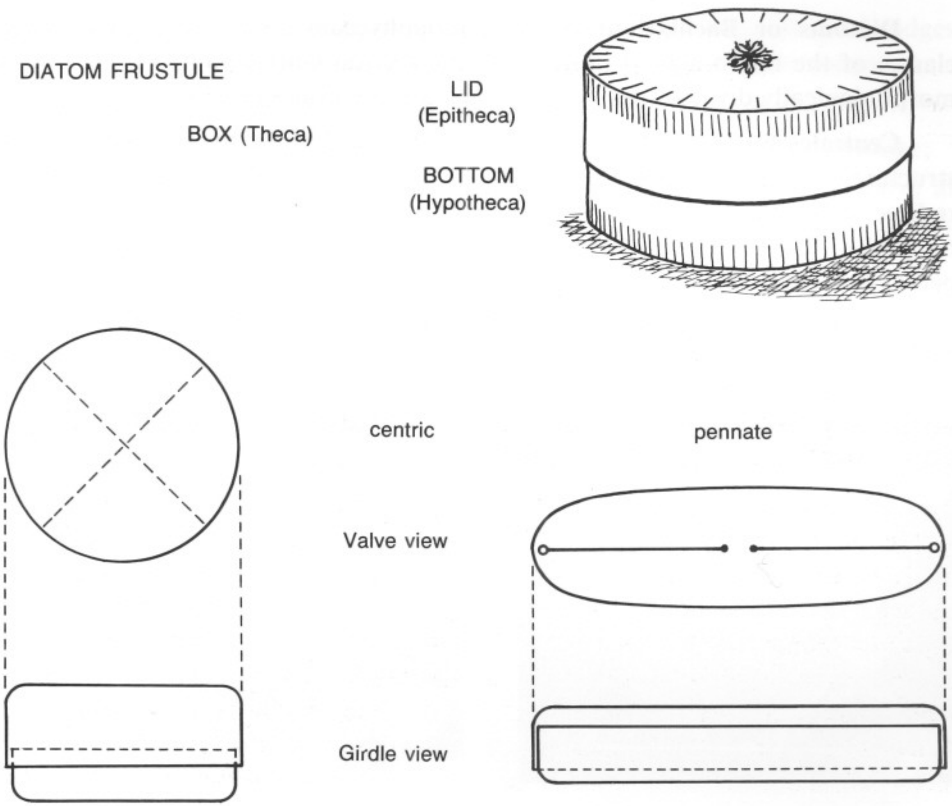


*Fig. 3. A diatom frustule (*theca*) is like a box consisting of two halves with a bottom and a lid.*

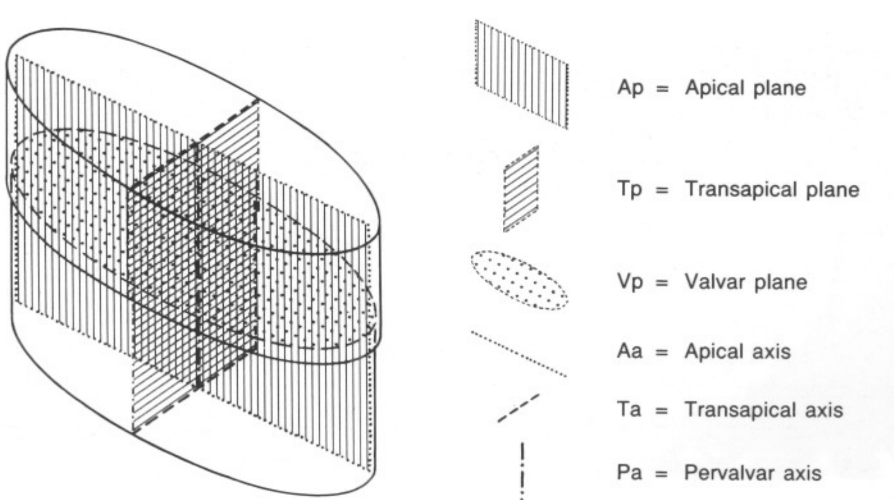


Fig. 4. The symmetry of a diatom cell is defined by three planes : valvar (Vp), apical (Ap) and transapical (Tp), and three axes : apical (Aa), transapical (Ta) and pervalvar (Pa).

Diatoms or Bacillariophyta (Bacillariaphyceae) form one of the main classes of the micro-algae belonging to the section Chrysophyta. Diatoms are morphologically divided into two main groups: Centrales and Pennales (Fig. 5).

Centrales have circular, polygonal or elliptical valve forms (Fig. 6). The structure is centric, orientated around a centre in an inordinate, ordinate, radiate, concentric or excentric pattern (Fig. 7). In many species the structure resembles a honeycomb with rows of regularly formed hexagonal or pentagonal areols (Fig. 8).

Pennales have a pennate, lineate to lanceolate valve form (Fig. 9a). The structure is feather-like, often orientated to an apical middle line (*raphe* or

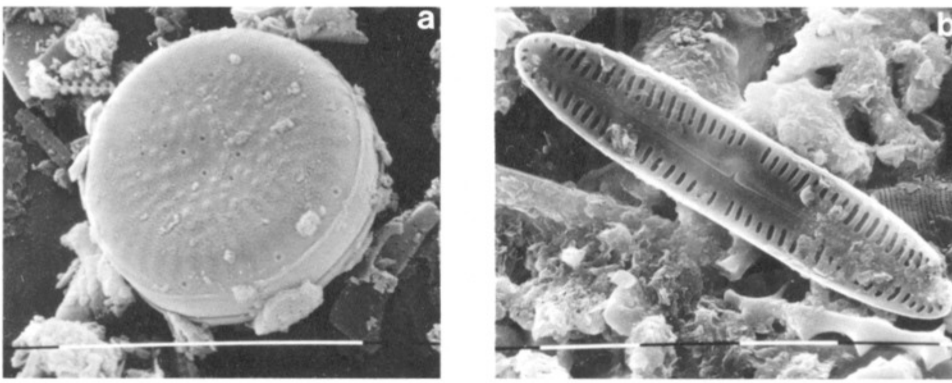


Fig. 5. Diatoms are morphologically divided into two main groups: Centrales and Pennales, illustrated here by the genera Cyclotella (a), Pinnularia (b). *White bar = 10 micron (1/100 mm).*

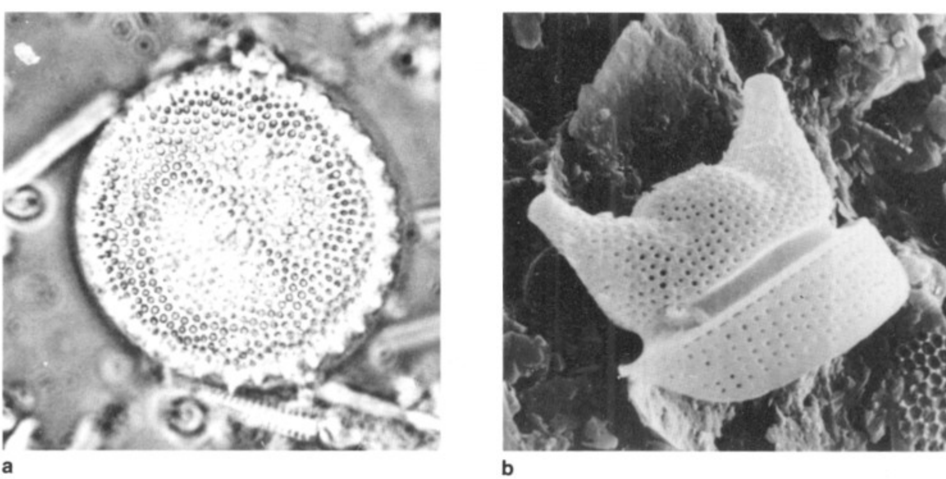
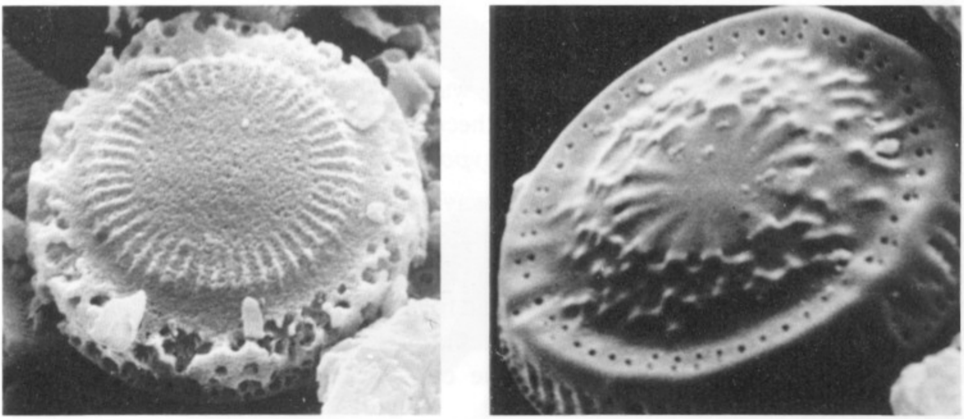


