The Danish Pesticide Leaching Assessment Programme

Site Characterization and Monitoring Design

Bo Lindhardt, Christian Abildtrup, Henrik Vosgerau, Preben Olsen, Søren Torp, Bo V. Iversen, Jørgen Ole Jørgensen, Finn Plauborg, Per Rasmussen, and Peter Gravesen.

Geological Survey of Denmark and Greenland
Ministry of Environment and Energy

Danish Institute of Agricultural Sciences
Ministry of Food, Agriculture and Fisheries

National Environmental Research Institute
Ministry of Environment and Energy

GEUS

Editor: Bo Lindhardt
Cover: Peter Moors
Lay-out and graphic production: Authors and Kristian Anker Rasmussen
Printed: September 2001
Price: DKK 500.00

ISBN 87-7871-094-4

Available from
Geological Survey of Denmark and Greenland
Thoravej 8, DK-2400 Copenhagen, Denmark
Phone: +45 38 14 20 00, fax +45 38 20 50, e-mail: geus@geus.dk
www.geus.dk

Tables of Contents

Preface

The Geological Survey of Denmark and Greenland (GEUS), the Danish Institute of Agricultural Sciences (DIAS), the National Environmental Research Institute (NERI), and the Danish Environmental Protection Agency (DEPA) have been requested by the Danish Government to set up and run a programme to assess the risk of pesticides leaching into surface waters and groundwater when applied in the prescribed manner. The programme was designed and the test sites established during 1999. This report describes the selected sites and the monitoring equipment installed.

The programme is managed by a project committee comprising:

Bo Lindhardt, GEUS
Jeanne Kjaer, GEUS (replaced Peter Gravesen as of 1 August 2000)
Svend Elsnab Olesen, DIAS
Arne Helweg, DIAS
Ruth Grant, NERI
Betty Bügel Mogensen, NERI
Christian Ammitsøe, Danish EPA
Christian Deibjerg Hansen, Danish EPA

Bo Lindhardt
August 2001

1. Introduction

There is a growing public concern in Denmark regarding pesticide contamination of groundwater and surface waters. The Danish National Groundwater Monitoring Programme (GRUMO) has revealed the presence of pesticides and their degradation products in approx. 30% of the monitored screens (GEUS, 2000). The increasing detection of pesticides over the past 10 years has raised doubts as to the adequacy of the existing approval procedure for pesticides. As the water sampled under the groundwater monitoring programme is usually more than 5 years old and often more than 20 years old, the results are of limited value as regards evaluation of the present approval procedure.

EU and hence Danish assessment of the risk of pesticide leaching to the groundwater is based mainly on data from laboratory or lysimeter studies. However, these types of data assessment do not provide satisfactory characterization of the leaching that might occur under actual field conditions. Soil (chemical properties and biological processes) and hydrogeology can vary significantly within as well as between fields, and climate conditions can vary during pesticide use. Furthermore, agricultural practice also varies between fields. Many of these parameters are not covered by laboratory or lysimeter studies as presently performed.

Laboratory and lysimeter studies provide little if any information on the inherent variability of the soil parameters affecting leaching. This is of particular importance for silty and loamy soils, where preferential flow may occur. Field studies abroad have demonstrated considerable transport of several pesticides to 1 m b.g.s. (**b**elow **g**round **s**urface) in loamy soils under conditions comparable with those in Denmark. The inclusion of field studies, i.e. test plots exceeding 1 ha, in risk assessment of pesticide leaching to the groundwater is considered an important improvement in risk assessment procedures. The US-EPA has requested such field studies to support the registration of pesticides suspected of potentially being able to leach to groundwater. Over the past decade, studies of more than 50 pesticides have been conducted. Based on this experience the US-EPA has published a set of guidelines for field studies (US-EPA, 1998). In Europe, EU Directive 91/414/EEC, annexe VI (Council Directive 97/57/EC of 22 September 1997) enables field study results to be included in the risk assessments.

1.1 Objectives of the programme

The aim of the Pesticide Leaching Assessment Programme (PLAP) is to monitor whether pesticides or their degradation products leach to groundwater under actual field conditions when applied in the prescribed manner. The programme is designed such that the findings can be evaluated in relation to the drinking water quality criterion, i.e. 0.1 µg/l.

The programme encompasses six test sites selected to represent the dominant soil types and the climatic variation in Denmark. To provide early warning of unacceptable leaching, the sites were selected where the groundwater was located 1-4 m below the ground surface, thus ensuring a short response time. Pesticides are applied to the test fields as part of routine agricultural practice and in accordance with the current regulations, thereby enabling the occurrence of pesticides or their degradation products in the groundwater downstream of the test field to be related to the current approval conditions pertaining to the pesticides.

The programme will only include pesticides used in arable farming. Pesticides used in forestry, fruit orchards and horticulture are not encompassed by the programme.

1.2 Schedule

Work on designing the programme started in August 1998. The six sites were selected during 1999 and the equipment for sampling drainwater and groundwater was installed the same year. This report presents the site characterization and the monitoring design of each site. Monitoring was initiated between May 1999 and April 2000. The results will be published in forthcoming reports.

1.3 Structure of the report

Chapter 2 provides a detailed description of the criteria used in selecting the test sites. Chapter 3 describes the monitoring equipment and methods while Chapter 4 presents the geological and pedological methods used to characterize the sites. Chapter 5 briefly describes the six test sites with regard to instrumentation, pedology and geology. For a more detailed characterization of each site the reader is referred to the accompanying annexes. Finally, Chapter 6 presents the pesticides encompassed by the programme.

2. Site selection

Selection of the sites is critical with respect to ensuring that the results are generally applicable and hence can be utilized in the pesticide approval procedures. The risk of groundwater contamination by pesticides mainly depends on soil type, hydrogeology, climate and agricultural practice. Site selection depends not only on these parameters, but also on such factors as site access, i.e. permission from the owner, all year round road access, access to electric power and, in the case of drained sites, an old and well described tile drain system. This chapter presents the site selection criteria used and briefly summarizes the six selected sites.

2.1 Soil type

The Danish EPA requires that pesticide testing is conducted under "worst case" conditions. The test sites consequently need to be located on "vulnerable" soil types as regards possible groundwater contamination. Coarse-textured sandy soils with a low organic matter content were previously considered to be among the most vulnerable soils. Over the past decade, however, evidence has accumulated that pesticide leaching also occurs on structured soils (Flury, 1996). The findings of the Danish National Groundwater Monitoring Programme (GRUMO) also indicate that pesticides can leach to the groundwater in regions dominated by structured soil types (GEUS, 2000). Only a few studies have tried to compare the mass flux of pesticides from different soil types under identical agricultural practices and climate conditions. At present, no information is available concerning how to identify the most "vulnerable" soil types in Denmark as regards leaching of pesticides to the groundwater. As suitable scientific documentation on which to base selection of the most "vulnerable" soil types and hence the "worst case" scenarios is lacking, we decided to select a number of sites representing the soil types on which pesticides are most commonly applied in Denmark.

The geological composition of sediments down to 5-10 m b.g.s. in Denmark is known from geological maps, profiles, excavations, well data and sometimes also geophysical measurements. The composition of the uppermost metre of deposits is mainly known from the systematic mapping of Quaternary deposits carried out by GEUS. This started in 1888 and is still going on, about 80% of the Danish land area now having been mapped. At deeper levels, knowledge of the geological deposits is mainly based on well data. The deposits commonly vary considerably in grain size, internal structure and min-

eralogical and geochemical composition over short distances in both the vertical and horizontal directions. In addition, glaciotectonic activity has commonly overprinted and dislocated the deposits.

The map of Quaternary deposits shows that 40% of Denmark's land area consists of clay till, 28% of meltwater sand, 12% of Post-Glacial and Late-Glacial marine sand and aeolin sand, 12% of Post-Glacial freshwater sand, 3% of sand till and 7% of different subordinate Quaternary deposits. Pre-Quaternary deposits account for less than 1% of Denmark's surface. In considerable areas, however, Cretaceous and Danian limestone and Tertiary clay are reached within a depth of 5 m b.g.s. In view of the above-mentioned distribution it was decided that the sites should be located in both areas with Quaternary clay and areas with Quaternary sand.

2.1.1 Areas with Quaternary clay

Clayey sediments occurring near the ground surface are dominated by clay till deposits. These characteristically consist of a very unsorted sediment with a clay content exceeding 12–14%. The till deposits were formed in contact with ice, either laid down beneath the ice (lodgement till) or deposited from the surface of the ice as it melted (ablation and flow tills). Lodgement tills are more consolidated than ablation and flow tills due to the heavy burden of the ice during their deposition. Clay tills are generally chararacterized by containing fractures formed by glaciotectonic forces or by desiccation and freeze-thaw processes. Subsurface Pre-Quaternary deposits may considerably affect the composition of the overlying till. For instance, the clay or chalk content may be very high in the case of a clay till deposited by a glacier that has passed an area with exposed Tertiary clay or Cretaceous chalk. The till deposits which form the ground surface in Denmark were generally deposited by ice advances that occurred 20–14,000 BP during the Late Weichselian Period. In western Jutland, however, an older glacial landscape occurs as hill islands in the Weichselian outwash plains. The meltwater and till deposits that form part of this landscape were deposited during the Saalian period 140,000 BP, and hence have been exposed to weathering, erosion and soil-forming processes for a very long period.

2.1.2 Areas with Quaternary sand

The meltwater sediments were transported and deposited by meltwater from glaciers. Grain size thus diminishes from meltwater gravel to meltwater sand with increasing distance from the former ice front. They are subdivided into glacial meltwater sediments, which are sometimes deformed by subsequent ice advances, and Late-Glacial extramarginal meltwater sediments, which have not been overridden by glaciers. The

extramarginal meltwater sediments form large outwash plains east of the Main Stationary Line marking the westernmost extension of the Weichselian ice sheet in Jutland.

Post-Glacial and Late-Glacial marine sand was formed when land areas were flooded due to an interplay between isostatic uplift and eustatic sea level rise caused by melting of local and global icecaps, respectively. Today these sediments form raised seafloor plains in the landscape as a result of subsequent isostatic uplift.

Aeolian sediments were deposited in the Post-glacial period and consist of well sorted, fine-grained sand deposited as dunes, mainly in coastal regions, and as coversand when deposited inland.

Freshwater sand was mainly deposited along streams and in lakes during the Post-glacial period.

2.2 Climate

Together with soil type, one of the most important parameters controlling pesticide leaching is the precipitation. The most common way to express the regional variation in precipitation is by the annual mean. The annual mean precipitation in Denmark during the period 1961–90 was 712 mm/year, varying from 550 mm/year in the Store Bælt region to 900 mm/year in the southern part of Jutland (Frich et.al., 1997). The inter-annual variation in annual mean precipitation at individual single sites varies by a factor two. Thus while the annual mean precipitation ranged from 456 to 744 mm/year during the period 1988–97 in the Roskilde region, it ranged from 557 to 1,032 mm/year in the Jyndevad region.

The variation in pesticide leaching cannot be ascribed to the variation in annual mean precipitation alone. The transport of pesticides through unsaturated soil is controlled by a complex interaction between the degree of saturation and the intensity of the precipitation. This interaction is not a useful parameter for selecting sites. Only the annual mean precipitation is of practical usefulness when selecting site location.

Other climate parameters that affect pesticide leaching, e.g. temperature and evaporation, do not vary much in Denmark. Thus only the variation in precipitation has been taken into account when selecting the sites.

The sites may not be further than 8 km away from an automatic climate station in order to ensure access to additional good quality climate data and historical time series. Pre-

cipitation is also measured at the sites along with soil temperature and soil water content.

2.3 Hydrogeology

The depth of the water table is an important site selection factor. In order to ensure a rapid response in the groundwater downstream of the test field and to facilitate sampling, the water table must be as near to the surface as possible and no deeper than 5 m b.g.s. The Danish EPA defines groundwater as water that leaves the root zone 1 m b.g.s. In large parts of Denmark, the water table is less than a few metres below the surface.

The sites must be located inside the infiltration area and have a downward gradient. To ensure a stable response in the monitoring well, a steady hydraulic gradient is required. Sites located within the radius of influence of irrigation or production wells have thus been as far as possible avoided. Where this is not possible it is necessary to obtain information on the production from the wells.

The infiltration of water and hence leaching of pesticides is influenced by surface runoff. To minimize surface runoff the selected sites have a low topographic slope – less than 2% slope in general.

