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X-rays applied to the study of the pore structure in soils

H. Rogaar and R. A. H. Thiadens

Department of Soil Science and Geology, Agricultural University, Wageningen, the Netherlands

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Summary

X-ray radiography, which has proved to be a useful tool in tackling palaeontological, geological and soil mechanical problems, is shown to be useful as well in the study of the pore structure in soils. The authors discuss the advantages of X-ray radiography, some limitations and the necessity to combine this technique with others. The method is useful in the field of soil research as well as in education. In illustration, radiographs of subsoil samples of a marsh and three polder soils of the Wash area (Norfolk, England) are added.

Introduction

Voids in the soil are three-dimensional entities and all the voids together form a three-dimensional structure. In spite of this, voids are usually studied in two dimensions only (profile walls in the field, soil peels and thin sections in the laboratory). In this way reasonably reliable results are obtained about quantities and size distribution of pores (van der Plas & Slager, 1964; Bouma & Hole, 1965; Geyger & Beckmann, 1967; Jongerius et al., 1972; Bouma & Anderson, 1973), but other morphological aspects like their course, shape, and mutual connections, can only be guessed at. Studies including the third dimension may be accomplished by: photographing successive sections of impregnated soil samples as proposed by Beckmann (1964); impregnating wet soil samples by polyester resin to obtain casts of the voids (Rogaar, 1974) or, as Bouma (1969) suggested, by X-ray radiography. The latter is a non-destructive method already applied in several earth sciences and in soil mechanics in order to study sedimentary and other structures and to trace objects in sediments (Hamblin, 1962; Bouma, 1969; Krinitzsky, 1970).

The method is based on differences in absorption of transmitted X-rays by individual bodies and the adjoining soil mass. Where voids are present radiation is absorbed and scattered less than in the surrounding solid soil material. The resulting differences in transmitted radiation are recorded on X-ray film and in this way projections of the structural differences, objects and voids are obtained.

The fundamentals of X-rays and their application in absorption techniques may be found in handbooks on X-rays. X-ray radiography for earth science studies has

Table 1. Technical data of the applied radiographical technique.

Equipment	: Senograph C.G.R.
Focal spot	: 6 mm, made of molybdenum
Filter	: molybdenum
Potential	: 35 kV
Current	: 35 mA
Time	: variable
Distance, Focus to film	: 40 cm
Film type	: Kodak Définix
Objects	: impregnated soil samples; thickness of slabs 0.1, 0.2 and 0.5 cm

been extensively discussed by Bouma (1969) and by Krinitzky (1970). Studies in this field have been completed by several workers (e.g. Hamblin, 1962; Calvert & Veevers, 1962; Rioult & Riby, 1963; Bouma, 1963, 1964; Bouma & Boerma, 1964; Sorauf, 1965; Patchen, 1967; Werner, 1968; Bé et al., 1969; Baker & Friedman, 1969; Thiede & Larsen, 1971; Liboriussen, 1973).

In this paper the application of X-ray radiography to the study of voids in the soil is shortly discussed. Some illustrative examples were taken from a marsh and three polder soils from the Wash (England).

Procedure

In the present study the medical X-ray unit Senographe C.G.R. has been applied. The important technical data are listed in Table 1. The exposure (strength of current × time) was varied with the type and the thickness of the samples, the other factors being fixed.

Stereo photography turned out to be very useful, allowing more detailed study of the radiographs. The stereo effect was produced by moving the tube over an angle of 5° to both sides of normal incidence, leaving the object in place (Fig. 1).

The obtained stereo radiographs were studied with the aid of a light table and a mirror stereoscope, as is commonly used in aerial photo interpretations. The radiographs presented in this paper (Fig. 4-7) are mounted in such a way that they may be studied by a pocket stereoscope.

The samples were slabs, 7 × 15 cm, of oven-dry (105 °C) impregnated soil material of 5, 2 and 1 mm thickness. They were mounted on clear acrylate plate of 3 mm thickness. The impregnation with polyester resin (Synolite 544/S 36) was accomplished as described by Jongerius & Heintzberger (1963). The use of impregnated material was preferred above fresh unconsolidated soil samples, which are quite troublesome in cutting and storage and do not allow additional study by microscope. The polyester resin itself does not noticeably influence the quality of the radiographs (Bouma, 1969). The disadvantages of drying before impregnation, to which the samples in the present study were still subjected, have largely been overcome by a recently developed impregnation technique without preliminary drying (Miedema et al., 1974).