Fig. 6. Centrales have circular, polygonal or elliptical valve forms, illustrated here by the genera Thalassiosira (a) *and* Biddulphia (b). *Magnification x 1,000.*

pseudoraphe) and composed of areol rows (*striae*) between elevated ridges (*costae*) without any structure visible (*hyaline*) under light microscope.

The apical middle line can be developed in following ways:

a. on both valves as hyaline axial areas (*psedoraphe*) — **Araphid(in)eae**;
b. on one valve as a hyaline axial area (*psedoraphe*) on the other valve as a furrow (*simple raphe*), interrupted in the middle part (two raphe arms) — **Monoraphid(in)eae**;
c. on both valves as furrow with two arms, varying in length by different groups (*genera, species*) — **Biraphid(in)eae**.



a b

Fig. 7. The structure of Centrales is centric, e.g. Melosira sulcata (a) *and* Cyclolella striata (b) *have a radiate orientation of the centric structure.*

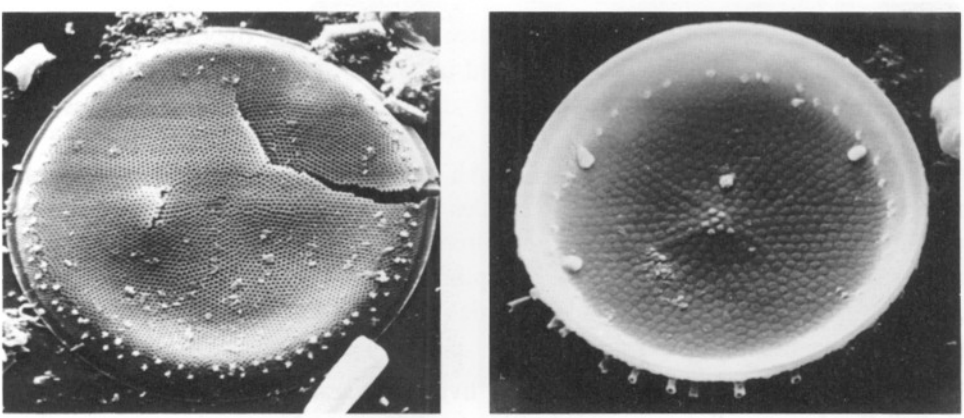


Fig. 8. Many diatom species of the genera Coscinodiscus *and* Thalassiosira *have a structure like a honeycomb. Illustrated here by* Thalassiosira baltica, *exterior and interior views.*

The interrupted central part of the raphe is called the central nodule (*nodulus*). The polar ends of the valves have polar nodules. Central and polar pores and hyaline areas occur in connection with the nodules.

The biraphide type of raphe described above is called naviculoid. The common diatom genus *Navicula* has this type of raphe (Fig. 9b).

Pennales with bent valves have another type of raphe, so-called keel raphe, which is situated in the marginal part of the valve on a heel or wing (Fig. 9c). The cell plasm in the raphe of living pennate diatoms gives the diatom cells a limited own locomotion.

Reproduction

Cell-division is the most common way of diatom reproduction. Both of the new individuals keep one of the theca halves from the mother-cell. The other half, always the smaller one (*hypotheca*), is newly formed.

Auxospore formation is another way of diatom reproduction. It can be sexual or asexual. Resting spores of diatoms are not reproductive but are a means of survival. They are formed when the environmental conditions deteriorate, sink to the bottom and wait for better times. All diatom cells can form resting spores with extremely thick and resistant cell walls. In this way they contribute to the survival of the cells and the preservation of fossil spores in the sediments.

Ecology

(The occurrence and life of diatoms)

Most diatoms live in water as autotrophic algae, i.e. they can only live in water which has sufficient light to build up their organic substance by photosynthesis. The assimilation product of diatoms is oil. A few diatoms, so-called soil diatoms — the aerophilous or terrestric ones — can also live on wet surfaces (wet ground, walls etc). All other diatoms live in lakes, ponds, rivers, seas and oceans. Diatom frustules have a perfect structure for sieving water and therefore serve as water-filters. At the same time, they are an important source of nutrition for zooplankton and fish. Planktonic diatoms have thin and porous frustules, which facilitate floating. Bottom-living species have more compact frustules.

There are different diatom floras living in freshwater, brackish and salt water. Freshwater diatoms are sensitive to different pH-concentrations and in this way good indicators of changes in pH (eutrophication, acidification).

Diatoms are most numerous in spring time (April-May) and in autumn (September-October). During these periods water can be sometimes brown-