The sites with structured soil have to be drained and the tile drain system must be well known and only cover the test field. Moreover, the tile drains must be more than 10 years olds so that the overlying soil has had time to consolidate, thereby avoiding artificial infiltration to the drain system. The base flow must be as low as possible to avoid dilution of the response. In order to facilitate sampling of the drainwater it is important that the drainage system feeds into a single outlet.

2.4 Site area

The size of the test field is crucial. On one hand it needs to be sufficiently large to adequately cover the variation in soil structure, particularly on clay soils where preferential flow is expected to form the key route for pesticide transport down through the unsaturated zone. On the other hand, the area must not be too large because the variation in the soil structure would then complicate interpretation of the results. That sampling costs increase with increasing test field size also points to the selection of as small a site as possible. The test field should only encompass single soil series, with a small spatial variability in the soil parameters. Test sites between 1 and 4 ha are assumed to be an

acceptable compromise. The US-EPA guidelines for prospective groundwater monitoring studies requires test sites of equal size (US-EPA, 1998).

To eliminate artificial flow patterns it is important to select sites with undisturbed soil. Areas where sampling by drilling has taken place or where excavation has been performed should thus be avoided.

2.5 Site history

The previous crop rotation on the site is expected to influence the fate of the pesticide. The test field should previously have been subjected to conventional agricultural practices as regards crop rotation and soil tillage, thus excluding the use of fields with minimal or conservation tillage, organic farming, horticulture and set-aside.

We prefer fields that have been cultivated as one parcel with the same crop within recent years, and exclude sites that have been used for plot experiments or have been disturbed by excavation, drilling or deep soil sampling.

Pesticide use at the sites must have been recorded for at least the previous 5-year period.

2.6 Site access

Pesticide leaching studies are typically conducted over a 2–3 year period for each application. As the present programme will run for a period of up to 10 years, sites could only be included if a long-term lease was possible.

For practical reasons there must be good road access to the sites all year round to enable sampling. Moreover, in order to obviate the necessity to establish an on-site power supply to run the sampling equipment, mains electricity had to be within reasonable reach.

The sites also had to be located within approx. 10 km of a state experimental farm such that the pesticides and tracers could easily be applied by trained personnel from the state experimental farms. However, standard agricultural operations such as soil tillage, sowing and harvesting could be done by the landowner when deemed appropriate.

2.7 The six selected sites

The programme encompasses six sites. This number of sites is a compromise balancing monitoring intensity with the number of different soil types represented by the programme. Two of the sites are located on sandy soil and four on clayey soil. The key data for each of the six sites are presented in Table 2.1. The location of each site is shown in Figure 2.1.

Three of the sites (1 sandy and 2 clayey) are in regions with relatively high precipitation, while the other three are in drier regions. A brief description of each site is given in Chapter 5.

Table 2.1. Key data for the six selected sites encompassed by the Danish Pesticide Leaching Assessment Programme.

Name	**Tylstrup**	**Jyndevad**	**Silstrup**	**Estrup**	**Faardrup**	**Slaeggerup**
Location	Brønder-slev	Tinglev	Thisted	Vejen	Slagelse	Roskilde
Crop						
1999	Potatoes					
2000	Spring barley	Winter rye	Fodder beet	Spring barley	Winter wheat	Spring barley
2001	Winter rye	Maize	Spring barley	Peas	Sugar beet	Peas
2002		Spring barley	Winter wheat	Winter wheat	Spring barley	Winter wheat
B x L, m	70 x 166	135 x 184	91 x 185	120 x 105	160 x 150	165 x 130
Area, ha	1.1	2.4	1.7	1.3	2.3	2.2
Soil type	Fine sand	Coarse sand	Clayey till	Clayey till	Clayey till	Clayey till
Deposited by	Saltwater	Meltwater	Glacier	Glacier	Glacier	Glacier
Tile drain	No	No	Yes	Yes	Yes	Yes
Precipitation, mm/year[1)]	668	858	866	862	558	585

1) Yearly normal based on a time series from 1961-90

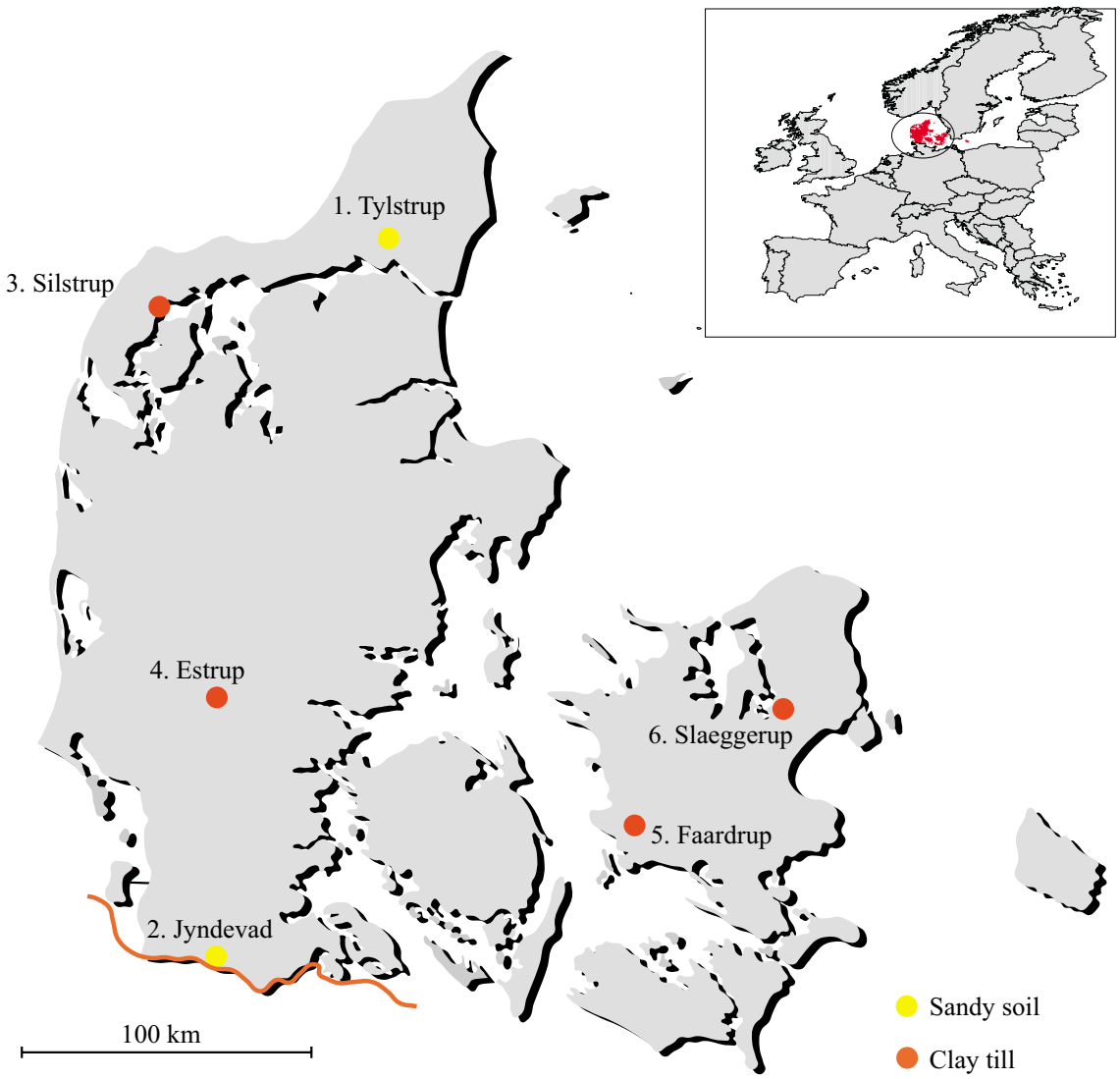


Figure 2.1. Location of the six test sites in Denmark.

3. Monitoring design

Characterization and instrumentation of the sites was carried out in an integrated manner with the soil cores from the monitoring well boreholes being used to develop a conceptual hydrogeology model for the sites. The different types of devices installed at each site are described here.

The monitoring equipment used and aspects monitored include:

- Piezometers – potentiometric pressure of the groundwater
- Vertical and horizontal monitoring wells – sampling of groundwater
- Suction cups – water samples from unsaturated soil
- Automatic ISCO samplers – sampling of drainwater
- Weather stations – precipitation
- TDR-probes – soil water content
- Pt-100 sensors – soil temperature
- Pressure sensors – barometric pressure

Figure 3.1 shows the typical lay-out of monitoring devices at a site.

To avoid any artificial leaching of pesticides, drilling and excavation have not been carried out inside the plot used for pesticide treatment. All installations and soil sampling deeper than 20 cm b.g.s. are restricted to a buffer zone around the treated plot.

3.1 Groundwater monitoring

3.1.1 Piezometers

Four multiple-level piezometers each with three separate piezometer screens have been installed at each site. The casings and the screens are made of the same material and have the same dimensions. High-density polyethylene (HDPE) pipes from Filter Jensen (DK) with an outside diameter of 63 mm and a wall thickness of 5.8 mm were used. The screens are 50 cm long and contain two 0.5 mm aperture slits per cm.

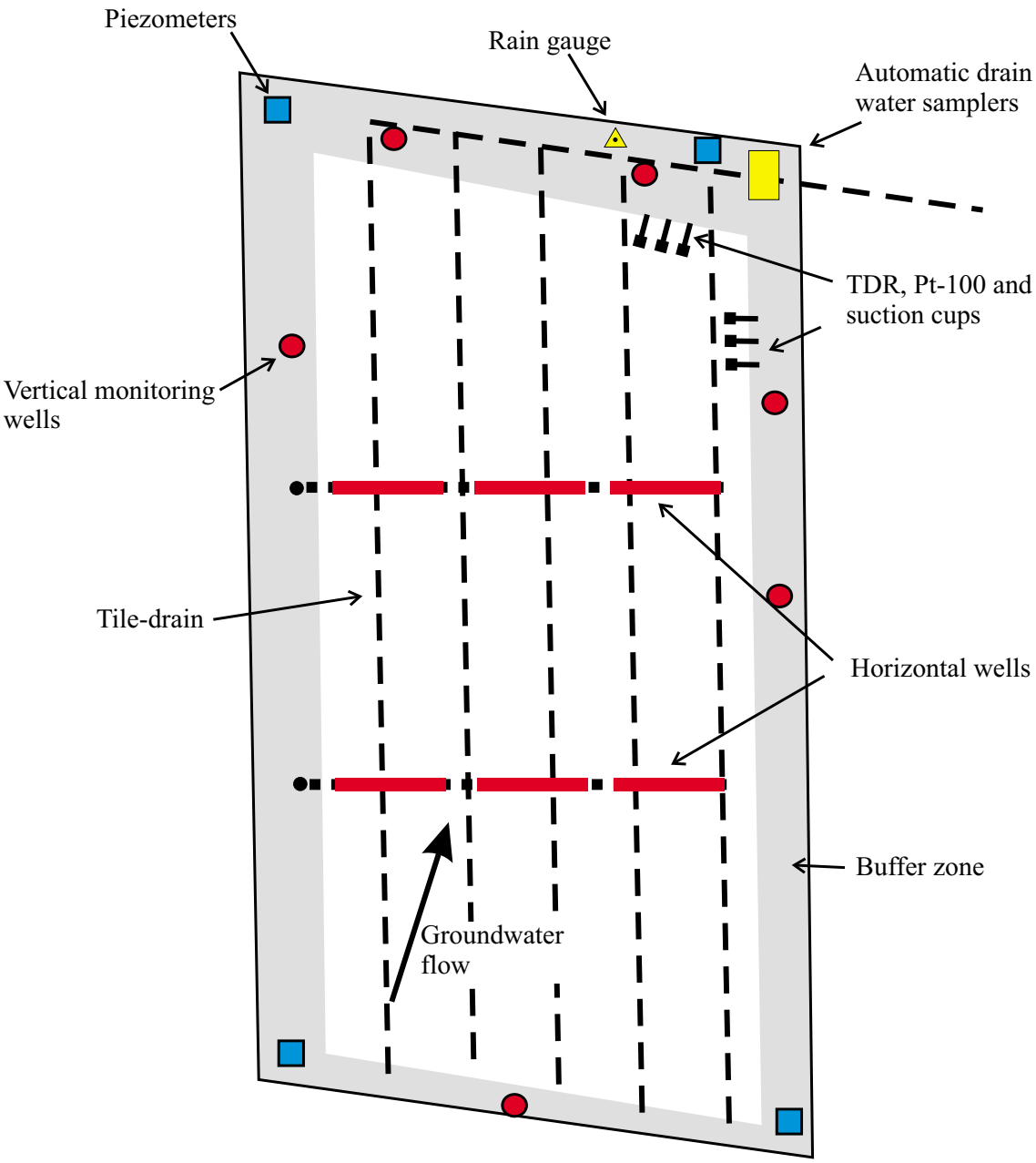


Figure 3.1. Typical lay-out of monitoring devices at a tile-drained site.