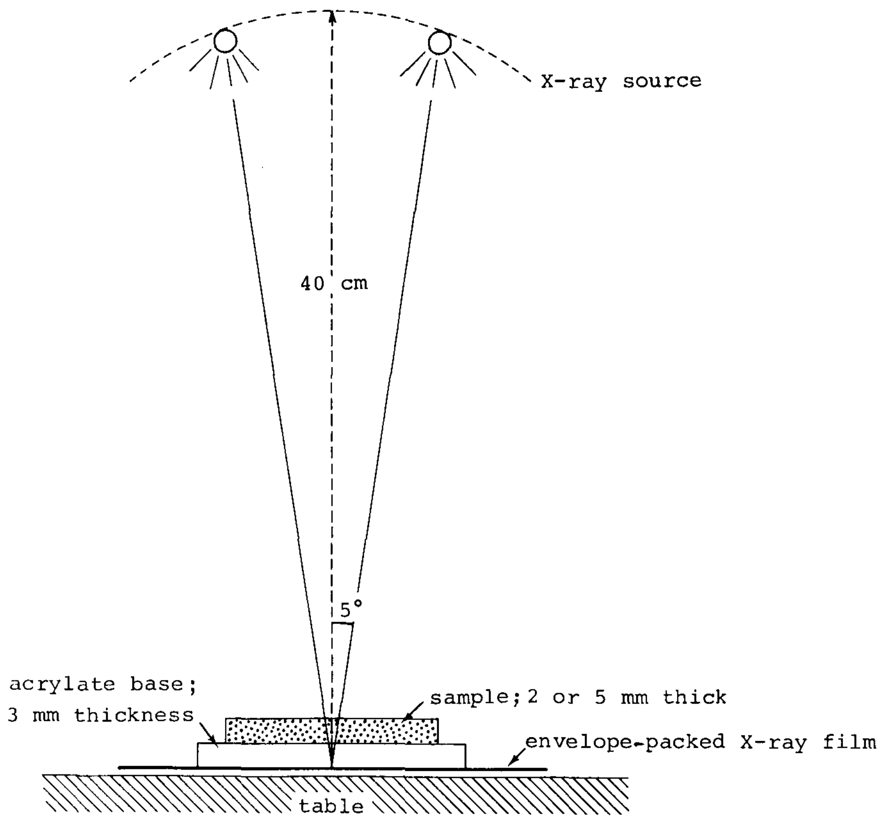

Fig. 1. Stereo radiography. To obtain the stereo effect the tube is turned over an angle of 5° to both sides of the perpendicular. To produce the stero pair of radiographs the film has to be replaced, after which the sample has to be put back accurately into the same position.

Variation in sample thickness is necessary since the resolution of the radiographs decreases with increasing thickness (Table 2). Very detailed studies require the use of thin sections, but on the other hand very thin samples are not suitable for the study of the larger voids and violate the 3-dimensional conception. Considering this problem and the fact that pores of 0.1 - 0.2 mm diameter are very common in soils, the slabs with a thickness of 2 mm proved to be most generally

Table 2. Thickness of samples in relation to the lower limit of the perceptibility of the voids.

Thickness	Lower limit of visible voids
0.1 cm	about 0.05 mm
0.2 cm	about 0.075 mm
0.5 cm	about 0.150 mm

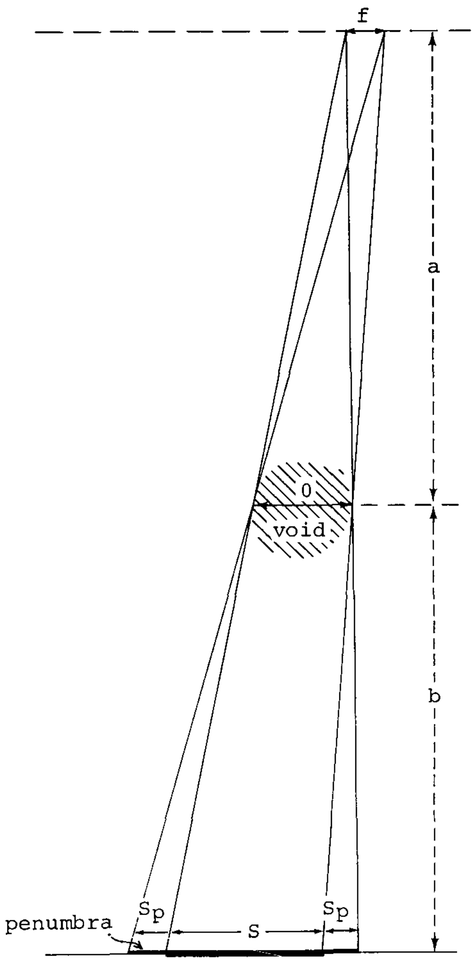

Fig. 2. Formation of the radiographic image. S = cast shadow, S_p = penumbra, f = size of focus, 0 = size of object, a = distance from focus to object; b = distance from object to film.

suitable, the others providing additional information. Sections thicker than 5 mm yield little information due to the superimposing of images. Since the thickness of the samples is still limited, both horizontal and vertical cuts through the soil at the same site have to be studied. Moreover accurate field observations are essential for proper interpretation and to add information about very large objects.

