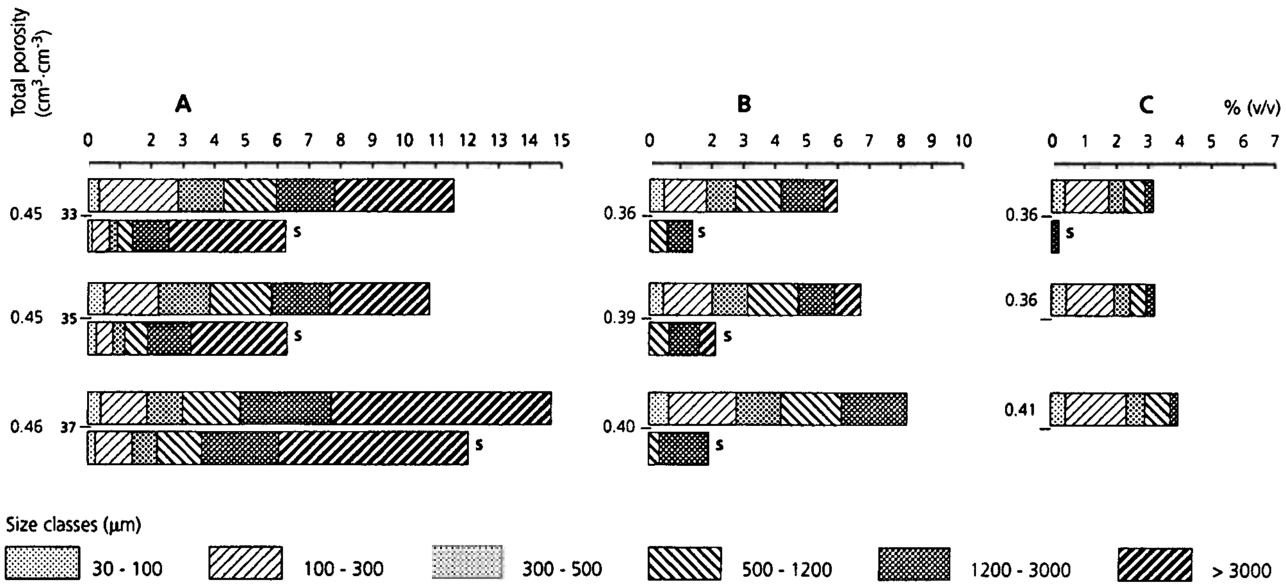

Figure 6. Total porosity and pore-size distribution by image analysis of horizontal thin sections of 33, 35 and 37 cm depth prepared from soil columns stained with methylene blue A. permanent pasture land; B. arable land with a primary ploughpan; C. arable land with a recompacted ploughpan, three years after deep tillage. s: proportion of voids with stained walls (adapted from Kooistra et al., 1985).

non-stained and stained voids explained the soil physical behavior of these layers and attributed to improved management of these soils (Kooistra et al., 1985).

During the last 10 years the staining of biological materials in soil thin sections has gained more attention to trace the presence of various groups of organisms. Non-fluorescent stains as well as fluorochromes are being developed (Altemüller and Haag, 1983; Tippkötter et al., 1986; Altemüller and Van Vliet-Lanoë, 1990; Postma and Altemüller, 1990). The latter aimed to examine the spatial distribution of certain bacteria strains and tested among other things the fluorescent brightener calcofluor white M2R. They developed a useful staining procedure, which is sufficiently documented for subsequent replication. The details are given in the referred publication. Bacterial cells, but also fungal hyphae and plant roots were clearly visible in relation to the groundmass. Most of the inoculated bacterial cells were detected, along surfaces of larger voids. Indigenous bacteria were less intensively stained and were found in smaller voids. The comparison to observations on stained soil smears suggested that some smaller cocoids, starving cells and bacterial spores remained unstained.