The three screens of each piezometer are installed in the same borehole. The diameter of the borehole is 152 mm (6"). In the clay soils drilling was carried out with a solid stem auger while a bailer technique was used below the water table in the sandy soils. Surface casing was used when necessary. For filter packing we used Grejs No. 2 (0.7–1.2 mm) (Grejsdalens Filterværk, DK). A filter pack seal of at least 100 cm bentonite (Pellerts, QS, Cebro, NL) was installed approx. 10 cm above each screen (Figure 3.2). Each nest of multiple-level piezometers is protected at the surface by a 0.6 m dia. concrete ring closed by a padlocked metal cover.

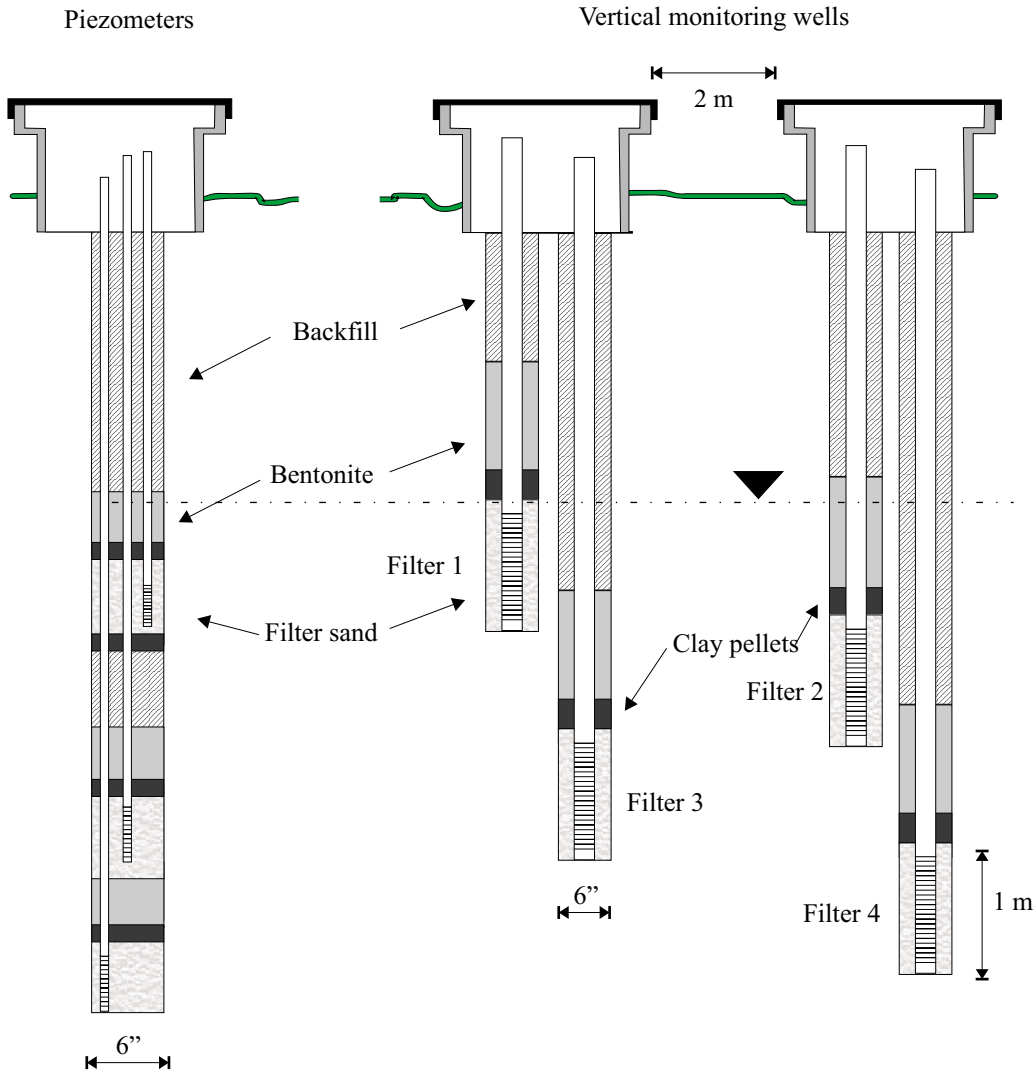


Figure 3.2. Construction of a multiple-level piezometer and monitoring well at a clay till site.

The lower screen in each nest is located between 11.5 and 12 m b.g.s. The top screen is located such that the water table is expected to be permanently above the screen. At the clay sites the screens are placed in the most sandy horizon.

The water level is measured either manually by using a “water level indicator” or continuously using one of three different transducer-logger systems. Every time samples are collected, the water level in all the piezometers is measured manually. In the piezometer closest to the “shed” the water level is measured on-line every hour using a differential pressure transducer (Druck, Limited, UK) connected to a Campbell datalogger. At the sandy sites, the water level is monitored in one screen. At the clay sites two Druck

transducers are installed – one in the upper screen and another in the lower screen. The water level in the piezometer diagonally opposite the corner where the shed is located was initially measured continuously every hour using an Orphimedes-logger (OTT, D). In early spring 2000, this system was exchanged for a D-diver (RoTek a/s, DK), which is a pressure transducer and a data-logger. As the D-diver does not take into account changes in barometric pressure, the raw data have to be corrected using the barometric pressure measured at each site.

3.1.2 Vertical monitoring wells

For sampling groundwater, seven vertical monitoring wells were installed at each site. The drilling techniques and the materials used for the casings and screens are the same as for the piezometers. Sorption of pesticides to the HDPE piping is expected to be insignificant (Fetter, 1999; US-EPA, 1998). The pipe material was tested for release of any compounds that could contaminate the water samples and no evidence was found of any contamination that might interfere with analysis of the 39 different pesticides included in the Danish Groundwater Monitoring Programme (GEUS, 2000).

Each monitoring well consists of four screens. The length of each screen is 100 cm. The screens are placed so that they cover the upper 4 metres of the groundwater. The top of the upper screen is placed above the highest seasonal water table. To avoid vertical movement of water along the casing, each screen is installed in its own borehole. To optimize sealing, clay pellets (Tonkugeln, Duranit VFF; D) were used as back-fill. Monitoring well construction is shown in Figure 3.2.

For water sampling, a Whale pump (GP9216, 13 l/min, 72 watt, 12 V, RoTek a/s, DK) was permanently installed in each screen connected to a PE-tube (6 x 1 mm or 10 x 1 mm, RoTek a/s, DK).

One monitoring well is located upstream of the test field, while the other six are distributed downstream of the test field (Figure 3.1).

3.1.3 Horizontal monitoring wells

The water flow transporting the pesticides is difficult to monitor in areas with clayey till because of the effect of vertical preferential flow and the frequent occurrence of sandy lenses, which can cause lateral flow. To overcome these difficulties a number of horizontal monitoring screens have been installed approx. 3.5 m b.g.s. inside the treatment plot at the four sites on clayey till.

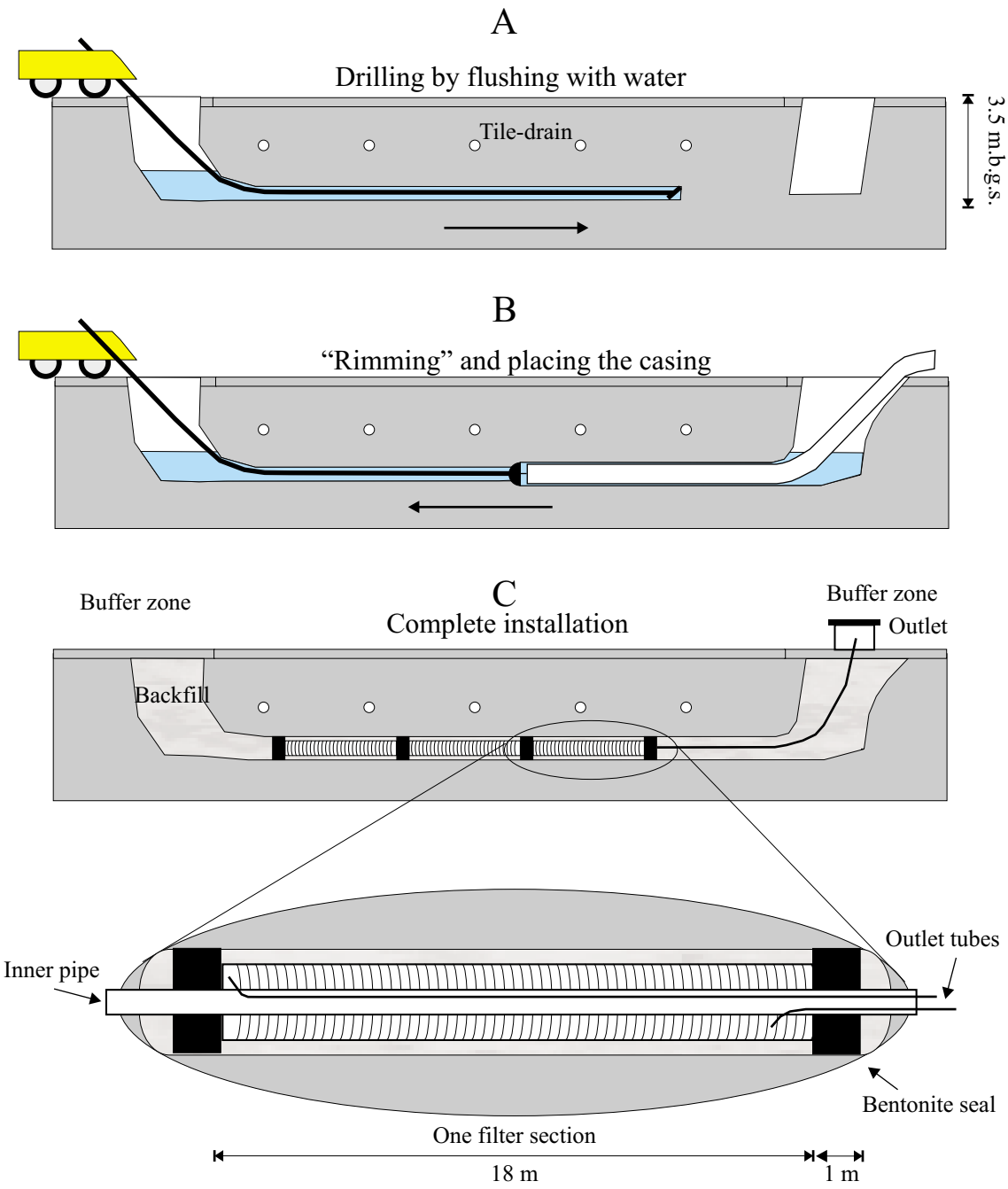


Figure 3.3 Installation of horizontal monitoring wells and a section of the horizontal screen.

The horizontal screens are installed by drilling from the buffer zone on one side of the treated plot to the buffer zone on the opposite side without causing any disturbance to the topsoil inside the plot. The technique used for drilling these horizontal boreholes is well known from installing power cables or pipelines beneath roads, etc. The drilling rig is placed on the surface and drilling performed in two steps: Firstly, forward drilling by a water flushing technique and secondly, reaming whereby the rod is drawn back. The diameter of the final boreholes is 200 mm. In the first step the drilling rod can be steered by changing the position of the rod head, which is continuously monitored at the surface by a radio signal. The sediments are released by flushing with water and transported out of the borehole by the water flow. The diameter of the borehole made by forward drilling is 110 mm. To reduce the water pressure, a mud pit is excavated at the entrance to the borehole just outside the test field in the buffer zone (see Figure 3.3A). When the rod has traversed the treated plot and penetrated an excavation on the other side a reamer is installed on the rod together with a 160 mm o.d. casing. The screens with bentonite packers are placed inside the casing and the casing then drawn into the borehole at the same time as the "rimming" takes place (Figure 3.3B). At the specific positions the screens are fixed by retaining them with a wire while the casing is drawn out of the borehole. The complete installation procedure is shown in Figure 3.3C.