Some limiting factors

Several factors influence the formation of images on the radiographs (Bouma, 1969). In this context it should be realised, that the projections of the voids form like shadows (Fig. 2). Due to the divergent radiation, the projections will be larger than the original voids, following the equation $S \simeq (a + b)\frac{0}{a}$ (see Fig. 2). For the presented technique the enlargement amounts 2 % at the most. Around the cast shadow a penumbra of less intensity will develop, due to the linear shape of the focus (Fig. 2). The size of this penumbra is given by $Sp = b\frac{f}{a}$ (see Fig. 2). Its presence causes blurring of boundaries and an increase or decrease of the size of image, dependent on the ratio focus size: object size and on the perception of the penumbra, as belonging to the image or not. The divergent radiation causes also a slight displacement of the projection with regard to the original voids. For the presented technique this is 2.2 mm at the most for slabs of 5 mm thickness. To limit the disadventeous effects of the mentioned geometrical factors

- a long distance from focus to object,
- a short distance from object to film, and
- a small sized focus

are required.

Blurring of boundaries is also caused by the scattering of radiation on its way from the object to the film. The non-image-forming, scattered radiation also contibutes to the background blackening of the radiographs, lowering the perceptibility of the weak projections of very fine voids. To reduce the effect of the scattering, the distance from the object to the film should be kept as short as possible and the very weak radiation, which is most liable to scattering, should be intercepted by filters. The use of harder radiation, generated at higher kV values (e.g. Calvert & Veevers, 1962; Rioult & Riby, 1963; Baker & Friedman, 1969) is not advisable, because of the loss of detail. In Table 2 the lower size limits of visible pores are given for the presented technique. Improvement of the contrast by photographic contrast enhancement (Dronkers & van der Zwaag, 1974) or by electronically controlled printing (Bouma, 1969) may be accomplished afterwards.

Interpretation of radiographs

The resulting radiographs yield the dark projections of voids, which vary in contrast along their course. Inclined tubular voids running from the far plane of the sample to the plane adjoining the film show black near ends with clear boundaries, grading into increasingly vague traces with distance away from the film plane. Sometimes the upper end is also clearly depicted. Presumably the images of the pores which are very near to the film closely resemble their real size, being hardly influenced by scattering and other factors. Apparently the sizes of the vaguer parts of the voids are less, but on close examination this could not be proved for the larger ones. Small pores, on the contrary, may be diminished in apparent size by 25 % and indicate that the small voids are obviously most effected by the factors mentioned above.

Due to this, radiography is not a self-supporting technique in the study of the soil pore morphology and can only be applied in combination with other techniques. The length, orientation, twisting, branching and spatial distribution of the tubular voids may be studied directly from the transparent radiographs, by means of a mirror stereoscope, a light table and transparent scales for the estimation of size, length and curvature. To obtain accurate information about the size distribution of the voids on the horizontal and vertical faces in the soil, counts may be made on the same polished plates as used for the radiography by a binocular microscope with incident light (Rogaar, in prep.). More detailed studies about the size distribution and other micromorphological phenomena may be accomplished by preparing thin sections from the impregnated samples, which are studied by microscope.

Scope of the method

X-ray radiography is a useful tool in the study of the voids in the soil. It adds the third dimension to the usual methods of two-dimensional study. The technique is less complicated than previous three-dimensional approaches and has the advantage of displaying a clear, reproducible picture of the pore system. Moreover it is a non-destructive method, and can be applied to fresh as well as impregnated soil material. The method is sufficiently reliable to obtain semi-detailed quantitative observations on the location, orientation, distribution, twisting and branching of tubular voids. Combination with other optical techniques adds the information about the sizes of the voids.
The method is applicable in the field of soil research as well as in education. Research objects may comprise pure soil morphological studies, but also the study of the burrowing activity of the soil fauna and the study of the distribution of roots in virgin or homogenized soils.