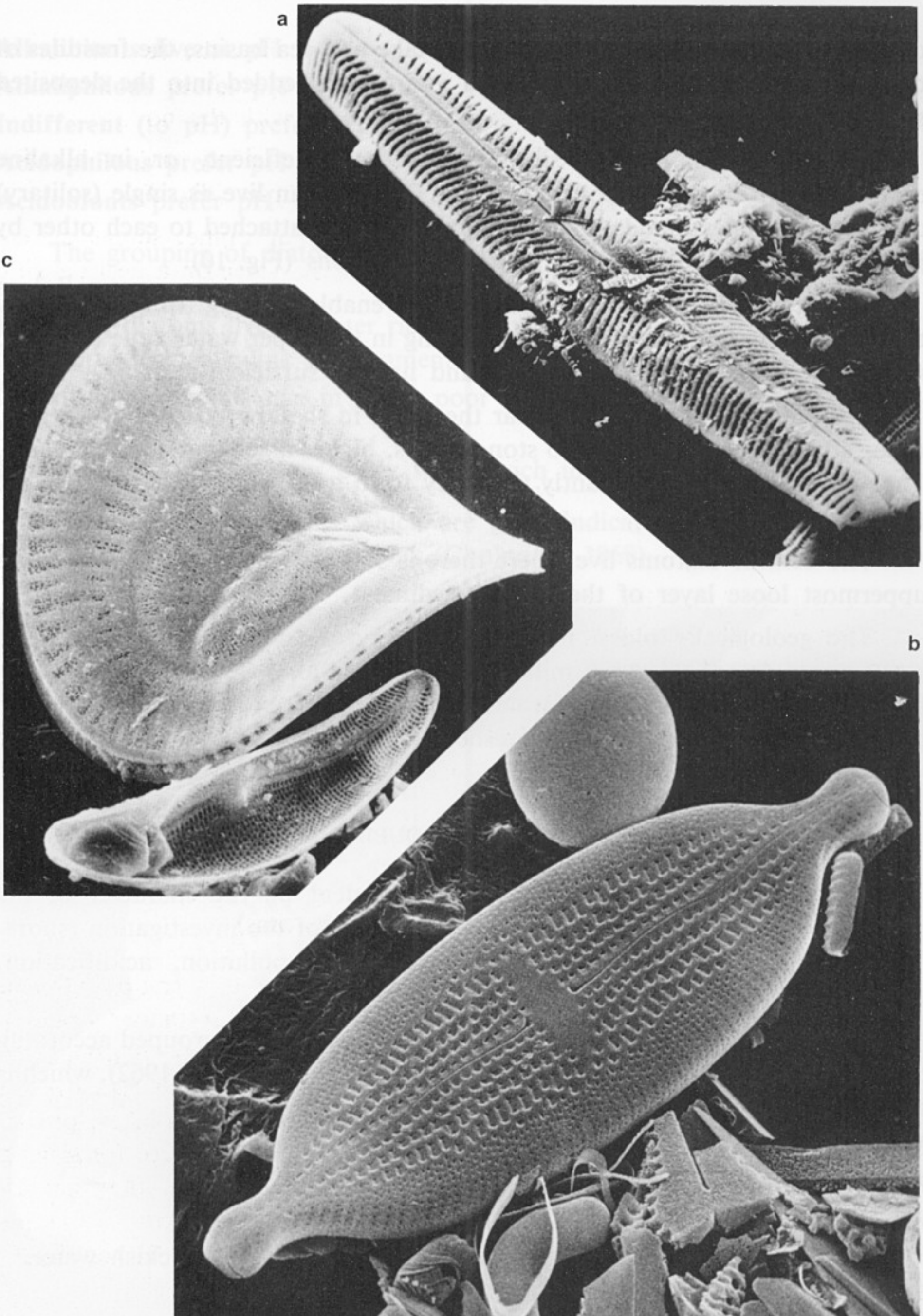


Fig. 9. (a) Pennales have a elongated valve form, illustrated here by Navicula oblonga. *Magnification x 1,300 ; (b) The diatom genus* Navicula *is biraphide with a naviculoid type of raphe, illustrated here by* Navicula Tuscula. *Magnification x 2,200 ; (c) Pennate diatoms with bent valves have a raphe which is situated in the marginal part of the valve in a keel (keel-raphe, channel-, wing-), illustrated here by* Campylodiscus clypeus. *Magnification x 500.*

colored by diatoms (water-blooming). In lake and sea basins, the frustules of dead diatom cells sink to the bottom and are embedded into the deposited sediments.

When the amount of silica in water is deficient, or in alkaline environments, diatom frustules dissolve. Diatoms can live as single (solitary) cells or in colonies (bands, chains, stars) with cells attached to each other by jelly threads and bolsters or zip-like constructions (Fig. 10).

Planktonic diatoms have appendages to enable floating. In this way they can also live in deep lakes and seas floating in the upper water zone (down to 40 m) where the supply of oxygene and light is sufficient.

The epiphytic diatoms live near the shore in shallow water of the littoral zone, attached by jelly stems to stones, piles, higher algae and aquatic plants. They often occur so abundantly that they form a brownish jelly layer on the substratum.

The benthic diatoms live where there is still sufficient light on and in the uppermost loose layer of the bottom sediment.

The geologically oldest fossil diatoms known are from Jurassic/Cretaceous strata (more than 100 million years old). Most diatoms are cosmopolite. Only among marine diatoms can indicator species of arctic and temperate environment be distinguished.

Ecological systems of grouping diatom taxa

The systems of grouping taxa are dependent on the character of the composition of the diatom floras and on the aim of the investigation (shore-line displacement, environmental changes, water pollution, acidification, eutrophication).

At shore-line displacement studies, the diatom flora is grouped according to the **halobion system** (Kolbe, 1927; Hustedt, 1957; Simonsen, 1962), which is simplified as follows:

Marine or **polyhalobious** (> 30 ‰ salinity)

Brackish or **mesohalobious** (30-0.2 ‰ salinity)

Freshwater or **oligohalobious**:

a. **Halophilous** (salt-tolerant) diatoms can live in slightly brackish water,
b. **Indifferent** (to saline) live mainly in fresh-water,
c. **Halophobous** (salt-intolerant) live exclusively in freshwater (< 0.2 ‰ salinity).

The **pH-system** of grouping diatom species (Nygaard, 1956; Hustedt, 1957; Foged, 1964) is applied to studies of freshwater environments. Diatoms live in a range of pH 2.5 (acid) to pH 9 (alkaline). Most diatoms prefer a pH of 7,5 - 7.

Alkalibionts live at pH > 7

Alkaliphilous prefer pH > 7

Indifferent (to pH) prefer pH around 7

Acidophilous prefer pH < 7

Acidobionts prefer pH < 5.5, but can live at pH < 7.

The grouping of diatom flora according to the nutrient requirements is as follows:

Eutrophic diatoms live in water rich in nutrients (mineral salts, phosphorous, nitrogen), often alkaline environments.

Oligotrophic diatoms live in water poor in nutrients — often acid environments.

Dystrophic diatoms live in peaty waters rich in humus colloids.

There are also diatoms which are good indicators of polluted waters. They are called **nitro-heterogenous** (Cholnoky, 1968).

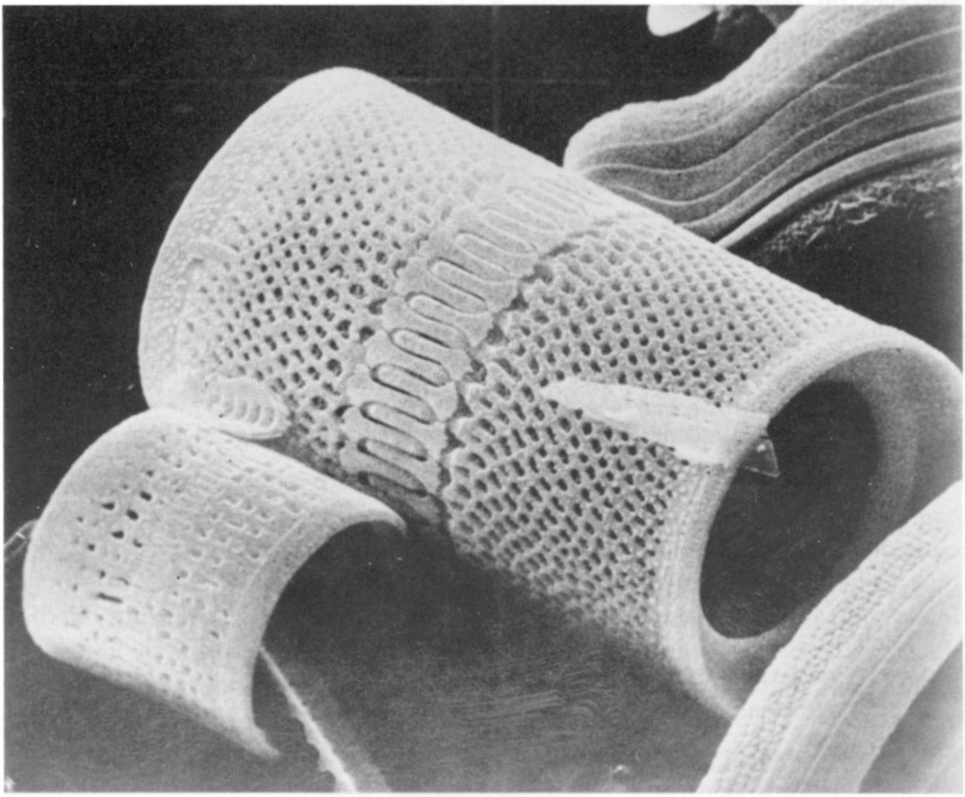


Fig. 10. The diatom cells can be attached to each other in many different ways, forming colonies. The genus Melosira *has zip-like constructions, illustrated here by* Melosira italica *var.* valida, *(to the right) and* Melosira distans *(to the left). Magnification x 4,000.*

According to the **life-form** diatoms taxa are grouped:
planktonic (pelagic, floating),
epiphytic (attached),
benthic (bottom-living).

Epiphytic and benthic diatoms together are called **periphytic**.

According to the water depth diatoms are grouped as:
shallow-bottom, living in the supralittoral and littoral zones,
deep bottom, living in the sublittoral zones,
tychopelagic, floating in deeper water and facultatively benthic.

Plankton can be grouped **oceanic** (deep sea), **neritic** or coastal, near-shore and shallow-water plankton.

Planktonic diatom species seem to have salinity and temperature as principal limiting criteria for their geographical range (Hendey, 1964).

There are also **rheophilous** diatoms living in streaming water, and the above mentioned **aerophilous** diatoms or terrestric diatoms living on wet surfaces on land.