The screens are 18 m long with an outer diameter of 125 mm and a wall thickness of 5.8 mm. The screens have two 0.5 mm aperture slits per cm. Two tubes are installed at each screen. The outer diameter of the inside pipe is 63 mm (Figure 3.3) while tubes are 10 mm in diameter with wall thickness of 1 mm. The screens are made of HDPE and the tubes of PE. Three individual screens are installed in each borehole separated by 1 m bentonite seals.

Sampling from the screens is performed with a peristaltic pump on the surface.

3.2. Drainwater collection

The four clayey till sites are located in areas with an existing tile drainage system. As a criterion for selecting the sites the drainage system had to be systematically described and easily isolated to represent a well-defined monitoring area. At all four sites it was necessary to cut off some drainpipes and/or to install additional pipes to ensure a defined catchment area. The modifications made at each site are described in the accompanying Annexes 1–6.

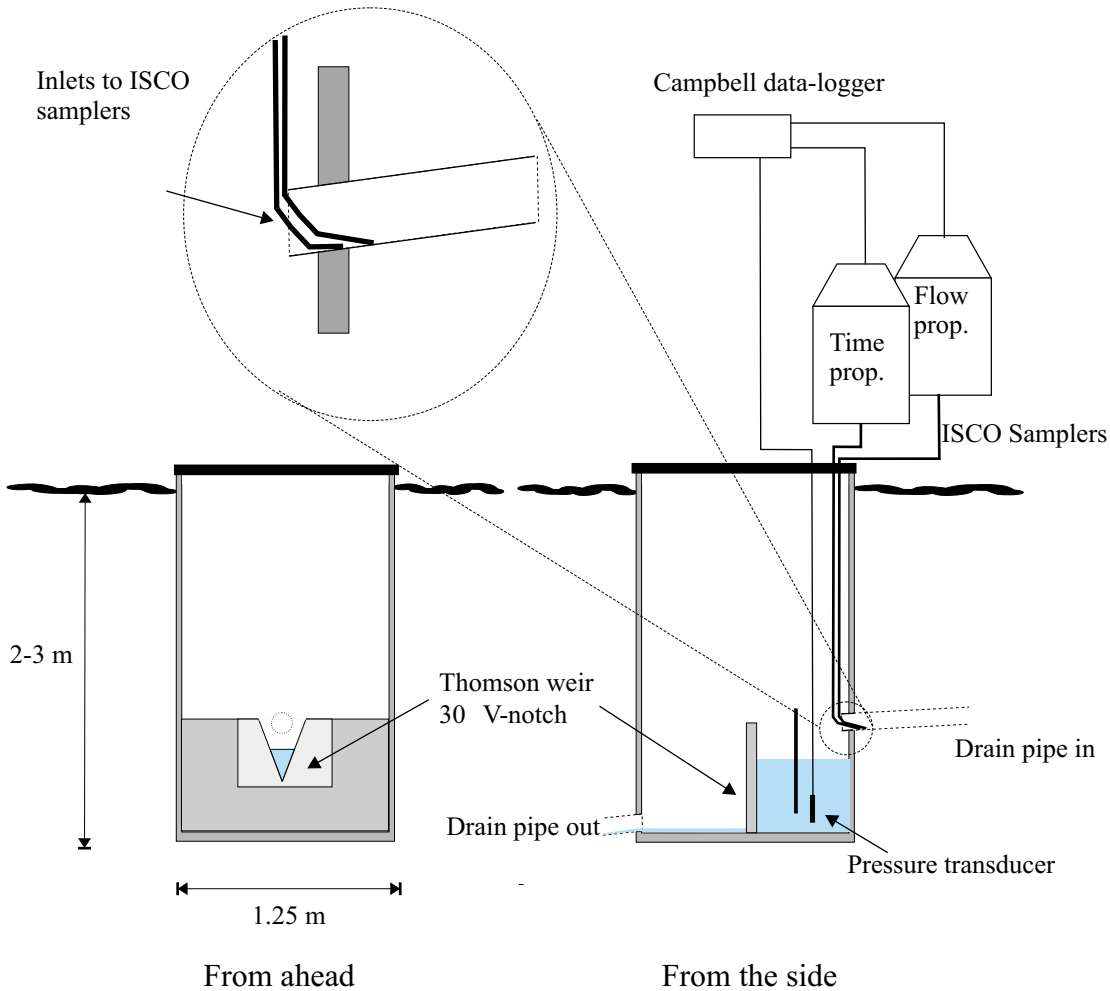


Figure 3.4. Drainwater monitoring well with Thomson weir and water sampler.

In order to enable the measurement of drainage runoff and the collection of drainwater samples a concrete monitoring well was established at the outlet of each drainage system. The wells are 1.25 m in diameter and 2–3 m deep.

The monitoring wells are constructed with a sharp-crested V-notch weir (Thomson weir) made of 5 mm galvanized iron plate. The Thomson weir is the most exact profile for measuring runoff with a large variation in flow rate (Bos, 1976). A 30° V-notch angle was chosen as a compromise between high precision at relatively low flow rates and low sensitivity to blockage of the notch. The height of the notches is not less than 30 cm.

Table 3.1. Infiltration per ha vs. flow in the drainage system.

Height above the Thomson weir, cm	Flow in drain, Q (l/s)	Infiltration, q mm/ha/day
5	0.23	2
10	1.2	10
20	6.8	59
30	19	164

A Thomson weir requires a free fall from the weir notch of at least 25 cm. The water level above the V-notch is monitored using a pressure transducer (Druck PDCR 1830, Druck Limited, UK). The transducer is mounted in a stainless steel tube (length 1,100 mm, diameter 21.5 mm) fixed to the wall of the well by means of a stainless steel clamp (Figure 3.4). To protect the transducer from turbulent water at high flow rates, it is placed in a special chamber behind the weir and as far away from the drain inlet as possible (Figure 3.4). The pressure transducer is connected to the central Campbell datalogger.

The water samples are collected using ISCO 6700 (Isco, Inc. US) samplers equipped with eight 1,800 ml glass bottles (boron silicate), teflon suction tubes and intakes of stainless steel. The intakes are placed a few centimetres into the inlet of the drainpipe so as to ensure sampling of flowing drainwater and particulate matter. Two samplers are used at each site: One for time-proportional sampling and one for flow-proportional sampling. The time-proportional sampler is equipped with refrigerated bottles such that the water samples can be collected over a 7-day period. The flow-proportional sampler is only activated during storm events and sampling is carried out for 1–2 days depending on the intensity of the event.

The monitoring wells are each located inside a shed so as to protect the equipment from the weather. Two electrical heaters in each shed prevent the temperature from dropping below 5°C.

3.3 Soil water sampling

Soil water in the unsaturated zone is under tension, and hence cannot flow into a well as groundwater does. Monitoring of soil water in the unsaturated zone thus requires the use of suction cups, etc.

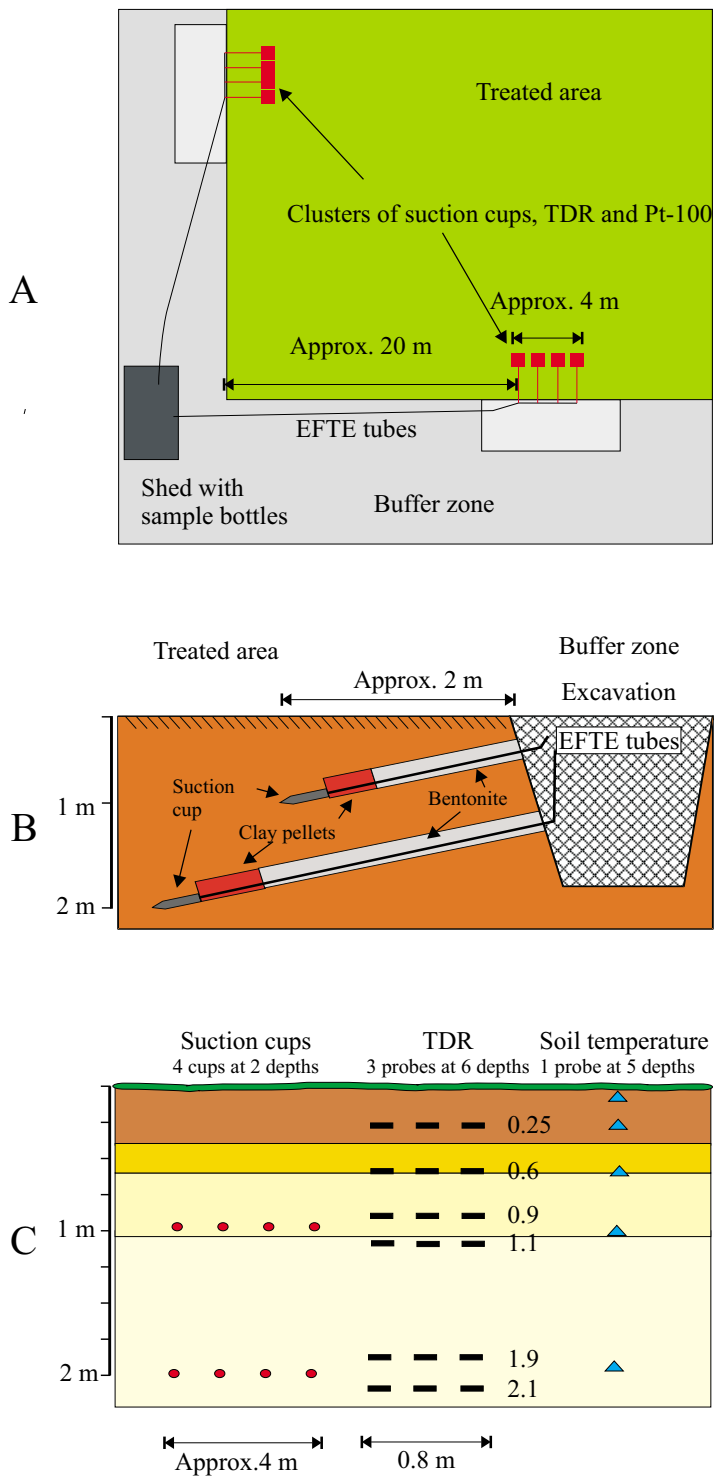


Figure 3.5. A) Location of suction cups, TDR and soil temperature probes, B) a cross section showing the installation of the suction cups, and C) a plan view of an excavation wall indicating the location of the suction cups, TDR and soil temperature probes.

A total of 16 suction cups have been installed at two locations at each site – one on each side of the test field about 20 meters from the downslope corner (Figure 3.5A).

At each location, four suction cups are installed at a depth of 1 m b.g.s. and four at a depths of 2 m b.g.s. (Figure 3.5B/C). The horizontal distance between suction cups installed at the same depth is 1 m while that between suction cups installed at different depths is 0.5 m.

The suction cups were installed from two excavation pits at the edge of each test field via holes drilled obliquely to the desired depth. This procedure ensures that the soil directly above the suction cups remains undisturbed.

The suction cups installed at a depth of 1 m are located at a horizontal distance of 2 m from the edge of the test field while the suction cups installed at a depth of 2 m are located at a horizontal distance of 2.5 meters from the edge of the field. The installation holes were drilled from 0.5 m b.g.s. in the case of the suction cups installed at a depth of 1 m and from 1 m b.g.s. in the case of those installed 2 m b.g.s.

The installation holes were drilled with a 50 mm air-driven hand auger to the desired length minus 20 cm. The final 20 cm of the installation holes were completed using a 21 mm steel rod corresponding to the diameter of the suction cup.

100 ml of a thick slurry of water and silica flour was poured to the bottom of the hole just before installation of the suction cup. Immediately after installation of the suction cup a further 100 ml of the slurry was poured into the installation hole, which was then sealed with 20 cm of clay pellets before being back-filled with bentonite pellets.

Each suction cup is connected to the sampling bottle via a single length of PTFE tubing. From the excavation pit to the shed the PTFE tubes run through a protective tube buried in a 70 cm deep trench. The sampling bottles are located in a refrigerator in the shed. The soil water is extracted using a continuous vacuum technique.

The suction cups used are PRENART SUPER QUARTZ (Prenart, DK) consisting of porous PTFE mixed with quartz. The soil water sampler is 21 mm in diameter and 95 mm in length with 2 micron pores. The tubes used consist of 1/8" x 2.0 mm PTFE tubing. The sampling bottles are 1 or 2 litre glass bottles. All fittings that come into contact with water are made of stainless steel.