Some examples

In this section some radiographs of soils of the Wash (England) are presented. They show structures which were met in a present-day salt marsh near Stiffkey (Norfolk)

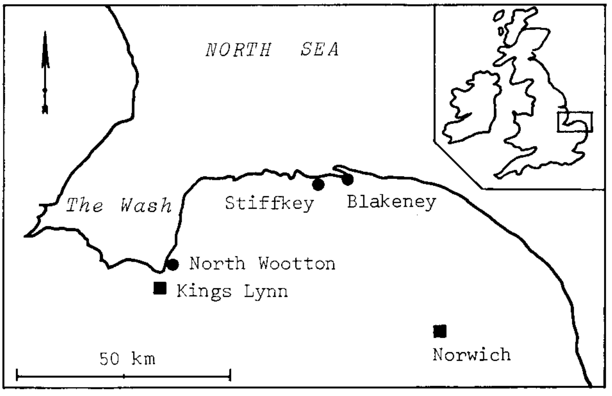

Fig. 3. Origin of the samples.

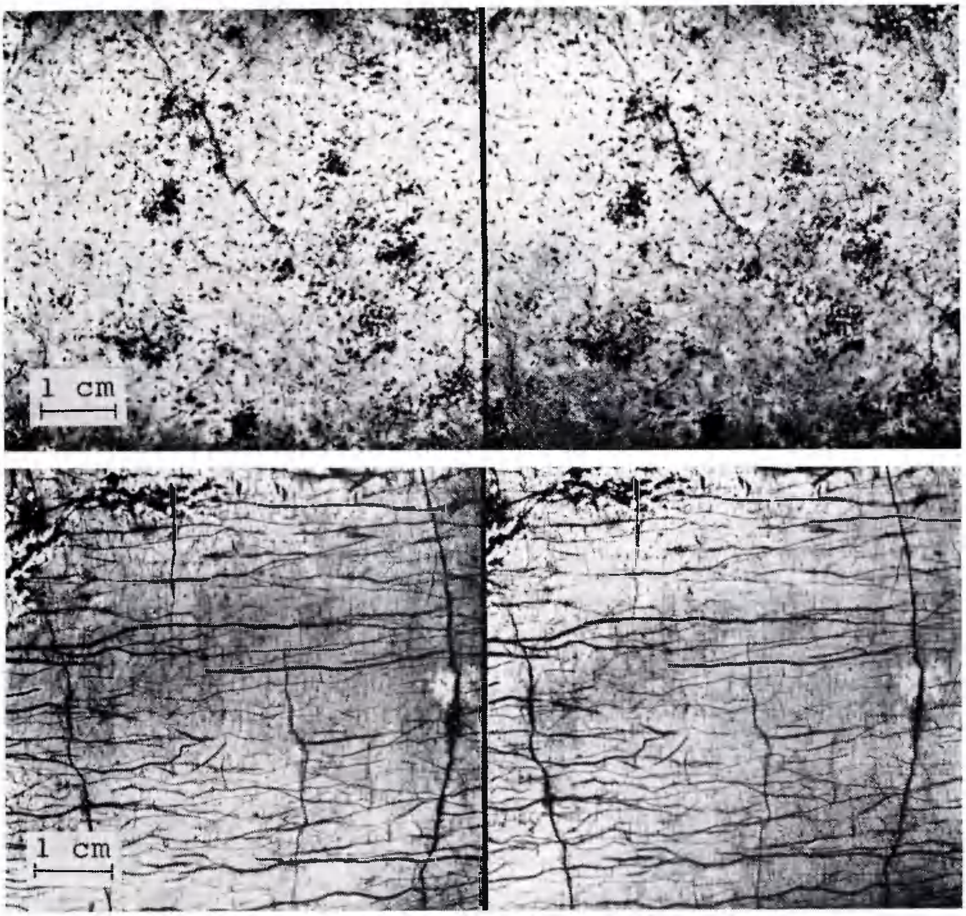

Fig. 4 to 7. Stereo radiographs of horizontal and vertical cuts through soils. Enlargement 1:1. Fig. 4a, 5a, 6a and 7a are horizontal cuts, Fig. 4b, 5b, 6b and 7b vertical cuts, with the soil surface to the right. The radiographs are mounted in such a way that they can be studied by means of a pocket stereoscope.
Fig. 4a (top) and 4b (bottom). Salt marsh at about 60 cm depth; 2 mm thick.

and in some embanked soils near Blakeney and North Wootton (Norfolk) (Fig. 3). The additional data are based upon binocular observations of the polished surfaces of the slabs and on field observations.

Salt marsh (Fig. 4)

Soil. Salt marsh near Stiffkey (Norfolk) consisting of half ripened, non-calcareous silty clay, silted up to high-water level; the zone of permanent reduction begins at 130 cm depth. Grazed by sheep at least from the 16th century up to 1935; at present vegetated by mainly *Limonium vulgare*, *Triglochin maritima*, *Artemisia maritima*, *Aster tripolium*, *Puccinellium* sp. and some *Halamione portulacoïdes*; animal activity is lacking. Classification: Haplic Hydraquent (Anon., 1970).