Single phenomena can also be studied when the soil material is disturbed. One of the most common phenomenon studied in disturbed soil material is the aggregate structure of soils. The size, quantity and stability of aggregates determined, reflect the local equilibrium of environmental forces which enhance aggregation or cause disruption. Kemper and Koch (1966) proposed a standard procedure for measuring aggregate stability, but modifications to the standard methodologies are increasingly being used. Nowadays the soil material can be disrupted with physical disruption as ultrasonic dispersion (North, 1976), with chemical dispersing agents (Tisdall and Oades, 1979), with gently misting and slaking (Elliott, 1986), dry-sieving (Gupta and Germida, 1988) and other methods. Beare and Bruce (1993) compared methods for measuring water stable aggregates and emphasized the value of comparing soil specific responses to different pretreatment procedures. They recommend that results of aggregate analyses be always accompanied by complete descriptions or references of the procedures applied, as these data can be critical to the interpretation of the data. Aggregate analyses are performed for different research questions varying from the structural stability in relation to faunal excrements to the physical separation of soil organic matter fractions.

A good example of the latter is the method for physical separation and characterization of soil organic matter fractions of different size classes developed by Cambardella and Elliott (1993). The method aimed to isolate and characterize soil organic matter fractions originally occluded within the aggregate structure to increase the current level of understanding about how the aggregate structure controls the turnover of soil organic matter. They improved the quantitative estimations of soil organic matter fractions in cultivated grassland systems. They concluded that adoption of reduced tillage management could be an important step towards the goal of sustainable production, which optimizes long-term profits to the farmer and minimizes damage to the environment.

Vittorello et al. (1989) combined a particle size fractionation (5 fractions sieved at different mesh sizes plus alkaline extractable C) with $^{12}C/^{13}C$ isotope ratios of the organic carbon for soil 12 and 50 years after conversion from forest to sugarcane. This isotope ratio allows distinction between organic material from plants with a C4 photosynthetic pathway (such as sugarcane) and material from plants with the more normal C3 photosynthesis. Their results show that 12 years after conversion, in the coarse sand fractions the majority of C was derived from sugar-cane and in the clay fractions 90% of the C still had a forest signature. Fifty years after conversion, about 70% of the clay fraction still had a forest signature. These data illustrate the importance of clay-organic matter linkages as C protection mechanism.

A recently developed method for fractionation of soil samples in suspended silica solutions of various physical densities, in combination with sieving (Meijboom et al., 1995; Hassink et al., 1993; Hassink, 1995) has a similar objective. Fresh plant material has a physical density of about 1 mg cm^{-3}; if organic material gets more and more associated with mineral soil particles (e.g. by faunal activity) it enters heavier fractions.

C. Spatial Correlation of Two or More Phenomena

All the methods dealt with in the previous section for describing the distribution of single phenomena *in situ* are also utilized to study the occurrence and spatial correlation of two or more phenomena. Depending on the research objectives more or less sophisticated qualitative methods are developed. The simplest way is a descriptive one for example noting that rare pollen grains as well as the few charcoal fragments, detected with microscopic analyses in thin sections of the subsoil, occurred in the partly infilled large root channels (Smeerdijk et al., 1994). A next step is the mapping of different phenomena on transparent sheets e.g. the occurrence of roots, cracks and crop residues in different soil horizons in a profile pit (see section B) or in thin sections. These results can be used for quantitative analyses, e.g. by means of an image analyzer.

Tests of spatial correlation can be based on the null-hypothesis of independent random distribution patterns. By quantifying the frequency of feature A in zones with increasing distance to feature B a simple test of synlocation is possible. Van Noordwijk et al. (1993c) gave examples of the distribution of roots and freshly introduced plant residues, quantified as a function of distance to the nearest macro voids in a soil profile. Two approaches are possible: enumerate all events x and determine their nearest neighbour of element y, or consider zones around all elements y with increasing distance and determine the density (number per unit area) of elements x. With image analysis computers the second approach is