3.4 Climate parameters

An automated monitoring system has been installed at each site for measurement of precipitation, barometric pressure, soil temperature, soil water content and soil water pressure. At the four sites on clayey till, the system also controls two drain water sampling devices (Section 3.2).

The automated system consists of various items of hardware and sensors and commercially available software tools in which dedicated software codes have been implemented. The central unit is a Campbell CR10X 2M datalogger (Campbell Sci, UK). User communication from office PC to this datalogger is established via modem using fixed telephone lines or GSM phone transmission. The data are collected automatically every night.

Precipitation

Precipitation is measured on site with a tipping bucket rain gauge (Type 1518Wilh. Lambrecht, BmbH, D). The gauge is accurate to 0.1 mm and is well suited for measuring high precipitation intensity. Sampling is carried out every minute and hourly values are stored.

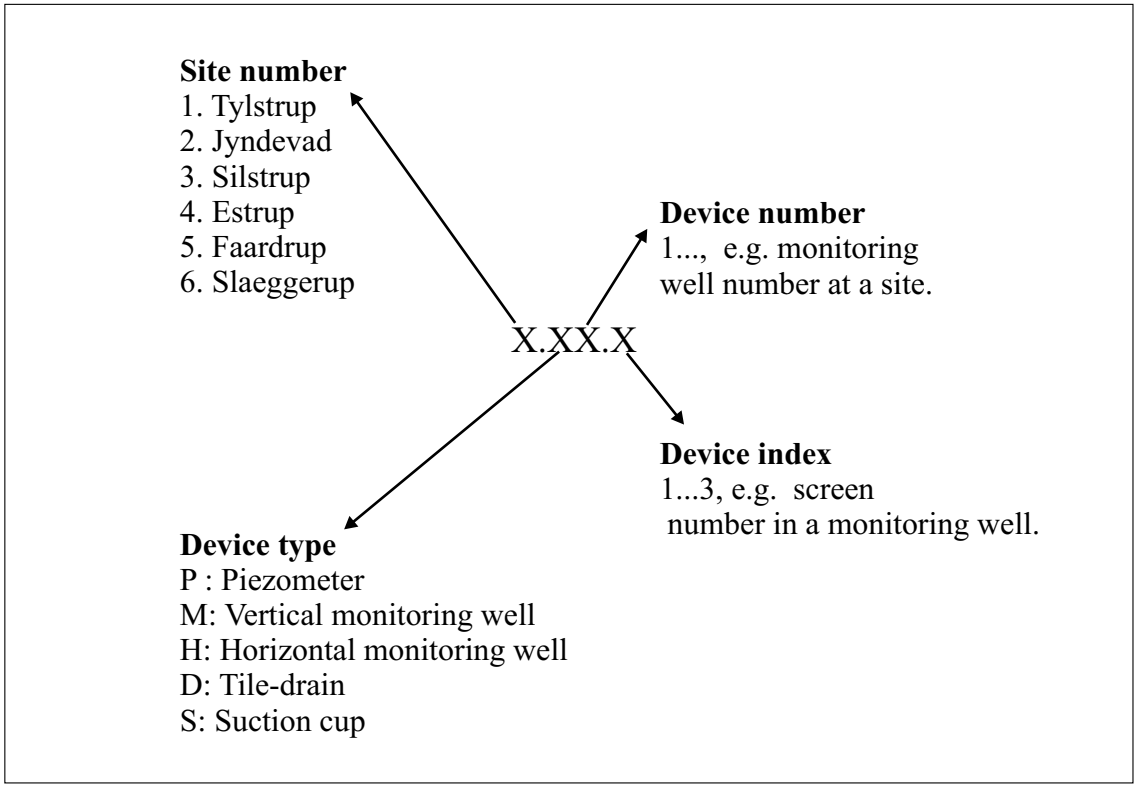
Soil moisture

Soil moisture is measured using a CR10X-controlled Time Domain Reflectometry (TDR)-system. The central unit in the TDR-system is the cable tester from Tektronix 1502C (Tektronix Inc., Beaverton, OR, USA). The soil water probes are developed at Research Centre Foulum and consist of a 40 m coaxial cable (Mikkelsen Electronic A/S, DK) connected through a solid plastic box to three 30 cm steel rods spaced about 2 cm apart. The accuracy of the soil water measurements is around ±1 vol %.

Soil water content is measured in two profiles at each site at the depths of 0.25, 0.6, 0.9, 1.1, 1.9 and 2.1 m (Figure 3.5C), with three replicate probes at each depth. Soil water content is measured and stored every hour.

Soil temperature

Soil temperature is measured with platinum resistance thermometers (Pt-100, length 10 mm and diameter 5 mm). The accuracy of the measurements is ±0.1°C. Soil temperature is measured in two profiles at each site with one sensor at each of the following depths: 0.1, 0.25, 0.6, 1.0 and 2.0 m (Figure 3.5C). The temperature is measured and stored hourly.



Barometric pressure

The barometric pressure is measured with a pressure sensor (PTB101B, Vaisala, SF) with an accuracy of ±2 mB. Measurements are taken and stored hourly.

3.5 Monitoring device codes

To ensure unique identification of all samples collected in this programme, all sampling points are described by a code that includes the site identification, the type of sampling device, and the number of sample points in each device. The code system is illustrated in the box above.

By way of example, a vertical monitoring screen on the Tylstrup site will have the code 1.M4.3, indicating screen number 3 in vertical monitoring well (M) number 4 at site number 1.

The screens in the vertical monitoring wells and the piezometers are coded with increasing numerical value from the surface and downward.

4. Geological and pedological methods

4.1 Geological methods

4.1.1 Geological field work

The initial field work at the sites included drilling of one to four shallow boreholes with a hand auger in order to determine whether the desired geology was present. Subsequently, four 12 to 23 m deep wells each fitted with three piezometers were drilled to monitor the potential head of the shallow groundwater flow and determine the direction of flow. Once the direction of flow had been determined, seven monitoring well clusters were established – six downstream of the test field and one upstream.

A geologist in the field supervised all drilling and the geology was described in the field in accordance with Larsen *et al*. (1995). Samples were taken for each 0.5 m or at least one sample from each described layer. All well data and the geological description are stored in the GEUS water well database JUPITER.

Test pits

At the four clay till sites (Silstrup, Estrup, Faardrup and Slaeggerup) a 5 m deep 10 x 10 m test pit was excavated in the buffer zone with profiles perpendicular to each other at three levels: 0.5–2.0 m, 2.0–3.5 m and 3.5–5.0 m. This test pit structure enabled all fracture orientations to be observed. The profiles were described according to Klint and Gravesen (1999). The test pits were used for the following tests and investigations: field vane tests, fracture description and characterization, fabric analysis and lithological description. Samples were collected for grain size analysis, total organic carbon (TOC) and $CaCO_3$ content, clay mineral analysis and exotic stone counts.

4.1.2 Laboratory analyses at GEUS

Total organic carbon (TOC)

TOC content was determined as follows: 300–500 mg of sample was treated with 5–6% H_2S0_3 to remove carbonate minerals and then combusted in a LECO CS 200.

$CaCO_3$

Each bulk sample was gently crushed sufficiently to pass a 2 mm sieve. 25 ml 0.5 M hydrochloride acid and demineralized water was then added and the sample heated to boiling point for 20 minutes. Thereafter the suspension was titrated with 0.5 M sodium hydroxide using phenolphthalein as indicator.

Grain size

Grain sizes larger than 0.063 mm were determined by sieving according to DS 405.9 but with a ½ phi sieve column.

Material smaller than 0.063 mm was sieved through a 0.1 mm sieve cloth and the material larger than 0.1 mm dried, treated with 50 ml 0.005 M $Na_4P_2O_7$ x 10 H_2O and centrifuged. After 12 hours of shaking the sample was measured using a Micromeritics Sedi-Graph 5100.

Permeability

The plug dimensions were measured with a calliper and the plug then mounted in a special Hassler core holder at a confining sleeve pressure of 1.75 bar. The required fluid and fluid upstream pressure of 0.2–1.5 bar was delivered by a constant flow rate pump. At least one pore volume of liquid was allowed to flow through the sample before the measurements were initiated. The flow rate was measured volumetrically over a period ranging from a few hours to more than one day.

Porosity and grain density

The porosity was measured in cleaned and dried samples by subtraction of the measured grain volume and the measured bulk volume. The grain volume was determined using the helium technique (Boyle's law) applying a double-chambered helium porosimeter with a digital readout. The bulk volume was measured by submersion of the plug in a mercury bath using Archimedes' principle. Grain density was calculated from the grain volume measurement and the weight of the cleaned and dried sample.

Porosity by weight loss

The porosity of loosely consolidated sediments, e.g. till samples that are saturated to 100% with a liquid, can be analysed by drying at 110°C and recording the weight loss. The weight loss was recalculated to a liquid volume equal to the pore volume. The sample bulk volume was determined from calliper measurements of the saturated sample before drying.

Clay mineralogical analysis

The samples were gently crushed to pass a 2 mm sieve and treated with sodium acetate at a pH of 5 to remove carbonates. The sand and silt fraction was then removed by elutriation and centrifugation, and the 2-30 µm fraction and clay fraction < 2 µm were separated in a particle size centrifuge. The clay fraction was saturated with Mg^{2+} and K^{+} prior to X-ray diffraction analysis.

Oriented specimens were prepared by the pipette method and the following specimens analysed:

Mg^{2+} – saturated, air dry.
Mg^{2+} – saturated, glycolate.
K^{+} – saturated, air dry.
K^{+} – saturated , heated to 300°C.
X-ray diffraction was carried out with Co-Kα radiation, β-filter and pulse height selection.

Fine gravel analysis (Ehlers, 1978)

4.2 Pedological methods

4.2.1 Pedological field work

Excavation and description of soil profiles

Two or three soil profiles were excavated at each site to a depth of approx. 1.6 m using a backhoe. Major excavations performed by GEUS and used for geological site descriptions were also used to describe the upper 1.6 m of the soil profile.

Pedological description of all identified soil horizons was carried out in accordance with Madsen and Jensen (1988). Field reports from the sites included detailed maps showing the succession of identified and described soil horizons. Profile descriptions, photographs and drawings are presented in the annexes.

Soil samples from every identified horizon were collected for laboratory analysis. About 10 litres of bulk soil from each horizon were dried and stored at DIAS. The soil samples were analysed at the DIAS. A detailed description of the laboratory analysis methods used can be found in Hansen and Sørensen (1996). The most important methods and procedures are briefly summarized in Table 4.2.

Table 4.2. Summary of methods and procedures used in the laboratory analyses of soil samples.

Parameter	Description
Soil texture	Particle size analysis subdivided the soil samples into the following classes: clay <2 µm, silt 2–20 µm, coarse silt 20–63 µm, fine sand 63–125 µm and 125–200 µm, medium sand 200–500 µm, and coarse sand 500–2,000 µm.
TOC	The total organic carbon (TOC) content was determined using dry combustion. Soil samples containing significant amounts of calcium carbonate (exceeding 1%) were also analysed for $CaCO_3$ content.
pH	pH was measured following suspension of the soil in 0.01 M $CaCl_2$.
Fe and Al	Fe and Al were extracted using an ammonium oxalate solution and determined by atomic absorption spectrophotometry.
Total-P	Phosphorous content was determined spectrophotometrically following destruction of the soil by perchloric acid-sulphuric acid.
Total-N	The soil sample was combusted in an atmosphere of pure oxygen at 900°C. Water and CO_2 were removed and the nitrogen oxides were reduced to free nitrogen, which was then measured in a chemical conductivity cell.
Exchangeable cations	Exchangeable cations were extracted using ammonium acetate buffered at a pH of 7.0. Ca and Mg were determined using atomic absorption spectrophotometry. Na and K were determined by flame emission. Exchangeable hydrogen ions were determined by titration to equilibrium in a 0.06 M-nitrophenol solution.
CEC	CEC was calculated as the sum of cations.

The soil profiles were classified both according to the Danish system (Madsen and Jensen, 1985) and the USDA Soil Taxonomy (Soil Survey Staff, 1999). Nomenclature for textural classes in this investigation follows the Danish system, illustrated in Figure 4.1. The description and the analysis results from all the profiles have been stored in the DIAS soil profile database (Den Danske Jordprofil Database – DDJD (The Danish Soil Profile Data Base)).