Diatom analysis

Techniques: sampling, concentration and preparation of material for diatom studies under microscope (analysis) and diagram construction.

Sampling

Living diatoms in lakes and seas are sampled as follows:
a. plankton by sieving water through a net,
b. epiphytes by scratching the jelly layer from the surface (stones, rocks, piles, water plants etc.),
c. bottom-living diatoms (benthos) by taking sample material from the loose bottom layer.

Concerning fossil diatoms a mixture of planktonic and periphytic taxa is embedded in the sediment material. In soft sediments, coring with a Russian peat sampler delivers excellent material for stratigraphical studies. The upper loose bottom sediments can preferably be cored by a freezing method (Saarnisto, 1979; Renberg, 1981). In archaeologically excavated areas soil samples for diatom analysis can be cut out directly from the walls of trenches and pits.

Archaeological finds such as ship wrecks, building constructions in ancient harbours and dwellings (quays, jetties, piles etc.) may have a surface layer of epiphytic diatoms. Here careful scratching of the objects is recommended as a sampling method. Sediment samples of the material in which the finds are embedded should be taken for reference.

Concentration

The sample material (1 gram) is concentrated for diatom analysis as follows:

1. Lime (carbonates), if present, is dissolved in diluted hydrochloric acid (5 % HCl).
2. The organic material, if present, is bleached and destroyed by heating in hydrogen peroxide (15 % H_2O_2) or in sulphuric acid (conc. H_2SO_4).
3. Coarse mineral grains, if present, are eliminated by sedimentation.
4. The clay particles and colloids are eliminated by repeated washings, 2 hours sedimentation, careful decanting, until the water mixture is colourless and clean (Miller, 1964; Battarbee, 1986).

The residue is a mineral fraction (2-200 microns), corresponding to the grain size of silt, and also containing the diatom frustules.

Preparation of slides

Slides are prepared for analysis as follows:

1. One drop (about 0.05 ml) of the concentrated sample is spread out over a cover glass and slowly dried.
2. On an object glass, a small dab (or drop) of a strongly refracting embedding medium (NAPHRAX, Ri = 1.73) is warmed carefully until it is liquid (or the solvent has evaporated).
3. The cover glass, with the layer of dried diatom sample facing downwards, is put on the embedding medium, which slowly spreads out between the two glass plates.

The difference between the refraction indices of the diatom frustule (Ri = 1.48) and the embedding medium is important, as it produces more distinct diatom structures and facilitates the identification.

Analysis (studies using a light microscope)

Studies under a microscope should preferably be carried out under high magnification (about x 1000). Otherwise the more delicate structures of diatom frustules of the diatom frustules will not be recognisable or visible.

An oil immersion objective (x 100) and a phase contrast condensor are recommended. For detailed taxonomic studies and in the case of special problems, a scanning electron microscope (SEM) with magnification of up to x 50.000 is the best instrument.

Most commonly diatom analysis is carried out by counting and identifying all diatom frustules until a number of at least 300 specimens have been recorded. In the case of fossil material the diatom frustules are often separated into two halves (epi- and hypothecas, valves) or fragmented.

Therefore a counting of valves is recommended. The basic sum of counted valves is used for percentage calculations. This type of counting is called **relative, quantitative diatom analysis**. The percentages are calculated for either the individuals of each identified diatom species/taxon separately, or for a group of diatom taxa with the same requirements as regards ecological or environmental conditions (halobion groups, pH-groups, life-form groups etc.).

Presentation for stratigraphical application/(Diagram construction)

The results of diatom analysis can be presented as a total diatom spectrum, in which the sum of the different ecological groups is 100 %. It may also be presented as a silhouette diagram with separate percentage-curves (Fig. 11). The most important (indicative) diatom species, or groups, can otherwise be illustrated in a succession diagram shown in order of their appearance and frequency maxima (M.-B. Florin, 1946). Diatom taxa occurring in masses (x) should be excluded from the basic sum and presented as separate curves (calculated on the basic sum, or the basic sum + ×).

The sample depth, lithostratigraphy and diatom zones or diatom stratigraphical units, should always be included in diatom diagrams. If possible, correlations with pollen assemblage zones and chronostratigraphical divisions should also be included. Radiocarbon and archaeological datings in years B.P. (corrected for $\delta^{13}C$, reservoir and appearent ages) and calibrated to calendar years B.C. should be included in the diagrams (Olsson, 1986 and 1989, this volume, p. 161-177).

APPLICATION OF DIATOM ANALYSIS TO ARCHAEOLOGICAL STUDIES

Diatom analysis is a biostratigraphical research tool, by means of which the fossil diatom flora in sediments can help to reconstruct changes in the sedimentary environment. These changes, if caused by natural development, such as climatic, eustatic (sea-level), isostatic (land uplift) and vegetational changes, have also influenced the human (cultural) conditions and development. In their turn human activities have influenced the sedimentary environment (human impact on nature). Different periods of human activity and the consequences on the environment have been recorded stratigraphically in the sedimentary basins. By means of diatom and pollen analysis it is possible to determine the strata influenced by human impact and chronologically and date them chronologically. A relative dating is possible by means of pollen analysis and sometimes also through diatom analysis. Radiocarbon dating and archaeological dating of finds, are necessary for absolute age determination.

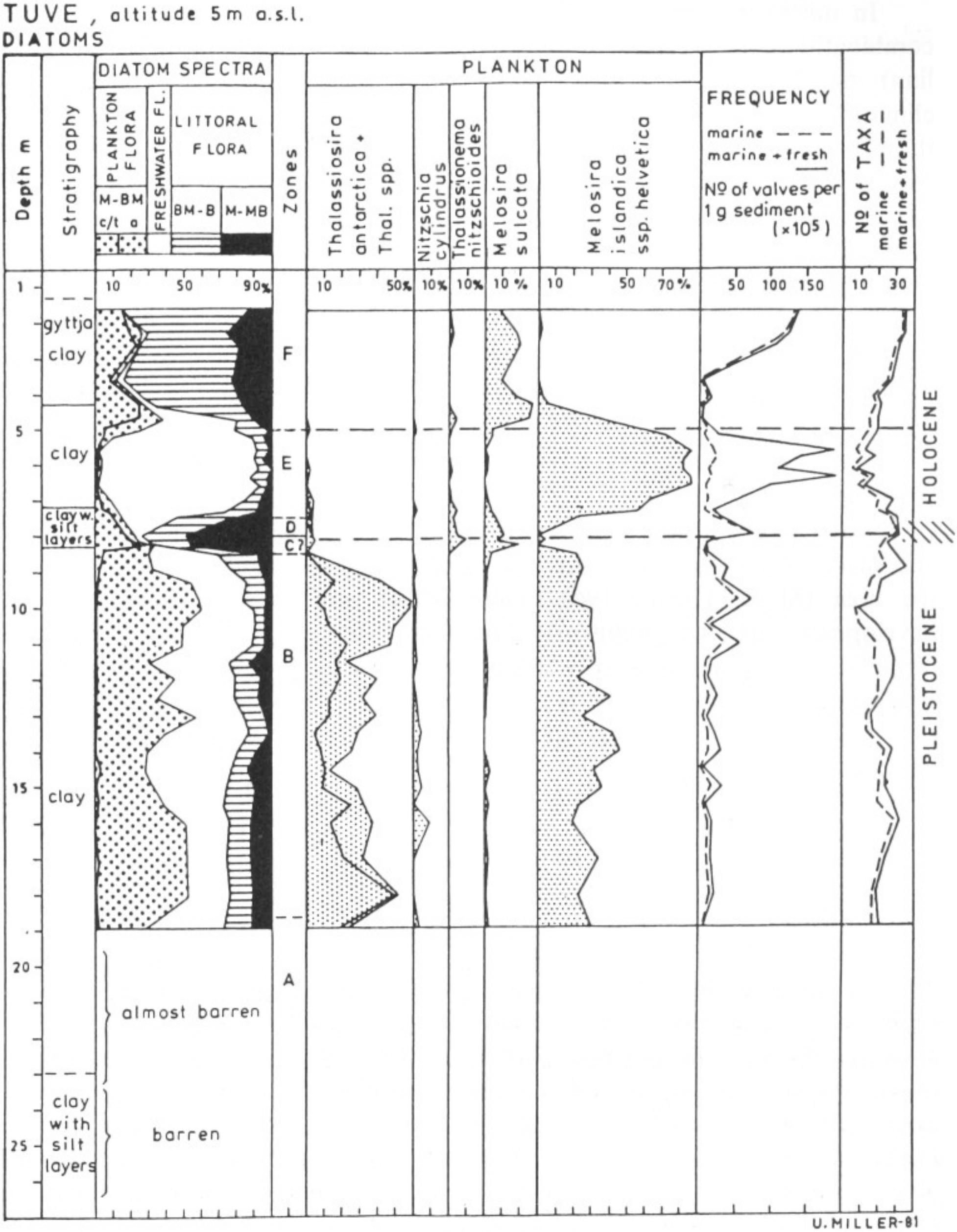


Fig. 11. Diatom diagram showing a total (100 %) of the different ecological groups and separate curves of some indicative diatom species, diatom frequency and number of taxa (Miller, 1982, Fig. 16:7).