Table 3. Size distribution of tubular voids; the horizontal course includes all directions deviating no more than 45° from a plane, parallel to the soil surface; the vertical direction includes all channels within 45° of the perpendicular to the soil surface.

Diameter:	0.1-0.3 mm		0.3-0.5 mm		0.5-1.0 mm		1-2 mm		2-4 mm		>4 mm	
Per :	1 cm²		1 cm²		10 cm²		10 cm²		100 cm²		100 cm²	
Course :	hor.	vert.	hor.	vert.	hor.	vert.	hor.	vert.	hor.	vert.	hor.	vert.
Plate 1	45	26	1	6	<1	13	0	0	0	2	0	0
Plate 2	8	10	0	2	<1	4	1	5	0	<1	0	<1
Plate 3	5	6	0	1	2	5	0	3	0	10	0	0
Plate 4	15	11	1	2	3	9	0	3	0	5	0	1

Depth and nature of the sample. Silty clay; Fig. 4a, 60 cm depth, horizontal, 2 mm thick; Fig. 4b 55-70 cm, vertical, 2 mm thick.

Pore structure. The plates clearly show an intensive system of vertical channels, mainly with 0.5 to 0.8 mm diameter. Only pores less than 0.3 mm diameter are abundant in horizontal as well as in vertical directions, although the horizontal channels outnumber the vertical ones almost twice (Table 3). In the size ranges from 2 to 4 mm only few, vertical channels were found, while the size ranges from 0.8 to 2 and larger than 4 mm are almost absent.

Diagonally oriented channels are sparse. The spatial distribution is rather even. Most of the pores are slightly twisting. The larger vertical channels bear horizontal side-branches, mainly of less than 0.3 mm diameter. Apart from this branching, mutual connections are sparse. The pore structure may be attributed to roots of the present vegetation. The large vertical channels of about 4 mm diameter are produced by *Limonium vulgare*, of which some are filled up by illuviated material. Burrowing activity of soil fauna is lacking. The white lining along some pores and the scattered white mottles represent (X-ray-absorbent) iron hydroxide segregations.

Embanked soil (Fig. 5)
Soil. 17th century polder near Blakeney (Norfolk), embanked from a salt marsh which was presumably comparable to the one described before (Fig. 4); at present it is a not very well maintained, imperfectly drained pasture.

The soil consists of a non-calcareous silty clay, which has not yet fully ripened below 85 cm depth; the lowest water-table is presumed to occur at 180 cm below surface; the vegetation consists mainly of grasses, with some thistles; the activity of earthworms is high and can be traced down to 140 cm depth. Classification: Aeric Haplaquept (Anon., 1970).

Depth and nature of the sample. Nearly ripened, unlaminated silty clay; Fig. 5a 125 cm depth, horizontal, 5 mm thick; Fig. 5b 120-135 cm, vertical, 5 mm thick.

Pore structure. The plates show a pronounced, not very intensive system of vertically oriented channels, mainly from 0.5 to 2 mm (Table 3). Channels from 0.1 to 0.3 mm are horizontally as well as vertically oriented and present in almost equal, but low amounts. Channels in other size ranges are scarce or absent. Diagonally oriented pores are sparse. The spatial distribution is rather even. Besides a few vertical channels of 1 to 1.5 mm diameter, which show some sharp bends, most of the pores are only slightly twisting. Branching of channels is present, but not intensive. Other mutual connections are lacking.

The pore structure resulted probably mainly from plant activity. The finer continuous, vertical channels are presumably due to grass roots, the larger vertical ones to reed, rushes or other monocotyls and are than fossil. Activity of earthworms is present but low at this depth. The other visible voids are cracks, which mainly resulted from the drying before impregnation.