Soil core descriptions

The soil core samples for description were retrieved to a depth of 1 m b.g.s. using a hand auger or until 1.2 m b.g.s. by using a hydraulic soil auger provided by DIAS. Soil horizons and soil texture have been described for approx. every 25 metres along the edge of the test field. The position of each described soil core was geo-referenced using DGPS to an accuracy of 0.2 m. Soil cores retrieved with the hand auger were determined using local fix points.

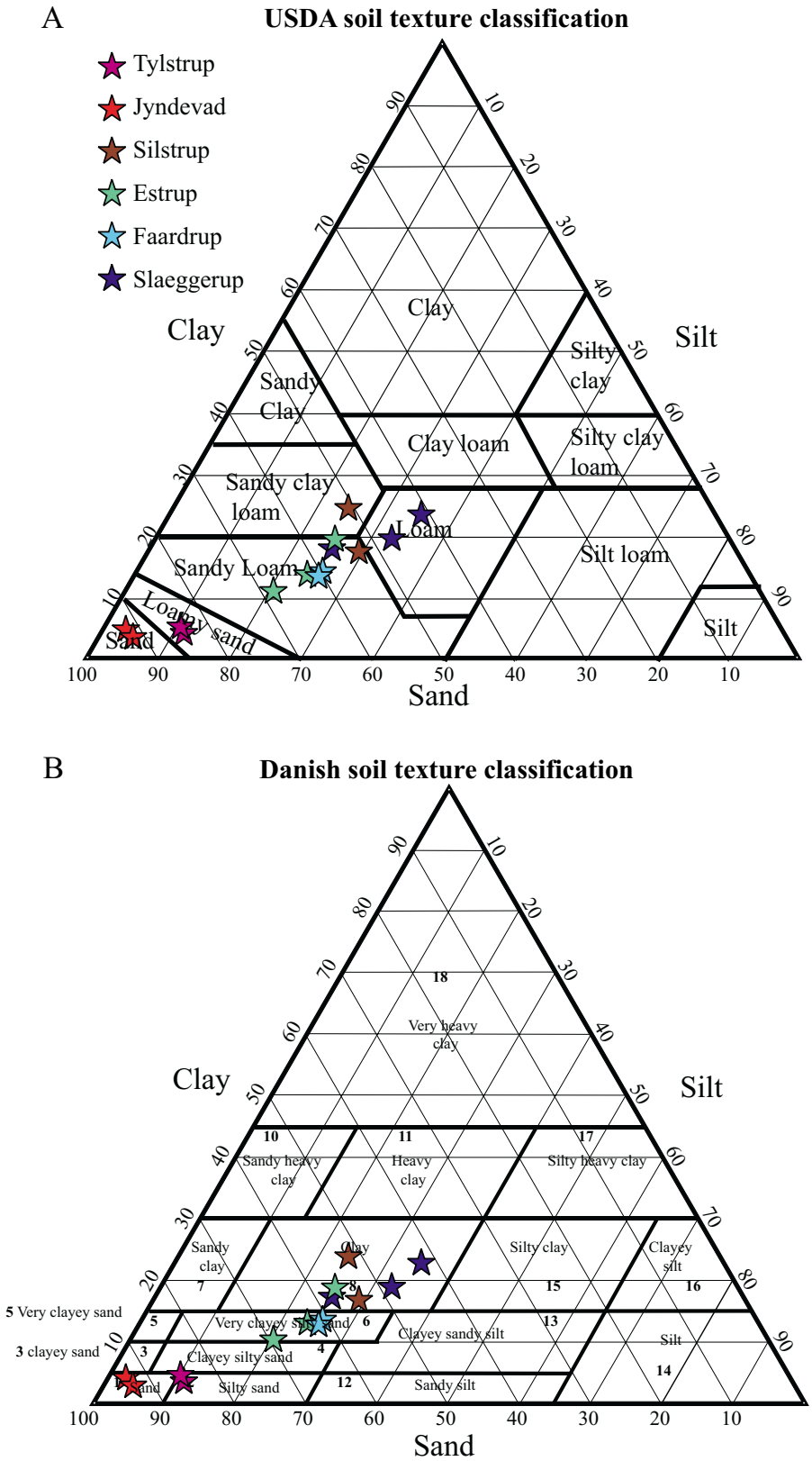


Figure 4.1. A) USDA (Soil Survey Staff, 1999) and B) Danish (Madsen and Jensen, 1988) soil classification triangel. Samples from the A-horizon taken at the soil profiles on each of the six fields.

Description of excavated trenches

Trenches excavated in order to establish the cut-of drainage pipes were used for mapping soil horizons and for determination of soil texture. Soil horizons and soil texture were described for every 25 m along the 0.8–1.6 m deep trenches.

Total carbon mapping

The topsoil (0–25 cm) at each site was sampled in a 20 m grid. Nine soil samples were collected at each grid point – one point exactly at the grid point and the other eight points arranged symmetrically around the grid point at a distance of 1 m. The nine samples were then pooled and the total organic carbon content determined at the Department of Analytical Chemistry, DIAS (Tabatabai and Bremner, 1970).

4.2.2 Soil hydrology

At all six sites, soil cores were taken from within three levels of the soil profiles corresponding to the A-, B-, and C-horizons. Five 6,280 cm^3 soil cores (large cores) and nine 100 cm^3 soil cores (small cores) were collected from each horizon. The nine small cores were divided into three groups with each group being collected near and around one of the large cores. To collect the large cores a large sampling cylinder was forced into the soil by means of a hydraulic press mounted on a tractor. To collect the small cores a small sampling cylinder was forced into the soil with a hammer using a special flange. All samples were protected from evaporation and stored at 2-5°C until analysis.

Analysis of large cores

In the laboratory the large cores were placed on a ceramic plate and saturated with water from below. The samples were then drained to a soil water potential of -50 cm. H_2O and air permeability were measured using a portable air permeameter (Iversen *et al*., 2001). The samples were then left to re-saturate and the near-saturated hydraulic conductivity was measured using a drip infiltrometer (van den Elsen *et al*., 1999). This works automatically and measures the hydraulic conductivity in the soil under steady-state water flow conditions at different soil water potentials. The soil column was placed on a sandbox and five ceramic cups connected to transducers were placed in the soil column. When steady-state water flow was reached, a measurement was conducted and the measurement continued at lower water potential. Upon completion of the drip infiltrometer measurements the samples were re-saturated and the saturated hydraulic conductivity measured using the constant-head method (Klute and Dirksen, 1986). Near-saturated hydraulic conductivity and air permeability were only measured on three out of five samples, whereas saturated hydraulic conductivity was measured on all five samples.

Analysis of small cores

Small soil cores were placed on top of a sandbox and saturated with water from below. Soil water characteristic were determined by draining the soil samples successively to soil water potentials of -10, -16, -50, -100, -160, and -1,000 cm H_2O (pF 1, pF 1.2, pF 1.7, pF 2, pF 2.2, and pF 3.0) using a sandbox for potentials from -10 to -100 cm H_2O and a ceramic plate for potentials from -160 to -1,000 cm H_2O. Soil water characteristics were also determined at a soil water potential of -15,850 cm H_2O (pF 4.2) after the soil had been ground and sieved through a 2 mm sieve (Klute, 1986). Air permeability was measured at a soil water potential of –50 cm H_2O using the same device as for the large soil cores. After the soil water characteristic had been determined the samples were re-saturated and the saturated hydraulic conductivity measured using the constant-head method (Klute and Dirksen, 1986). Finally, the soil samples were oven-dried at 105°C for 24 hours and weighed in order to determine the dry weight.

All analyses were carried out at the Department of Crop Physiology and Soil Science, DIAS except for the pF 4.2 analysis, which was carried out at the Department of Analytical Chemistry, DIAS.

4.3 Geophysical mapping

Geo-electrical mapping of the sites was performed using an EM-38 sensor and a CM-031 ground conductivity meter. Both instruments measure the apparent specific conductivity by electromagnetic induction (Durlesser, 1999). The electromagnetic conductivity of the soil is a function of such factors as the content of salts, clay and water (Rhoades and Corwin, 1981).

EM-38 mapping

Simplified maps generated by means of the EM-38 sensor delineate soil types according to their clay content (Nehmdahl, 2000). The measurement unit is millisiemens per metre (mS/m) and the penetration depth of the sensor is 1–1.5 m.

The mapping system developed at DIAS consists of a 4-WD motorcycle equipped with a GPS receiver and data-logger, pulling a sledge on which the EM-38 is mounted together with a GPS antenna.

Data from the EM 38 and GPS were stored simultaneously with a frequency of 1 measurement per second while navigating in parallel lines separated by a distance of approx. 10 m. Measurements were made at approx. 10 m intervals and used to produce interpolated maps of the soil electrical conductivity.

Conductivity meter (CM-031)

The electrical conductivity from 1 to 6 m b.g.s. was mapped at five of the six sites using a CM-031 ground conductivity meter (Geofyzika, Czech). A local 10 m by 20 m grid was established at the site and measurements made with both vertical and horizontal dipole orientations. The vertical dipole orientation corresponds to a penetration of 5.5–6 m whereas the horizontal dipole orientation corresponds to a penetration of approx. 1 m. The data were automatically stored in a HP palmtop during field work.

Note that the resistivity values at depths down to 1 m were measured with EM 38 whereas the measurements at 2.5–3 m b.g.s. and 5–6 m b.g.s. were made using the CM-031. The two instruments are operated at different heights above the ground surface.

Ground-penetrating radar (GPR)

To detect any larger sand or gravel lenses or other geological anomalies and obtain information about internal structures such as bedding plane, the area was mapped with ground-penetrating radar in a 20 to 30 m grid using a 100 MHz antenna. The GPR mapping was performed by FAXE Kalk A/S, DK.

5. Site characterization

In this chapter each of the six sites is described briefly in respect to instrumentation, pedology, and geology. For a detailed characterisation of the sites the reader is referred to the relevant Annexe.

5.1 Site 1: Tylstrup

This test field is situated at Tylstrup in northern Jutland. It covers an area of 1.08 ha and the width of the buffer zone is approx. 2 m towards the northeastern, 3 m towards the southeastern, 22 m towards the southwestern and 4.5 m towards the northeastern. Windbreaks run along the western and eastern side of the buffer zone and a road runs along the northern side of the site. All installations are shown in Figure 5.1.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 4.5–12 m b.g.s. An additional two piezometers consisting of ¾" electroplated pipes were also installed in the buffer zone and two were installed approx. 150 m south of the test field. The groundwater table fluctuates between 3 and 4 m b.g.s. Based on the groundwater potential in the piezometers in spring 1999 it was concluded that the direction of groundwater flow is towards west-southwest. The monitoring wells were therefore placed such that 6 of the 7 monitoring well clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering approx. the depth interval 2–6 m b.g.s. on the western side of the site and 1.6–5.6 m b.g.s on the eastern side.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the southwestern corner of the site, i.e. the downstream corner of the test field in relation to the direction of the groundwater flow.

Geology

The Tylstrup site is located on Late-Glacial fine-grained marine sand deposited in a shallow Arctic sea – the Yoldia Sea – approx. 15,000 BP. The area has subsequently

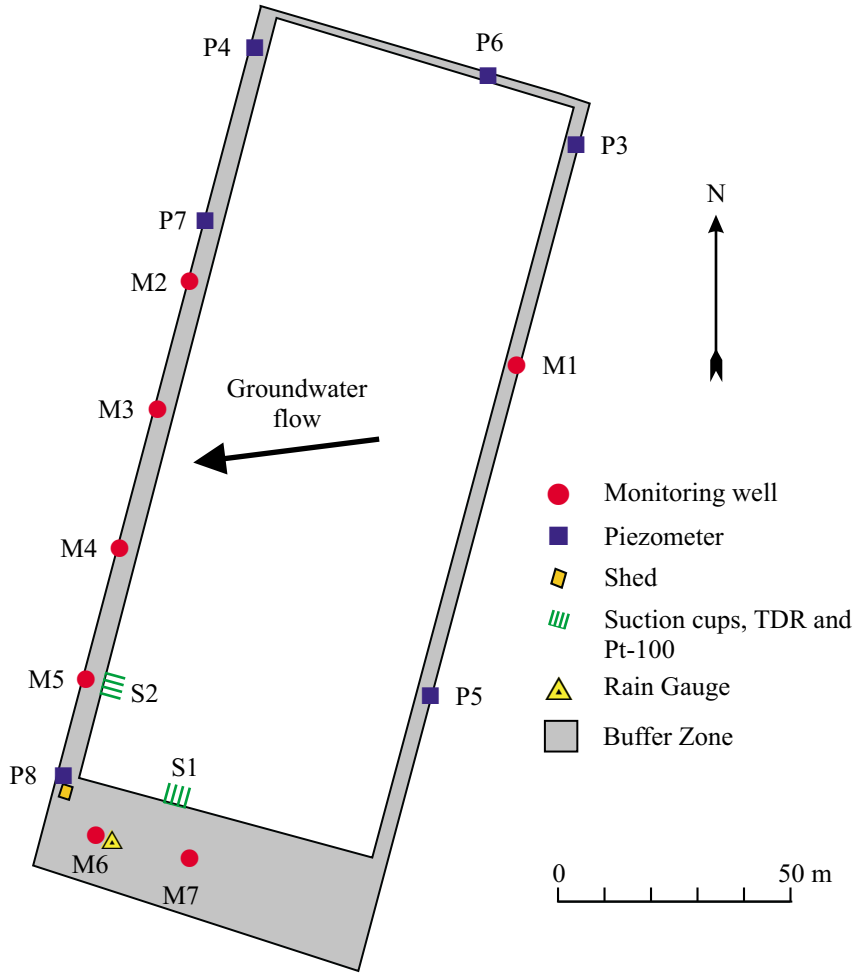


Figure 5.1. Sketch of the Tylstrup field showing the test and buffer zones, location of installations and the direction of the groundwater flow.

been subject to isostatic uplift and the Late-Glacial marine deposits are now found as one in a series of raised seafloor terraces.