Interaction of shore line displacement, climate and coastal dwelling

In northern Europe, generally, shore displacement is interpreted as the combination of isostatic land uplift after the latest glaciation (Late-Weichselian) and eustatic variations of the ocean sea-level, caused by Holocene climatic changes. The first shore displacement curve, which embodies both of these factors and combines them with the altitudes of coastal Meso- and Neolithic dwelling sites, was constructed by S. Florin (1944, 1948). The importance of sea-level fluctuations (transgressive, stable and regressive phases) in relation to the effect of land uplift is seen in the varying altitudes of coastal dwelling sites and settlements (Fig. 12). The sea-level fluctuations were, and are, closely connected with climatic changes (Fairbridge, 1962; Dansgaard, 1975). A regressive phase with falling sea-level usually corresponds to a colder and drier climate, transgressive phases with stable or rising sea-level to a warmer and more marine/humid climate. These palaeohydrological and palaeoenvironmental changes are registered in the sedimentary strata of the basins (Brunnberg *et al.*, 1985).

Sediment cores from different altitudes show a characteristic composition and succession of diatom floras in accordance of the shoreline displacement of the area (M.-B. Florin, 1944, 1946; Miller and Robertsson, 1981). The development of the prehistoric landscape and environment (distribution between land and sea, type of water body etc) can be reconstructed on the basis of diatom stratigraphical data (Miller, 1982, 1986). Combining diatom and pollen analysis, biostratigraphical guide levels can be established (cf. Miller, 1989, p. 43-47; cf. Risberg, 1989, p. 181-187; cf. Robertsson, 1989, p. 69-80, all this volume). Radiocarbon datings complement the results with chronostratigraphical records (cf. Olsson, 1989, this volume, p. 161-177).

Environmental changes caused by natural development and/or human activities

The palaeoecological and palaeohydrological changes of the sedimentary environment generally reflect the natural (geological) development described above (p. 147). In areas where permanent dwellings have existed, the human impact on the environment also has to be taken into the consideration. Forest clearing, building activity, slash and burn agriculture and deposition of waste material in the vicinity of a sedimentary basin will result in more or less distinct changes in the sediment composition. Diatom analysis, with other methods, is a valuable tool used to trace the changes caused by different kinds of human activity.

Erosion, redeposition

Superficial cultural layers from dwelling areas and cultivated fields are easily eroded by rain and wind when the natural vegetation which hinders

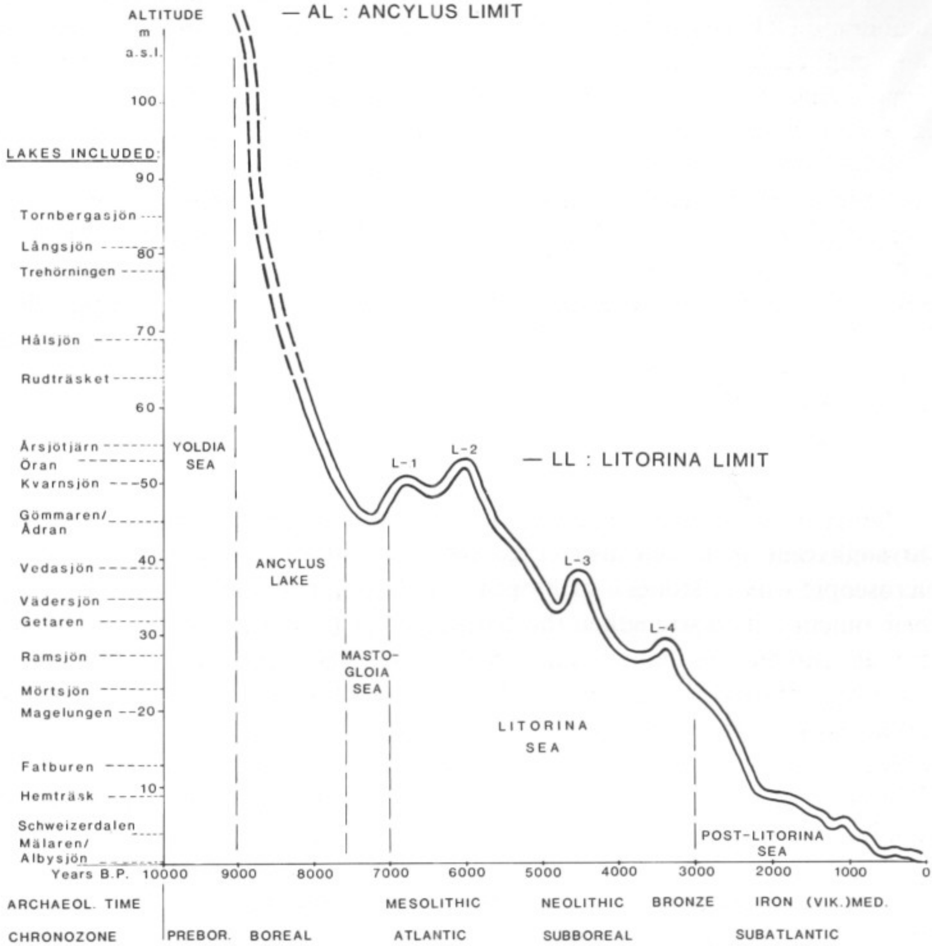


Fig. 12. The shore displacement curve of the Stockholm region shows the eustatic sea-level fluctuations in relation to the effect of isostatic land uplift, and the varying altitudes of coastal dwelling sites and settlements (Brunnberg, Miller and Risberg, 1985, Fig. 2).

erosion has been destroyed (forest clearance) and removed (cultivation). The eroded material is deposited in the adjacent sedimentary basins and document within the stratigraphy, periods of intensive human activities at the dwelling site (Vuorela, 1989, this volume, p. 117-131).

In the fossil diatom spectra the periods of soil erosion are recorded by the occurrence of terrestric (aerophilous) diatoms, which have been washed down or blown into the sedimentary basin. The most common soil diatoms are : *Hantzschia amphioxys, Pinnularia borealis* and *Navicula mutica* (Fig. 13). They live on wet ground and are resilent to periods of dryness.