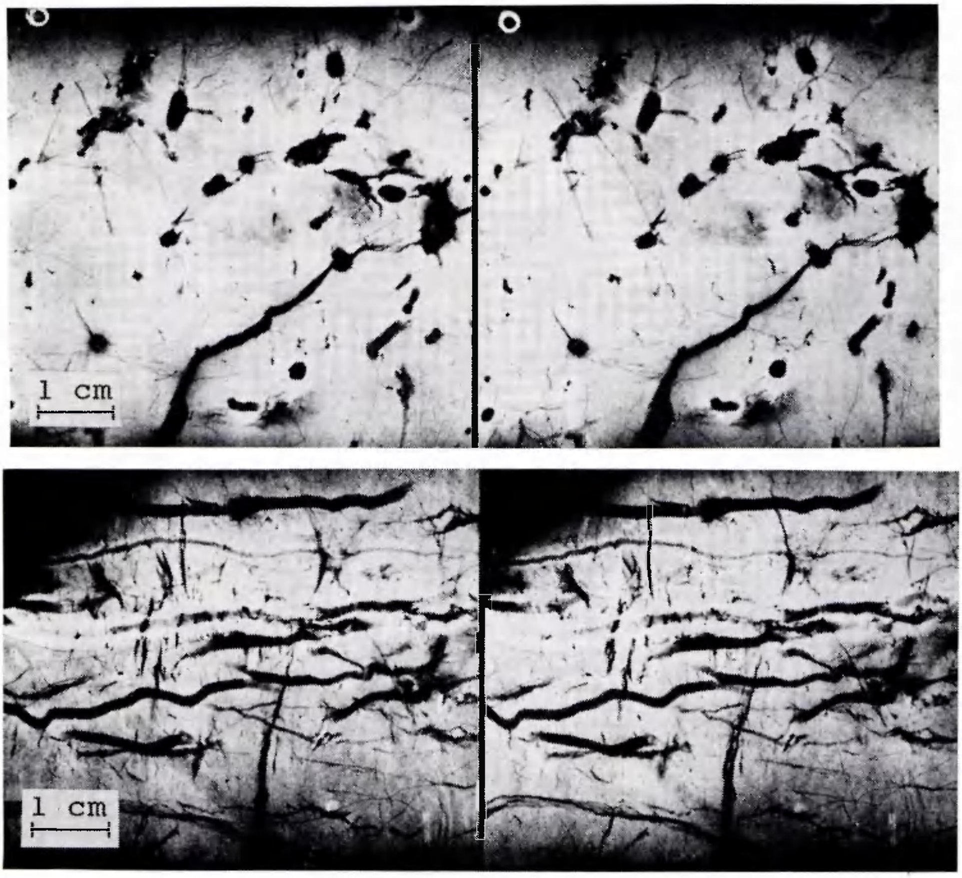

Fig. 5a (top) and 5b (bottom). 17th century polder soil at about 125 cm depth; slabs are 5 mm thick.
For further explanation, see caption to Fig. 4.

Embanked soil (Fig. 6)

Soil. Polder soil near North Wootton (Norfolk), embanked in 1966 from a mature salt marsh, which silted up since 1933; in use as arable land, producing cereals (mainly wheat), potatoes, sugar-beets and beans. The soil consists of calcareous, laminated marine sediments with silty clay-loam texture down to 75 cm depth, loam texture from 75 to 110 cm and loamy sand below 110 cm depth; lowest water-table at 130 cm below the surface; shallowest unknown, but probably at 100 cm depth; only the very topsoil has fully ripened. Classification: Typic Udifluvent (Anon., 1970).

Depth and nature of the samples. Laminated, higher mud flat sediments; Fig. 6a 92 cm depth, horizontal, 2 mm; Fig. 6b 88-103 cm depth, vertical, 2 mm thick.

Pore structure. The pore structure is dominated by short vertical channels, often U-shaped and with diameters ranging from 1 to 2.5 mm. They are not branching and shown a banded distribution pattern, resulting from occurrence in layers, parallel to the surface. Few channels narrower than 1 mm occur (Table 3). Some of them in the size range from 0.4 to 0.8 mm are