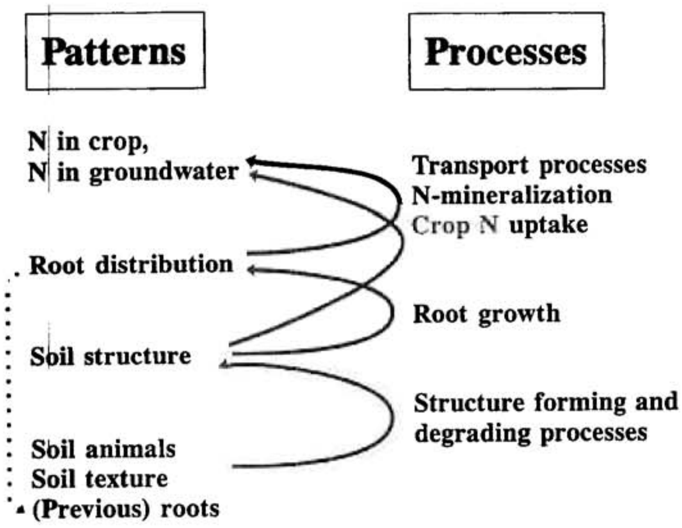

Figure 7. Chain linking patterns and processes from structure forming agents to N management.

preferrable and can run fully automatic, once elements x and y are properly identified and digitized.

III. Dynamics of Heterogeneity at a Range of Scales

A. General

The patterns of heterogeneity which can be observed with the methods of the previous section, are in a dynamic balance of rise and fall, due to counteracting processes. A causative chain of interrelations between "patterns" and "processes" can be developed (Van Noordwijk et al., 1993a), as patterns are derived from processes, but at the same time form the boundary conditions for such processes as well as those at a higher level of complexity. In general, patterns are more easily observed than processes, but processes can be better generalized and have a more universal value. In Figure 7 a possible chain linking the factors determining soil architecture with N management is summarized. This section is focused on the lower part of the chain, dealing with the processes (and underlying patterns) driving the dynamics of soil heterogeneity. These processes can lead to increasing or decreasing heterogeneity. The higher part of the chain is dealt with in the next section.

B. Processes Increasing Heterogeneity

Soil architecture is the dynamic result of many abiotic and biotic factors and processes. It may be difficult to imagine how heterogeneity, a non-uniform distribution, and patterns, a non-random distribution, can originate in a completely homogeneous environment. It is much easier to understand how existing heterogeneities are enlarged by processes taking place at different rates in the various micro-sites available. The basic, abiotic patterns with which biotic actors interact are: particle size distribution (texture) and gradients in soil water content, temperature and aeration between the soil surface and subsoil layers (with or without a water table). The latter group of patterns fluctuates in time with weather conditions. In non-cultivated land, the dynamics of heterogeneity in soil architecture are mainly governed by the weather regulating physical aggregate formation and biological processes. In cultivated land the human impact, viz. tillage, traffic and machinery, application of pesticides, fertilizers and manures, regulates the dynamics of heterogeneity in the topsoil throughout the year. The following subjects will be dealt with in more detail:

- physical aggregate formation,
- biological processes, especially plant roots and soil fauna,
- human impact (and related induced processes),
- preferential flow patterns.

1. Physical Aggregate Formation

The texture of the soil, especially the clay fraction ($\% < 2\ \mu m$), and the water content determine the basic physical soil structure. Depending on clay mineralogy and clay content, the soil material swells and shrinks upon wetting and drying. Due to desiccation shrinkage cracks are formed, which once formed reappear at the same place. These cracks may form specific patterns resulting in a pedal soil. Pedality is defined as the occurrence of individual, natural, soil aggregates or peds (Soil Survey Staff, 1975). The individual peds can be classified according to their shape and arrangement into prisms, columns, plates, blocky peds, granules and crumbs, delineated by planar voids. With increasing clay content of the soil the swell/shrink potentials increase and different kinds of pedality occur. Figure 8 gives an example of the different pedalities occurring in the subsoil of marine and riverine deposits in The Netherlands with increasing clay content. The figure shows that the various pedalities differ in range, but there are overlaps where more than one type occurs. Besides a stronger desiccation, the biological impact also plays a role in these overlaps. Between 8 to 30% clay the biological impact reaches a maximum, but the structure is still related to the physical swell/shrink potential of the soil. Desiccation is related