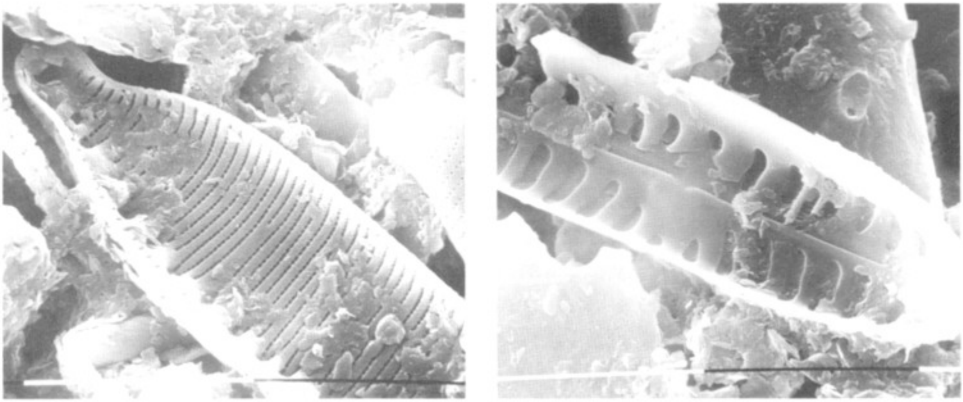


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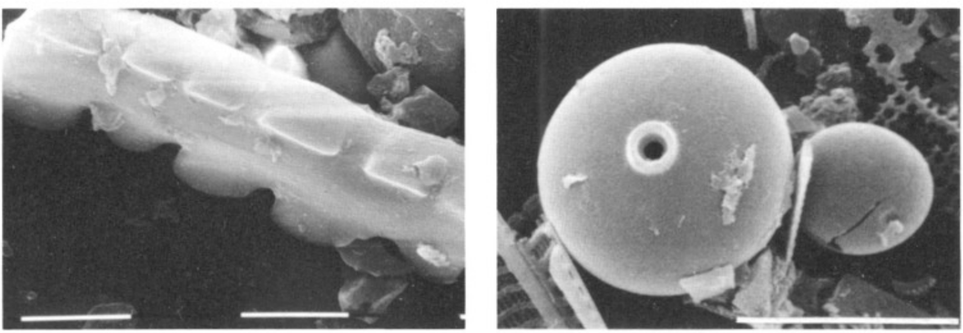
Fig. 13. a) Hantzschia amphioxys *and b)* Pinnularia borealis *are two of the most common aerophilous (terrestric) soil diatoms.*

Other erosion indicative siliceous microfossils such as **phytoliths** and **Chrysophyceae cysts** can also be present (Fig. 14). Phytoliths (Fig. 14a) are microscopic «plant stones» of biogenic silica (Rovner, 1971; Piperno, 1988). Their function is to strengthen the cell walls of e.g. nodes, leaves and needles. They are common in many plants, particularly grasses (including cereals). The first rich occurrence of phytoliths in sediments may register the start of cultivation of cereals in the catchment area (presence of palaeosols, ancient fields).

Chrysophyceae cysts (Fig. 14b) are abundant in soils and sediments rich in nitrogen, such as waste pits, latrines, cemeteries and highly eutrophic, organically polluted, waterways or ponds.



a b

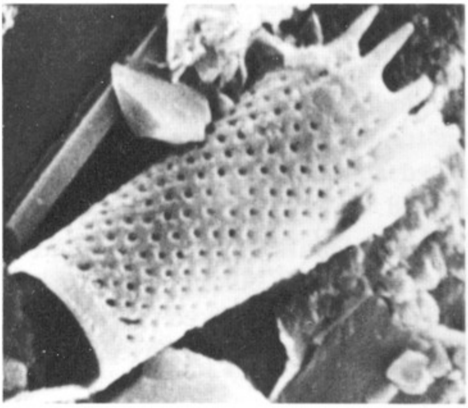
Fig. 14. a) Phytoliths are microscopic «plant stones» of biogenic silica, common in cereals. They occur abundantly in ancient field strata. In sediments phytoliths may indicate erosion of cultivated fields. b) Chrysophyceae cysts (Chrysomonadinae) are abundant in material from waste pits and cemeteries, also in sediments deposited in eutrophic environment.

Human activities such as fillings and levellings in connection with building constructions, digging of ditches and channels, dredging at harbour inlets or damming of lakes and water-courses all cause man-influenced reworking. In these cases older sediments, together with superficial ones, will be mixed and redeposited (Digerfeldt *et al.*, 1980; Miller and Robertsson, 1982). The same is valid for natural land slides and earth slips (Fredén *et al.*, 1981). Diatom spectra of all such sediments can be confusing and difficult to interpret. Knowledge of the geological conditions in the catchment area and around the dwelling site is necessary. Soil mapping with geomorphological studies and coring of stratigraphical sections is carried out to avoid misinterpretation of the diatom stratigraphical record.

Eutrophication, pollution

The composition of diatom spectra illustrates past and present ecological conditions in the basin very clearly. Eutrophication can either be a natural process in the history of development of a sedimentary basin, or it can be a result of human activities. In cultivated areas with clay soils the surplus of soluble fertilizers will be transported into water bodies and contribute to the eutrophication. Industrial and sewer drainage passing into the water-systems, cooling water from nuclear power plants, intensive cattle-breeding/pasture farming and human settlement increase the eutrophication.

Bird colonies are a natural source of eutrophication in coastal areas and shallow inland lakes (Linnman, 1981). Organic pollution caused by surplus nitrogen and phosphorous is registered in the diatom spectra by an increase of *Nitzschia*-species (*N. palea*-group), *Asterionella formosa*, and *Melosira granulata, Stephanodiscus hantzschii* (Miller and Robertsson, 1982). (Fig. 15a).


a

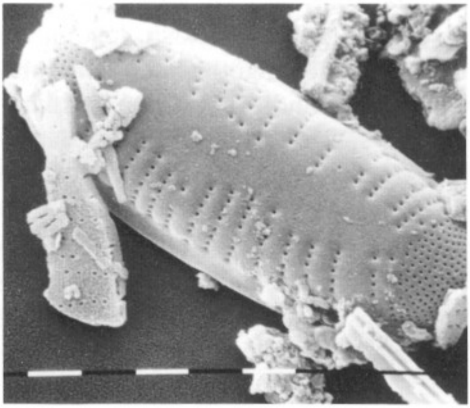

b

Fig. 15. a) Melosira granulata *is one of the diatom species common in sediments deposited in a organically polluted water. b) Many species of the diatom genera* Tabellaria, Eunotia *and* Pinnularia *are characteristic of acid waters, illustrated here by* Tabellaria binalis.

Acidification

Diatoms are one of the best tools to study, trace and document acidification (Renberg and Hellberg, 1982; Renberg, 1986; Battarbee, 1984, 1986). Acidification is a natural process in oligotrophic waterbodies. During the last decade the increase of fossil fuel consumption has accelerated the acidification rate in sensitive regions with naturally acid bedrock, soils and waters. Studies of pH-changes registered in the diatom stratigraphy of sedimentary sequences of different ages (earlier and present interglacials) contribute a valuable reference to the acidification problems of today. This knowledge also helps to make future prognoses (Miller, 1987; Robertsson, 1988).

The diatom species characteristic of acid waters with low pH-values have many representatives in the genera of *Tabellaria*, *Eunotia* and *Pinnularia* (Fig. 15b).

Diatoms as indicators of conditions of archaeological interest

Diatoms as indicators of sedimentary origin and environmental conditions

During excavations many questions about the sedimentary origin of the archaeological strata are of interest to archaeologists. To know if a stratum is water-lain or terrestrial, primary (*in situ*) or secondary (redeposited, reworked, filling) is valuable information for the archaeologist helping him/her to reliable hypothesis and correct interpretations. Many of these questions are easy to answer if diatom analysis is carried out on the sediment strata.

Water-lain sediments, if *in situ*, usually contain diatom species characteristic of the palaeoecological conditions prevailing at the time of deposition of the sediment. In most cases the answer can include data about the salinity of the water (fresh, brackish, lagoonal, marine), the nutrient supply (eutrophic, mesotrophic, oligotrophic), the pH-values (acid, circumneutral, alkaline), degree and kind of pollution and kind of pollution. Moreover, if characteristic diatom species are found, also data about streams and currents, water depth and transparency, wave-washing and exposed or sheltered environment at the dwelling site or settlement can be established.

Terrestrial deposits of eolian origin can be identified by rounded diatom fragments and mineral grains, the presence of terrestric diatoms and often of phytoliths as well. Redeposited terrestrial material can be traced in water-lain sediments by the presence of soil diatoms, phytoliths and Chrysophyceae cysts.