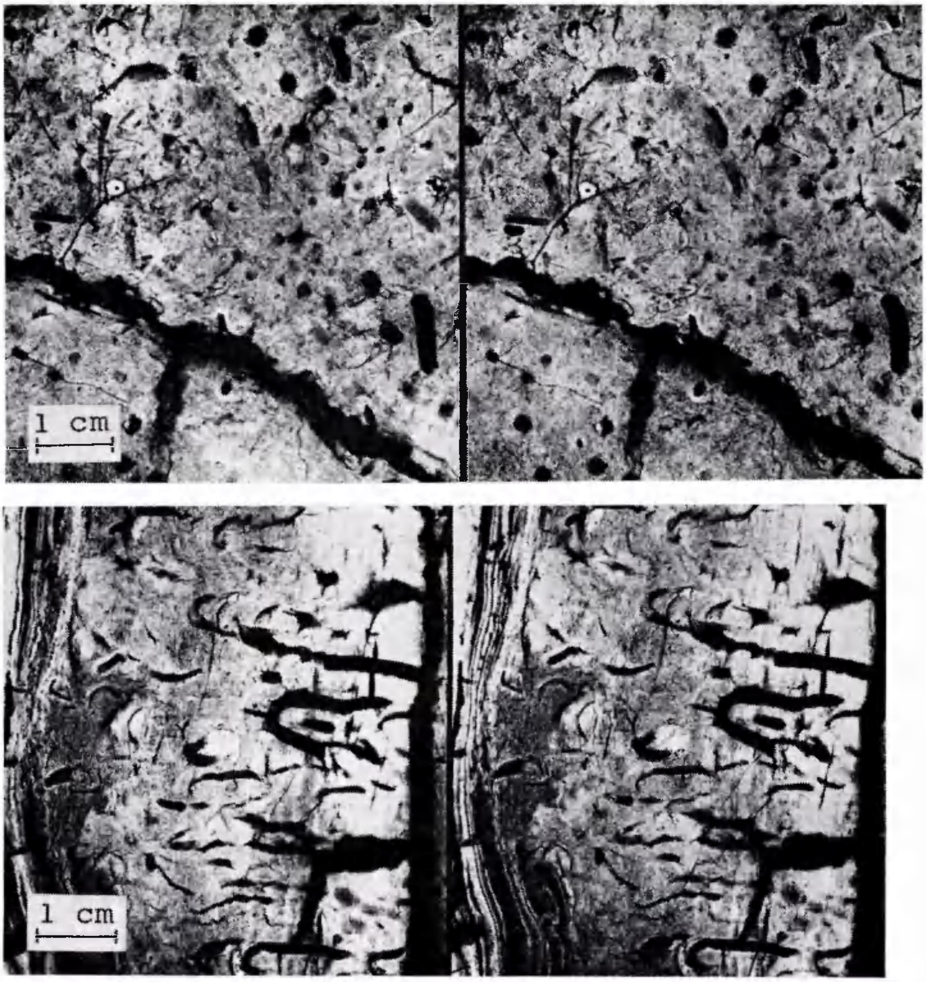

Fig. 6a (top) and 6b (bottom). Recently reclaimed polder soil at about 92 cm depth; 2 mm thick.
For further explanation, see caption to Fig. 4.

running closely vertical, the others do not show any explicite orientation. The distribution pattern is regular. Many of the pores are slightly twisting. The coarses ones within the 1 mm size range bear side branches, varying in diameter from 0.05 to 0.3 mm. Some channels of 0.3 mm are bifurcating into forks of the same diameter. Mutual connections of channels, other than branching, are sparse. Channels larger than 2.5 mm are lacking.

The channels wider than 1 mm resulted from the activity of *Corophium* sp. a marine crustacean, living on the unvegetated inner sand flats (Evans, 1965) and incidentally on the marshes among the vegetation. Also filled-up channels of *Corophium* are showing up as mottles with a slightly coarser texture than the adjoining soil mass.

The presence of narrower side branches on some of the vertical channels narrower than 1 mm indicate that they are the result of plant activity. They are mainly fossil, resulting from