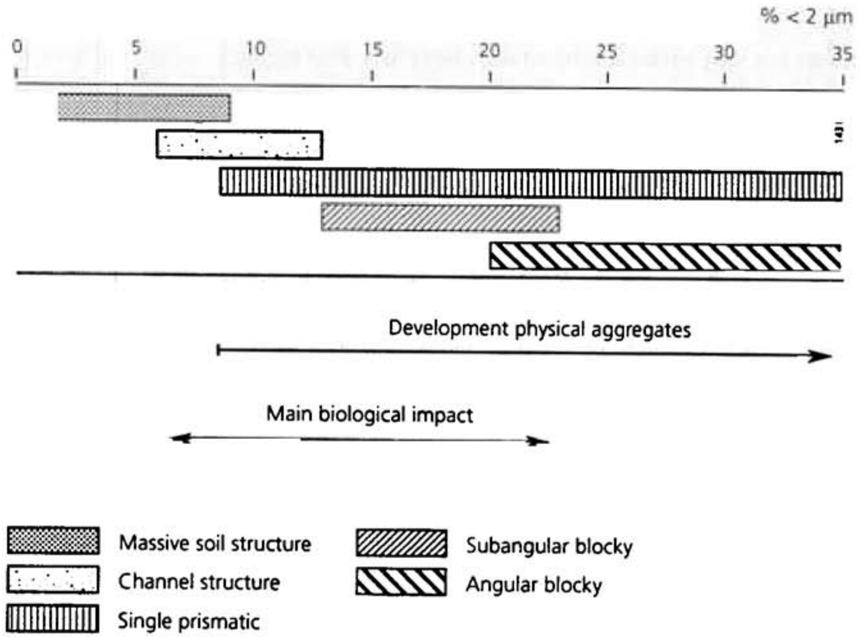

Figure 8. Pedalities occurring in the subsoil of marine and riverine deposits of The Netherlands with increasing clay content influenced by the physical aggregate formation and biological activity.

to the depth of water tables, the drainage and weather conditions. Soils with a high clay content, especially smectitic clays, strongly react on desiccation resulting in strong pedality. An example of this development, showing structure development on sedimentary deposits from sediment to vertisol is given by Blokhuis et al. (1990). The sequence in sedimentary deposits, subjected to a process of physical ripening (Pons and Zonneveld, 1965), starts with the development of widely spaced, wide and deep vertical desiccation cracks, followed by the formation of an angular blocky structure in the topsoil between the vertical cracks. Thereafter, large subhorizontal cracks develop in the ripening clays, which can be more horizontal, forming prisms that become subdivided into angular blocky structures (Inceptisols), or tend towards an oblique orientation, forming slickensides, that become subdivided into angular wedge-shaped structures (Vertisols).

2. Effects of Plant Roots

Roots not only give stability to the plant, they also regulate water, nutrient and oxygen uptake of the plant. Roots grow in such a way that they can fulfill these requirements. Roots, subsoil stem parts and filaments of algae produce channel systems by exertion of pressure on soil particles. Their diameter, more than their length, generally determines the effect on the soil. Roots and filamentous algae from about 40 μm in diameter can form lasting macropores.

They can produce systems of round channels which may be branched or not with different diameters. Roots often use available voids which they modify partly or completely by pressure during growth. In existing voids roots can adapt their own shape to a certain degree before modifying the void in which they grow (Figure 9a). Roots growing in larger voids can produce root hairs extending to the solid soil material to fulfill their nutrient requirements (Figure 9b). In the tilled zone of cultivated land, roots generally follow voids formed by tillage operations. Only a small percentage of the voids are primary root channels, which varies per crop and farm-management system. Sugar beet roots in a study of three cropping systems in The Netherlands in 1985 produced hardly any primary root channels in the tilled layer under conventional (i.e. moldboard ploughing, 20 to 25 cm) soil management, 0.4% in an integrated farming system (i.e. reduced N fertilization and pesticide use; and shallow tillage, 12 to 15 cm) and about 1% in a minimum tillage system. About 5% of the tillage voids in the conventional system were modified by the sugar beet roots and the percentage of modified voids in the integrated farming system and the minimum tillage system were not significantly higher (Kooistra et al., 1989). Below the tilled zone and in natural environments roots generally follow the cracks between the peds and faunal voids or former root channels which they all can modify to some extent.