The pattern of sediment distribution at the site indicates the presence of more fine-grained material, i.e. silt and clay layers, in the northern end of the field. The geophysical mapping is in good accordance with the well data and the field can be described as homogeneous. The pedological profiles at the site are classified as Typibrunsols. A geological-pedological model has been established on outcrop, borehole and geophysical data. The four units are presented below. A borehole croos section from the site is illustrated in Figure 5.2.

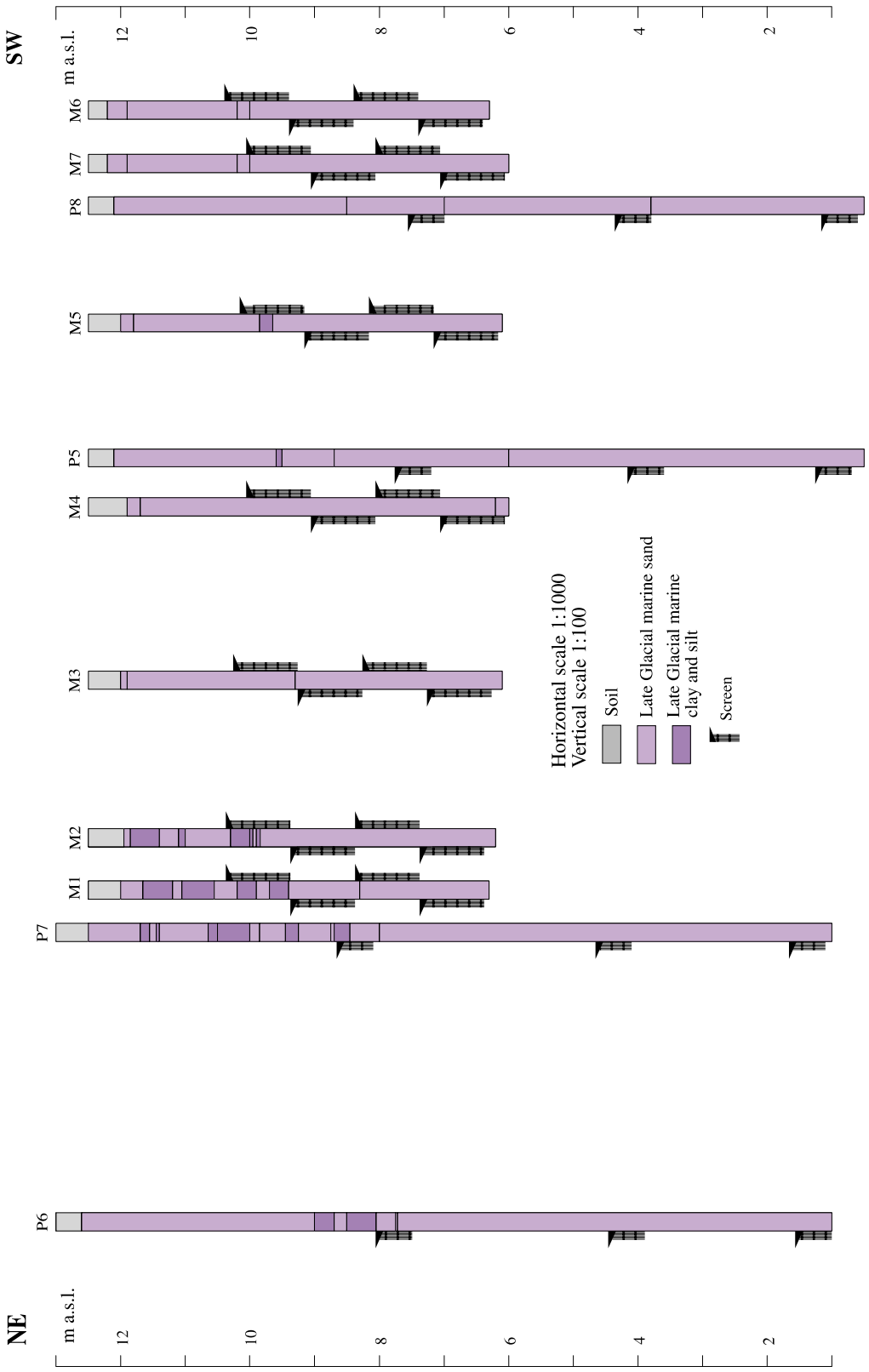


Figure 5.2 NE-SW cross section based on wells at the Tylstrup site. The location of the wells is shown in Figure 5.1.

Unit 1: Topsoil. 0–0.4 m b.g.s.

The very dark greyish brown sandy topsoil (loamy sand) contains humus (1.7–2.3% TOC), a varying content of burrows and roots, and is an Ap horizon. The material is noncalcareous. On the lee side of the windbreaks, Ap2 horizons are present, formed as a result of eolian sediment transport. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-5} m/s.

Unit 2: Oxidized noncalcareous weathered fine-grained silty sand. 0.4–1.6 m b.g.s.

This unit is a yellowish brown, brownish yellow or dark olive brown silty sand classified as a Bv and a Bc horizon with wormcasts and roots to a depth of 1.6 m. The TOC content is approx. 0.3–1.5%. Placic horizons and hydromorphic characters are also present in the unit. Sedimentary structures are obscured as a result of soil formation processes. In the northern half of the field the unit can be expected to contain some silt and clay layers. The saturated hydraulic conductivity is approx. 10^{-5} m/s.

Unit 3a: Oxidized noncalcareous silty sand. 1.6–approx. 4 m b.g.s.

The silty sand in the unit is yellow or light yellowish brown, fine grained and silty. In outcrops it contains a variety of sedimentary structures such as lamination cross-bedding and erosive surfaces. The TOC content is less than 0.1%. In the top part of this unit the saturated hydraulic conductivity ranges from 10^{-5}–10^{-4}m/s.

Unit 3b: Oxidized noncalcareous silty sand with clay and silt layers. 1.6–approx. 4 m b.g.s.

This unit is confined to the northern half of the field. It consists of interbedded sand, silt and clay layers. The sand in the unit is yellow or light yellowish brown and the clay-silt layers are light olive brown. The different lithologies often appear as heterolithic beds, i.e. thin alternating layers. Silt layers typically have a lateral extension of approx. 10 m. The TOC content is less than 0.1%.

Unit 4: Oxidized weakly calcareous silty sand. 4–12 m b.g.s.

This unit consists of light yellowish brown silty sand with very few silt or clay layers. The $CaCO_3$ content is approx. 1.5–2.0% and TOC content is less than 0.1%.

Regional aquifer

The regional aquifer in the area is an extensive 20–30 m thick meltwater sand and gravel unit of Weichselian age located approx. 3–20 m b.g.s.

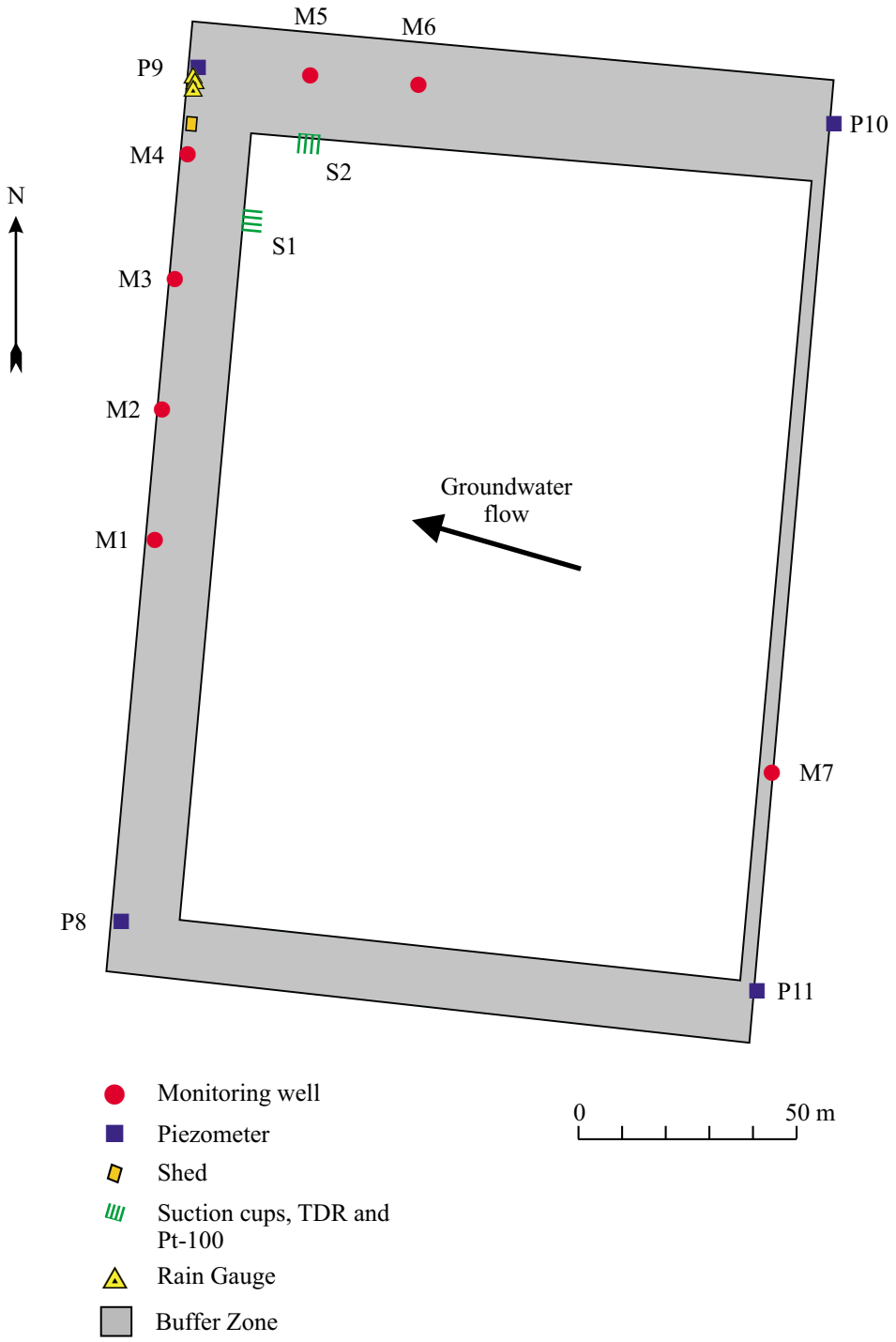


Figure 5.3. Sketch of the Jyndevad site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

5.2 Site 2: Jyndevad

This test field is situated at Store Jyndevad in southern Jutland. It covers an area of 2.39 ha and the width of the buffer zone is 24 m towards the north, 16 m towards the west, 14 m towards the south and 3 m towards the east. A windbreak borders the field to the east. All installations are shown in Figure 5.3.