Diatoms as indicators of the stratigraphical range and provenance (origin) of clays used in pottery and brick industry

The biogenic silica in diatom frustules tolerates heating up to 700° C. In ceramics and bricks fired at low temperatures the diatom frustules are preserved and identifiable. Very often phytoliths also occur together with the diatoms. In this way the stratigraphical range of the clays used in the pottery and brick industry can be determined. Sometimes also the provenance of the clay can be traced.

In the Netherlands detailed diatom studies in this field have been carried out (Jansma, 1977, 1981, 1984). In Finland and Sweden the application of diatom analysis to pottery and brick studies has also advanced during the last decennium (Alhonen *et al.*, 1980; Nieminen, 1980; Alhonen and Väkeväinen, 1981; Håkansson and Hulthén, 1986, 1988).

The stratigraphical range of the clays used in the pottery, identified by diatom analysis, seems to be late glacial and early postglacial (Holocene) slightly brackish and freshwater clays (in the Baltic basin — Yoldia and Ancylus clays) with low organic carbon and salt content. The marine Litorina clay with higher content of salt and organic carbon seems to have been avoided.

The provenance of clays suitable for pottery can be roughly located by soil mapping and through coring stratigraphical sections at the dwelling site area. The diatom content of the different clay strata has to be checked and the organic carbon content measured to provide convincible data. Diatoms are considered better indicators of salt content than chemical analysis. Diatoms, if present, will remain in the sediments whereas the salts can be leached.

Diatoms as indicators of the provenance of ships found as wrecks and their former sailing routes

Diatoms can live attached directly to ship bottom and sides or fastened to other organisms attached there (molluscs and *Balanus* shells, algae). In this way diatoms can be transported from one harbour to another. If the saltecological conditions are too different from one place to another the diatom cells may not survive the changes in the osmotic pressure, but the diatom frustules will remain even after the living cell has died. These qualities make diatoms valuable tracers of the origin (provenance) of ships found on the sea bottom or in the sediments and their former sailing routes. During the Helgeandsholmen excavation in the centre of Stockholm, samples were scratched from several ship and boat wrecks (Miller and Robertsson, 1982). Detailed analysis has been carried out on the epiphytic diatom flora attached to the wreck material. The final report on the palaeoenvironment at Helgeandsholmen will deal with these problems in more detail (Miller and Robertsson, in prep).

Diatoms as indicators of death by drowning

In criminal (forensic) investigations diatoms have been shown to be reliable indicators of death by drowning (Hendey, 1973). Sometimes it is difficult to decide if a person was dead before being thrown into the water or, if drowning has been the cause of death. When a person dies by drowning the water will penetrate the lungs and diatoms characteristic of the water-body will be found in the lung tissue. On the other hand, if the person is dead already no water will penetrates the lungs. Only a few terrestric diatoms, which occur in the lung tissue of all people, will be found (Peabody, 1977, 1980).

The applications mentioned above are fields of research where diatom analysis has proved to be of interdisciplinary value and interest. Diatoms are and will always be excellent indicators of environment changes. In the future new fields of applications certainly will be discovered. It is a challenging and stimulating task for diatomists to find new applications of using these sensitive microalgae.

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REFERENCES

ALHONEN, P., KOKKONEN, J., MATISKAINEN, H. and VUORINEN, A., 1980, *Applications of AAS, Diatom Analysis and Stylistic Studies of Finnish Subneolithic Pottery*, in *Bulletin of the Geological Survey of Finland*, 52 (2), p. 193-206.

ALHONEN, P. and VÄKEVÄINEN, L., 1981, *Diatom Analytical Studies of Early Comb Ceramic Vessels from Åland*, in *Suomen Museo 1981*, p. 67-78.

BATTARBEE, R.W., 1984, *Diatom Analysis and the Acidification of Lakes*, in *Phil. Trans. Roy. Soc.*, B 305, p. 451-477.

BATTARBEE, R.W., 1986, *Diatom Analysis*, in *Handbook of Holocene Palaeoecology and Palaeohydrology*, in BERGLUND, B.E., (*ed.*), Chapt. 26, p. 527-570.

BATTARBEE, R.W., 1988, *The Use of Diatom Analysis in Archaeology : A Review*, in *Journal of Archaeological Serwee*, 15, p. 621-644.

BERGLUND, B.E., (*ed.*), 1986, *Handbook of Holocene Palaeoecology and Palaeohydrology*.

BRUNNBERG, L., MILLER, U. and RISBERG, J., 1985, *Project Eastern Svealand: Development of the Holocene Landscape*, in *Iskos, Third Nordic Conference on the Application of Scientific Methods in Archaeology*, 5, p. 85-91.

CHOLNOKY, B.J., 1968, *Die Ökologie der Diatomeen in Binnengewässern*, Weimheim.

CLEVE, P.T., 1984-85, *Synopsis of the Naviculoid Diatoms* (*Kungl. Svenska Vetenskapsakademiens Handlingar*, 26 and 27).

CLEVE-EULER, A., 1951-55, *Die Diatomeen von Schweden und Finnland I-V* (*Kungl. Svenska Vetenskapsakad.* (KVA) *Handlingar*, 4 Series, 2:1, 4:1, 4:5, 5:4 and 3:3).

DANSGAARD, W., 1975, *Klimatsvängningar och människoöden*, in *Ymer*, 95, p. 197-215.

DIGERFELDT, G., HÅKANSSON, H. and PERSSON, T., 1980, *Palaeoecological Studies of the Recent Development of the Stockholm Lakes Långsjön, Lillsjön and Laduviken* (*University Lund Department Quaternary Geology Report*, 20).

EHRENBERG, C.G., 1854, *Mikrogeologie*, Leipzig.

FAIRBRIDGE, R.W., 1962, *World Sea-Level and Climatic Changes*, in *Quaternaria*, 6, p. 111-134.

FLORIN, M.-B., 1944, *En sensubarktisk transgression i trakten av södra Kilsbergen enligt diatomésuccessionen i områdets högre belägna fornsjölagerföljder*, in *Geologiska Föreningens Stockholm Förhandlingar*, 66, p. 417-448.

FLORIN, M.-B., 1946, *Clypeusfloran i post-glaciala fornsjölagerföljder i östra mellansverige*, in *Geologiska Föreningens Stockholm Förhandlingar*, 68, p. 429-458.

FLORIN, M.-B., 1984, *Någòt om kiselalger och kiselalgforskning*, in *Svensk Botanisk Tidskrift*, 78, p. 277-292.

FLORIN, S., 1944, *Havsstrandens förskjutningar och bebyggelseutvecklingen i östra Mellansverige under senkvartär tid, 1*, in *Geologiska Föreningens Stockholm Förhandlingar*, 66, p. 551-634.

FLORIN, S., 1948, *Kustförskjutningen och bebyggelseutvecklingen i östra Mellansverige under senkvartär tid, 2*, in *Geologiska Föreningens Stockholm Förhandlingar*, 70, p. 17-196.

FOGED, N., 1964, *Freshwater Diatoms from Spitzbergen* (*Tromsö Museums Skrifter*, 11).

FOGED, N., 1968, *Diatoméerne i nogle Potteskär fra Varanger*, in *Tromsö Museums Skrifter VII*, 6, p. 47-54.

FREDÉN, C., BRUSEWITZ, A.M., CATO, I., FÄLT, L.M., HÄGER, K.O., MILLER, U. and SAMUELSSON, L., 1981, *Tuveskredet 1977-11-30, Geologiska undersökningar* (*Sveriges Geologiska Undersökning, Rapporter och meddelanden*, 26).

HASLE, G.R. and FRYXELL, G.A., 1970, *Diatoms. Cleaning and Mounting for Light and Electron microscopy*, in *Trans. Am. Micr. Soc.*, 89 (4), p. 469-474.

HENDEY, N.I., 1964, *An Introductory Account of the Smaller Algae of Bristish Coastal Waters, V. Bacillariophyceae (Diatoms), Fishery Investigations, Ministry of Agriculture, Fishery and Food*, Series 45.

HENDEY, N.I., 1973, *The Diagnostic Value of Diatoms in Cases of Drowning*, in *Medical Sci. Law*, 13, p. 23-24.