If roots follow preexisting voids they will have no or only partial contact with the soil, except when they completely fill or expand a preexisting void. If, on the other hand, roots penetrate in the groundmass they will initially have a complete root-soil contact (100%). The degree of root-soil contact is an important parameter in studies on oxygen, water and nutrient uptake by plant roots (De Willigen and Van Noordwijk, 1987). Root-soil contact can be analyzed in thin sections which are freeze-dried before impregnation to avoid shrinkage of the roots. Analyses of maize (*Zea mays* L.) roots grown in pot experiments with soil material compacted to different bulk densities showed that roots do not shrink and that all root cross-sections are recognized (Van Noordwijk et al., 1992). In this pot experiment the degree of root-soil contact between the depths 9 to 14 cm was found to increase from 58 to 90% while soil porosity decreased from 60 to 44 % (Kooistra et al., 1992). The highest bulk density, corresponding with a total porosity of 44% reflect compacted layers in sandy loam soils. These soils are very susceptible to waterlogging after showers

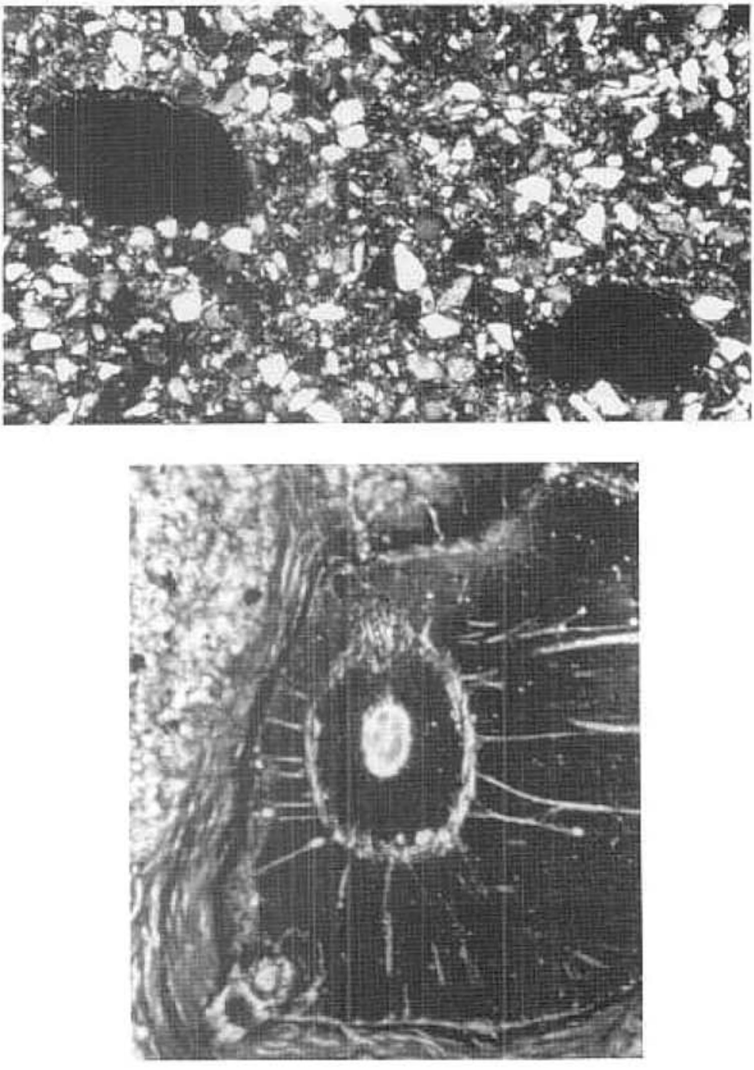

Figure 9. Roots in arable soils, a: modification of the root shape by growing into an existing void; b. production of roothairs when growing in large existing voids (magnification a: x 25; b: x 12).