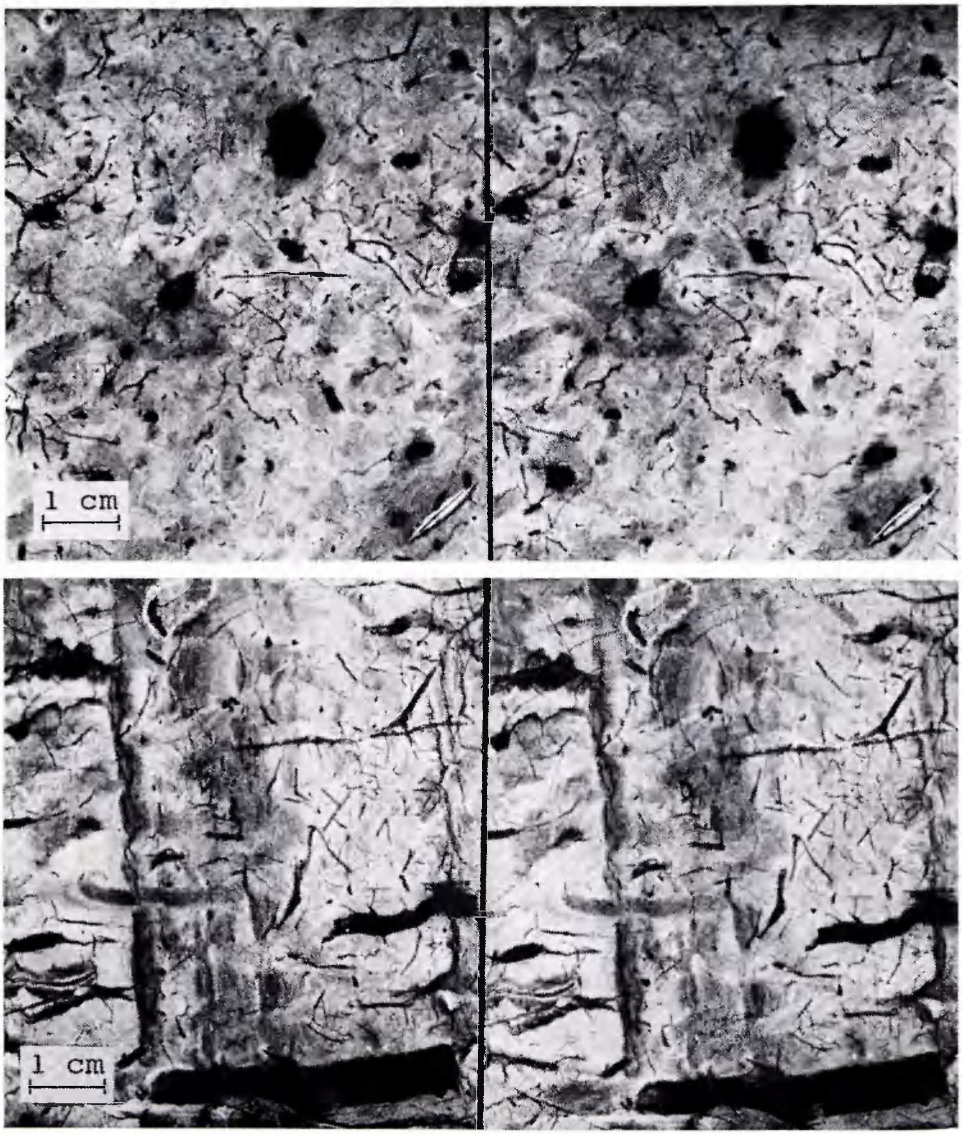

Fig. 7a (top) and 7b (bottom). Polder soil at 90 cm depth; 2 mm thick.
For further explanation, see caption to Fig. 4.

the marsh vegetation as is indicated by the many decaying roots in the profile. Part of these channels may have been recently formed by the arable crops. The winding channels of about 0.3 mm diameter, which divide into extensions of equal size, are possibly due to some marine annelid, being also fossil. The very large horizontal cracks are artefacts: they have resulted from the drying of the samples. Other phenomena shown, are iron hydroxide concentrations, visible on the radiographs as white wrappings around some channels.

Embanked soil (Fig. 7)
Soil. Polder soil near North Wootton (Norfolk), embanked in 1852 from a salt marsh; in use as pasture land up to 1914 and ever since under arable cultivation with a variety of crops. The soil consists of calcareous, laminated silty clay loam, which at 50 cm depth is merging into laminated, calcareous silt loam deposits which become sandier with depth. The profile is somewhat lighter textured than the profile of Fig. 6, but otherwise the sedimentation history is supposed to have been more or less comparable. The water-table fluctuates between 180 cm and about 130 cm depth; earthworm activity is evident. Classification: Typic Udifluvent (Anon , 1970).

Depth and nature of the sample. Laminated sandy loam, deposited at high mud-flat level; Plate 4a, 90 cm depth, horizontal, 2 mm thick, Plate 4b, 83-98 cm, vertical, 2 mm thick.
Pore structure. The plates show common to abundant, evenly distributed channels in all size classes up to 6 mm diameter. The pores wider than 0.3 mm are mainly vertical, which is more pronounced with increasing diameter (Table 3). The voids narrower than 0.3 mm do not show a dominant orientation, although many of them, branching from wider vertical channels, follow a more or less horizontal course. The vertical pores with 0.2 to 1 mm diameter commonly bear side branches narrower than 0.2 mm. The channels coarser than 1 mm normally not branch, nor was division into equally sized extensions noticed. Some of the voids between 1 and 2.5 mm are U-shaped. Many channels, especially the narrower ones, are slightly twisting. Since they are branching many of the pores smaller than 1 mm probably result from root activity, which agrees well with the field observations. The U-shaped channels are probablv fossil burrows of the marine crustacean *Corophium* sp. In the field fossil burrows of the marine annelid, *Nereis diversicolor*, were also recognized at this depth. They could be represented in the plates in the form of the larger tubular voids, but the presence of earthworm activity in the soil makes a definite statement about this impossible. Besides the open and filled-up channels some iron hydroxide concentration along channels as well as incorperated shells are visible in white.

When Fig. 7 is compared with Fig. 6 of the younger soil it is clear that the finer part of the pore structure has become much more intensive, which supports the opinion that most of the smaller channels have a terrestric origin, which have been formed after embankment. In addition the number of filled-up burrows with coarse, loose material has also increased, indicating another process of change after embankment.

Fig. 4 and 5 support the supposition of the existence of a relationship between the actual pore structure in the soil and the rooting of the vegetation. Fig. 4 shows a balanced situation, Fig. 5 the transition from one system into another. With a more elaborate radiographic study of the pore structure in soils, in view of the soil genesis, will be dealt elsewhere.

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