HUSTEDT, F., 1927-66, *Die Kieselalgen Deutschlands, Österreichs und der Schweiz unter Berücksichtigung der übrigen Länder Europas sowie der angrenzenden Meeresgebiete*, in *L. Rabenhorst's Kryptogamen-Flora von Deutschland, Österreich und der Schweiz*, VII : 1-3, Leipzig.

Hustedt, F., 1930, *Bacillariophyta (Diatomeae)*, in *Die Süßwasser-Flora Mitteleuropas*, 10, A. Pascher (*ed.*), Jena.

Hustedt, F., 1957, *Die Diatomeenflora des Fluß-Systems der Weser im Gebiet der Hansestadt Bremen*, in *Abhandlungen des Naturwissenschaftlichen Vereins Bremen*, 34, p. 181-440.

Håkansson, H. and Hulthén, B., 1986, *On the Dissolution of Pottery for Diatom Studies*, in *Norweg. Archaeol. Review*, 19 (1), p. 34-38.

Håkansson, H. and Hulthén, B., 1988, *Identification of Diatoms in Neolithic Pottery*, in *Diatom Research 3*, p. 39-45.

Jansma, M.J., 1977, *Diatom Analysis of Pottery*, in Beek, Brandt and Groeman-Van Waaterringe, *Ex Horreo*, Amsterdam.

Jansma, M.J., 1981, *Diatom Analysis from Coastal Sites in the Netherlands*, in *BAR International Series*, 94, p. 145-162.

Jansma, M.J., 1984, *Diatom Analysis of Prehistoric Pottery*, in *Proceedings of the Seventh International Diatom Symposium 1982*, p. 529-536.

Kolbe, R.W., 1927, *Zur Ökologie, Morphologie und Systematik der Brackwasser-Diatomeen. Die Kieselalgen des Sperenberger Salz- Gebiets*, (*Pflanzenforschung*, 7), Jena.

Linnman, G., 1981, *Seasonal Eutrophication by Windfowl in Basins Isolating from the Sea*, in *Hydrobiologia*, 103, p. 159-163.

Miller, U., 1964, *Diatom Floras in the Quaternary of the Göta River Valley (Western Sweden)* (*Sveriges Geologiska Undersökning*, Ca 44).

Miller, U., 1969, *Fossil Diatoms under the Scanning Electron Microscope*, (*Sveriges Geologiska Undersökning*, C 642).

Miller, U., 1979, *Reworked Lower Tertiary/Upper Cretaceous Diatoms in the Pleistocene Deposits of Scania, Southern Sweden, and Their Stratigraphic Application*, in *Nova Hedwigia*, Beiheft 64, p. 472-478.

Miller, U., 1981, *Diatom Analysis. A Method of Reconstructing Changes in Sedimentation Environment*, in *PACT News*, 9, p.40-52.

Miller, U., 1982*a*, *Shore Displacement and Coastal Dwelling in the Stockholm Region during the Past 5000 Years*, in *Annales Academiae Scientarium Fennicae, A.III*, 134, p. 185-211.

Miller, U., 1982*b*, *Diatoms*, in *The Pleistocene/Holocene Boundary in South-Western Sweden*, E. Olausson, (*ed.*), (*Sveriges Geologiska Undersökning*), C 794, p. 187-210.

Miller, U., 1986, *Ecology and Palaeoecology of Brackish Water Diatoms with Special Reference to the Baltic Basin*, in *Proceedings of the 8th Diatom Symposium, Paris 1984*, M. Ricard (*ed.*), p. 601-611.

Miller, U., 1987, *An Outline of the Nordic Natural Landscape in the Pleistocene*, in *Nordic Late Quaternary Biology and Ecology*, L.-K. Königsson, (*ed.*), *Striae*, 24, p. 4-14.

Miller, U., 1989, (this volume), *Geology and Environmental History of the Stockholm Region as Shown at the Museum of Medieval Stockholm, Helgeandsholmen*, in *PACT*, 24, p. 43-47.

Miller, U. and Robertsson, A.M., 1981, *Current Biostratigraphical Studies Connected with Archaeological Excavations in the Stockholm Region*, in *Florilegium Florinis Dedicatum*, L.K. Königsson and K. Paabo, (*eds.*), *Striae*, 14, p. 167-173.

MILLER, U. and ROBERTSSON, A.M., 1982, *The Helgeandsholmen excavation : An Outline of Biostratigraphical Studies to Document Shore Displacement and Vegetational Changes*, in *PACT, 7 (Second Nordic Conference on the Application of Scientific Methods in Archaeology)*, p. 311-328.

MILLER, U. and ROBERTSSON, A.M., (in prep.), *Helgeandsholmen - biostratigrafiska undersökningar i samband med de arkeologiska utgrävningarna 1978-1981, samt kompletteringar 1982-1986* (prel. titel), Riksantikvarieämbetet (RAÄ), Report.

NIEMINEN, P., 1980, *On the Use of Microfossils in Clay Research*, in *Nordic Diatomist Meeting 1980, Papers*, Geological Survey of Finland, p. 63-69.

NYGAARD, G., 1956, *The Ancient and Recent Flora of Diatoms and Chrysophyceae in Lake Gribsö, I*, in *Studies on the Humic, Acid Lake Gribsö*, K. BERG and C. PETERSEN, (*eds.*), *Folia Limnol. Scand.*, 8, p. 32-94 and 213-262.

OLSSON, I.U., 1986, *Radiometric Dating*, in *Handbook of Holocene Palaeoecology and Palaeohydrology*, B.E. BERGLUND, (*ed.*), p. 273-312.

OLSSON, I.U., 1989, (this volume), *The ^{14}C Method, Its Possibilities and some Pitfalls. An Introduction*, in *PACT*, 24, p. 161-177.

PEABODY, A.J., 1977, *Diatoms in Forensic Science*, in *Journal of Forensic Science Society*, 17, p. 81-88.

PEABODY, A.J., 1980, *Diatoms and Drowning - A Review*, in *Medical Sci. Law*, 20 (4), p. 254-261.

PIPERNO, D.R., 1988, *Phytolith Analysis. An Archaeological and Geological Perspective.*

RENBERG, I., 1981, *Improved Methods for Sampling, Photographing and Varve-Counting of Varved Lake Sediments*, in *Boreas*, 10, p. 255-258.

RENBERG, I., 1986, *Sjöarnas försurningshistoria avslöjas av kiseljalgerna i sedimenten* (*Statens naturvårdsverk (SNV) Rapport*, 3154.

RENBERG, I. and HELLBERG, T., 1982, *The pH-History of Lakes in Southwestern Sweden, as Calculated from the Subfossil Diatom Flora of the Sediments*, in *Ambio*, 11, p. 30-33.

RISBERG, J., 1989, (this volume), *Stratigraphical Methods Applied to Shore Displacement Studies*, in *PACT*, 24, p. 181-187.

ROBERTSSON, A.M., 1988, *Biostratigraphical Studies of Interglacial and Interstadial Deposits in Sweden*, (*Department of Quaternary Research (USDQR)*, Report 10).

ROBERTSSON, A.M., 1989, (this volume), *Pollen Analysis. Background, Laboratory Techniques and Identification*, in *PACT*, 24, p. 69-80.

ROVNER, I., 1971, *Potential of Opal Phytolithes for Use in Palaeoecological Reconstruction*, in *Quaternary Research*, 1, p. 343-359.

SAARNISTO, M., 1979, *Applications of Annually Laminated Lake Sediments ; a Review*, in *Palaeohydrology of the Temperate Zone*, 1979, Y. VASARI, M. SAARNISTO and M. SEPPÄLÄ (*eds.*), (*Acta Universitatis Ouluensis*, A 82, Geologica 3), p. 97-108.

SIMONSEN, R., 1962, *Untersuchung zur Systematik und Ökologie der Bodendiatomeen der westlichen Ostsee* (*Internationale Revue gesamt. Hydrobiologie, Berlin*, Systemat. Beihefte 1).

VAN HEURCK, H., 1880-85, *Synopsis des diatomées de Belgique*, Anvers.

VUORELA, I., 1989, (this volume), *Indications of Anthropogenic Erosion in A Palaeo-Environmental Context*, in *PACT*, 24, p. 117-131.