and an average root-soil contact of 90% may be the limit for adequate oxygen supply. The lowest bulk density reflects a situation in which root growth is becoming limited in field situations. Here adequate nutrient supply seems to become the limiting factor, which is related to an average root-soil contact less than 58%. Root-soil contact of field grown winter wheat (*Triticum aestivum* L.) growing in 1990 in two of the above mentioned agroecosystems was quantified in horizontally oriented thin sections at 15, 25 and 45 cm depth (Van Noordwijk et al., 1993d). One day before sampling the soil surface was ponded with a methylene blue solution to stain surface-connected voids. The two fields, conventional and integrated farm management had different frequency distributions of root-soil contact in the plough layer. The percentage of roots with 100% root-soil contact was 65 and 37, and those with 0% root-soil contact 5 and 14, respectively. The average root-soil contact in the plough layer was 84% for the conventional and 66 % for the integrated system. The roots without direct contact with the soil were mainly growing in surface-connected, continuous voids, which rarely have aeration limitations. The roots with 50-100% root-soil contact were mainly the smaller roots occurring in non-stained voids. Below the plough layer, in the natural subsoil, the root-soil contact was less. In these two farm management systems, the soil structure in the plough layer was different. In the integrated system, the macroporosity of the soil was more than double (15% and 6%, respectively) than the conventional system and the biological impact by soil fauna was much larger resulting in a more open structure (Boersma and Kooistra, 1994). The existing porosity and its stability influences largely the root growth and root-soil contact of the crops in the plough layer. With increasing clay content, roots more and more follow existing pedal cracks, especially when 2:1 lattice clays are concerned.

Decaying root channels can be a major determinant in water infiltration patterns, e.g. where natural forest has been cut and the land is used for crop production in the humid tropics (Van Noordwijk et al., 1991).

3. Effects of Soil Fauna

The soil fauna is comprised of those animals which pass one or more active phases of their life cycle in the soil. They occur in the soil for several reasons e.g. protection, food and reproduction and their effects on the soil can be multifold. Their main impact on soil architecture is that they produce voids and excreta, whereby soil material, both organic and inorganic, can be dislocated, organic material fragmented, and mineral and organic material mixed. The basic products, voids and excreta, are considered in more detail below.

Many species produce voids, most of which are channels, but also other types of voids occur. Channels can be straight, curved or very convoluted, with or without branching or chambers. They can resemble root channels, but are rarely

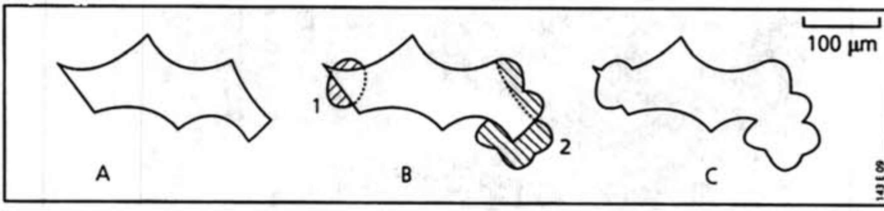

Figure 10. Modified void (c) developed from a void between earthworm excrements (a). In one end (b1) a root found its way; on the other end (b2) small mites modified the void.

as regular as these. The primary voids are formed in three ways: by pressure exerted on soil materials, by digging and removal of loose material and by soil consumption. Voids formed by pressure mainly occur in loosely packed, and in wet, plastic soil material and can be formed for example by worms and snails (Kooistra, 1978). Digging occurs in all kinds of soil materials. The result can be very regular channels as made by the dung beetle (Brussaard and Runia, 1984) or very irregular voids as made by termites. Also the digging purposes differ. Beetles dig to lay eggs at a specific depth and termites to collect fine-grained soil material for building and stabilization purposes. The same variety is found in voids due to soil consumption. Even within one group of soil organisms different void systems are produced. Earthworms, e.g. *Allolobophora longa*, can produce simple channel systems, while, e.g. *Hyperiodrilus* spp. and *Eudrilidae* can consume virtually all fine-grained soil material in specific zones in the soil in humid tropical forests (Kooistra et al., 1990). Soil animals also enlarge existing voids locally, which can be any type from cracks to root channels or other faunal voids. Necks in voids systems can be enlarged or cavities made in walls. Resulting voids can be very irregular (Figure 10). Many organisms can modify voids, especially mesofauna such as mites, collembola and enchytraeids. Void systems produced by soil fauna can start at the surface, but also deeper in the soil from existing voids. With increasing clay content, the effects of soil fauna become more restricted to modifications of existing cracks between the peds. Two features, produced by soil fauna, occur associated with faunal voids. These are wall plasters or coatings and cocoons. Plasters consist of fine-grained soil material or material from excrements. Termites generally use aggregates of fine-grained soil material, while earthworms use excreta, which are often darker coloured than the surrounding groundmass due to admixtures of organic material. The plasters occur in voids used for longer periods. Cocoons can locally be found in faunal void systems and consist of fine-grained soil material mainly derived from excrements. Earthworms can produce cocoons as retreat or hatching place for eggs (Figure 11a).

Recognizable excrements are only produced by soil fauna consuming solid materials, organic as well as inorganic. Excrements can be recognized by their shape, composition and/or organization. Many shapes can be distinguished, e.g. spheres, ellipsoids, cylinders, bacillocylinders, grooved plates, mammillated

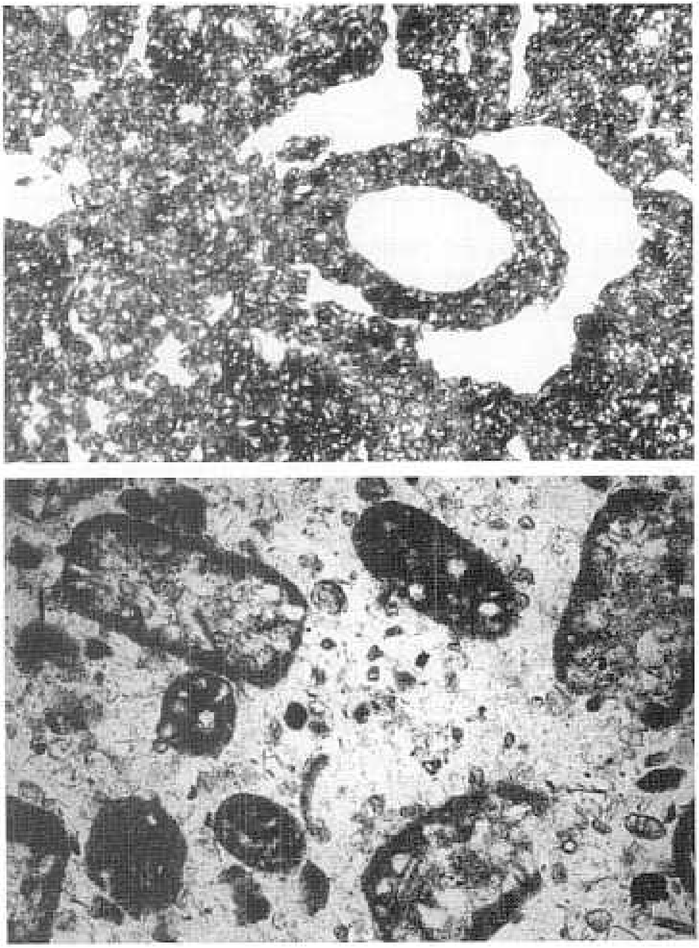

Figure 11. Faunal products, a. a cocoon produced by an earthworm; b. different shapes and composition of excrements in marine sediment, produced by pelecypods, worms and snails (magnification a: x 2.5; b: x 45).

excrements and threads (Bullock et al., 1985). Together with their size, some shapes can be ascribed to specific soil fauna. Excrements can be composed of only organic material or mixtures of organic and mineral material. The organic material is very varied and the mineral material is often fine-grained and has a distinct upper grain-size limit, which can be used for identification of the species (Figure 11b).