Instrumentation

Four wells each containing three piezometers were installed in each corner of the site in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 3.4–11.5 m b.g.s. An additional seven piezometers were installed at a distance of up to 900 m from the site. The groundwater table fluctuates between 1 and 2 m b.g.s. Based on the groundwater potential in the piezometers in summer 1999 the direction of groundwater flow was concluded to be west-northwest. The monitoring well clusters were therefore placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 0.6–5.4 m b.g.s. at the western side of the site and 1.6–5.6 m b.g.s at the eastern side.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northwestern corner of the site, which is the downstream corner in relation to the direction of the groundwater flow.

Geology

The site is located on a Late Weichselian outwash plain west of the Main Stationary Line marking the westernmost extension of the Weichselian ice sheet. The outwash plain consists of meltwater sand and gravel locally draped by Post-Glacial eolian sand. Meltwater sand and gravel with a few silt and clay layers dominate the site. The meltwater sand unit in the area is at least 25 m thick and the Pre-Quaternary surface is located at a depth of approx. 30–40 m.

The three soil profiles at the site have been classified as Typipodsols. equivalent to a Humic Psammentic Dystrudept.

The geophysical mapping is in good accordance with the well data and the field can be described as very homogeneous. A geological-pedological model has been established on outcrop, well and geophysical data. The four units are described below and cross sections are illustrated in Figure 5.4.

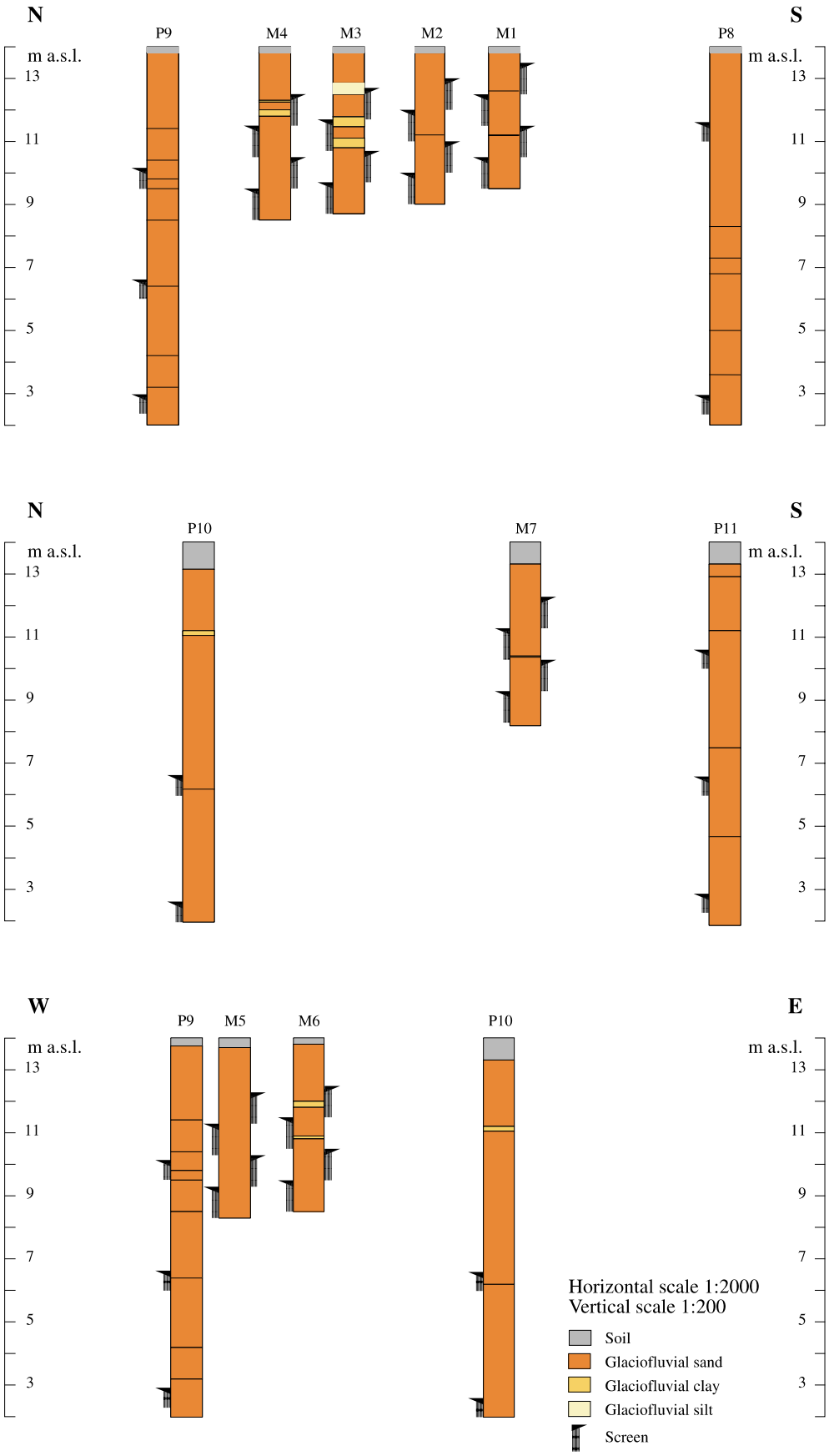


Figure 5.4. Cross sections based on wells at the Jyndevad site. The location of the wells is shown in Figure 5.3.

Unit 1: Top soil. 0–0.3 m b.g.s

The black topsoil consists of sand with a content of TOC at 1.5–2.5%, and is an Ap horizon. The saturated hydraulic conductivity ranges from 10^{-5}–10^{-4} m/s.

Unit 2: Weathered noncalcareous meltwater sand. 0.3–1.2 m b.g.s.

The black to yellowish brown unit consists of sand with small amounts of clay and silt. It contains three horizons: Bhs, Bs and BC. Remains of sedimentary structures such as cross-bedding and lamination can be observed. The TOC content is 0.25–0.75% and the saturated hydraulic conductivity is approx. 10^{-4} m/s.

Unit 3: Noncalcareous meltwater sand. 1.2–5.5 m b.g.s.

This unit is dominated by alternating beds of fine to medium-sized meltwater sand and medium- to coarse-grained meltwater sand. A few thin clay silt layers are present as well. Sedimentary structures such as cross-bedding and ripple lamination can be observed in the sand. Clay and silt account for less than 10% of the sand matrix. TOC content is lower than 0.2%. The saturated hydraulic conductivity ranges from 10^{-4}–10^{-3} m/s.

Unit 4: Unweathered weakly calcareous meltwater sand. 5.5–>12 m b.g.s.

This unit is similar to unit 3, but has a $CaCO_3$ content of 0–4.5%. The transition from oxidized to reduced conditions as indicated by colour changes is in good agreement with water well data from 10–12 m b.g.s.

Other deposits

In monitoring wells M3, M4 and M6, one or several clay and silt layer beds and stringer are present. In M3 the stringers are present to such an extent that the lithology takes on a heterolithic character.

Regional aquifer

The regional aquifer consists of extra-marginal meltwater deposits and to some extent more deep-lying Miocene quartz sand deposits.

5.3 Site 3: Silstrup

This test field is situated at Silstrup south of Thisted in northwestern Jutland. It covers an area of 1.69 ha and the width of the buffer zone is 18 m towards the west and east, 5 m towards the south (where a small road acts as an additional buffer zone) and more than 10 m wide towards the north. All installations are shown in Figure 5.5.

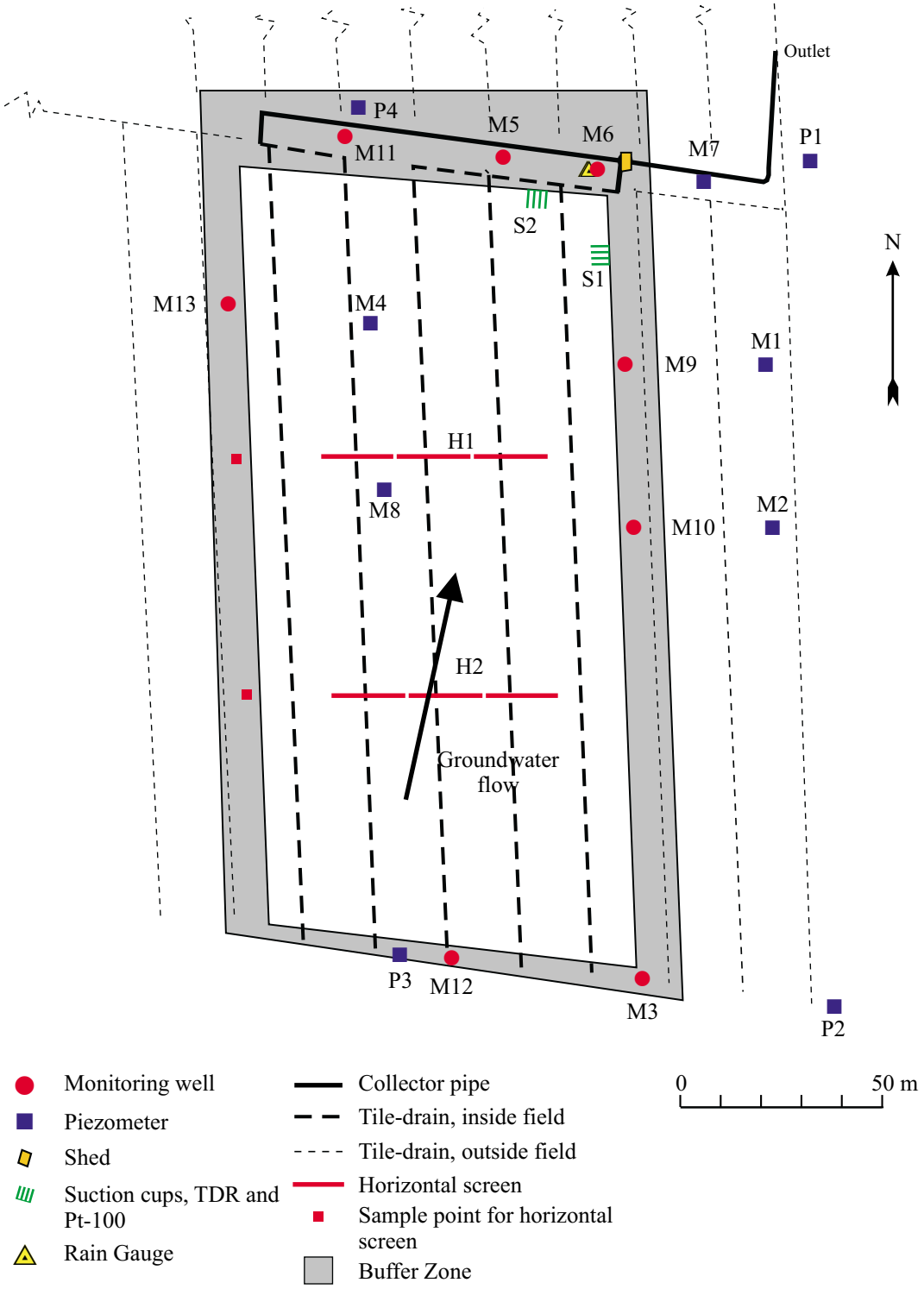


Figure 5.5. Sketch of the Silstrup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 2.0–12.0 m b.g.s. Based on the groundwater potential in the piezometers in summer 1999 it was concluded that the direction of the groundwater flow is towards the north. The monitoring wells were therefore placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 1.5–5.5 m b.g.s.

The drainage system at the site was installed in the 1960s. The design of the drainage system in the test field was simple, consisting of 5 parallel field drains running from south to north connected to two transverse collector drains at the northern end. All existing drainpipes are clayware. The lateral drains are 6.5 cm i.d. while the main drains are 8 cm and 10 cm i.d. The laterals appeared to have an envelope of seashells (mussels) to improve permeability.

The monitoring chamber was placed in the northeastern corner of the field. The two easternmost pipes exited towards the west, where a new 98 m PE pipe had to be laid along the northern boundary of the field to lead the water from the northwestern corner to the measuring chamber in the northeastern corner.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northeastern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Two 58 m long horizontal sampling wells H1 and H2 were also installed at Silstrup. Each consisted of three 18 m screen sections separated by 1 m bentonite seals. The first screens (H1.1 and H2.1) of both wells are situated within a lateral distance of 17 m from the edge of the test field.

The wells were drilled perpendicular to the edge of the field with the screens 3.5 m b.g.s. According to the drilling company, part of H2 follows a “pavement” probably comprised of a clay till rich in stones and boulders.

Geology

The Silstrup site is located north of the Main Stationary Line of the Weichselian Glaciation. Weichselian glacial clay till deposits dominate the site and only few thin bodies of

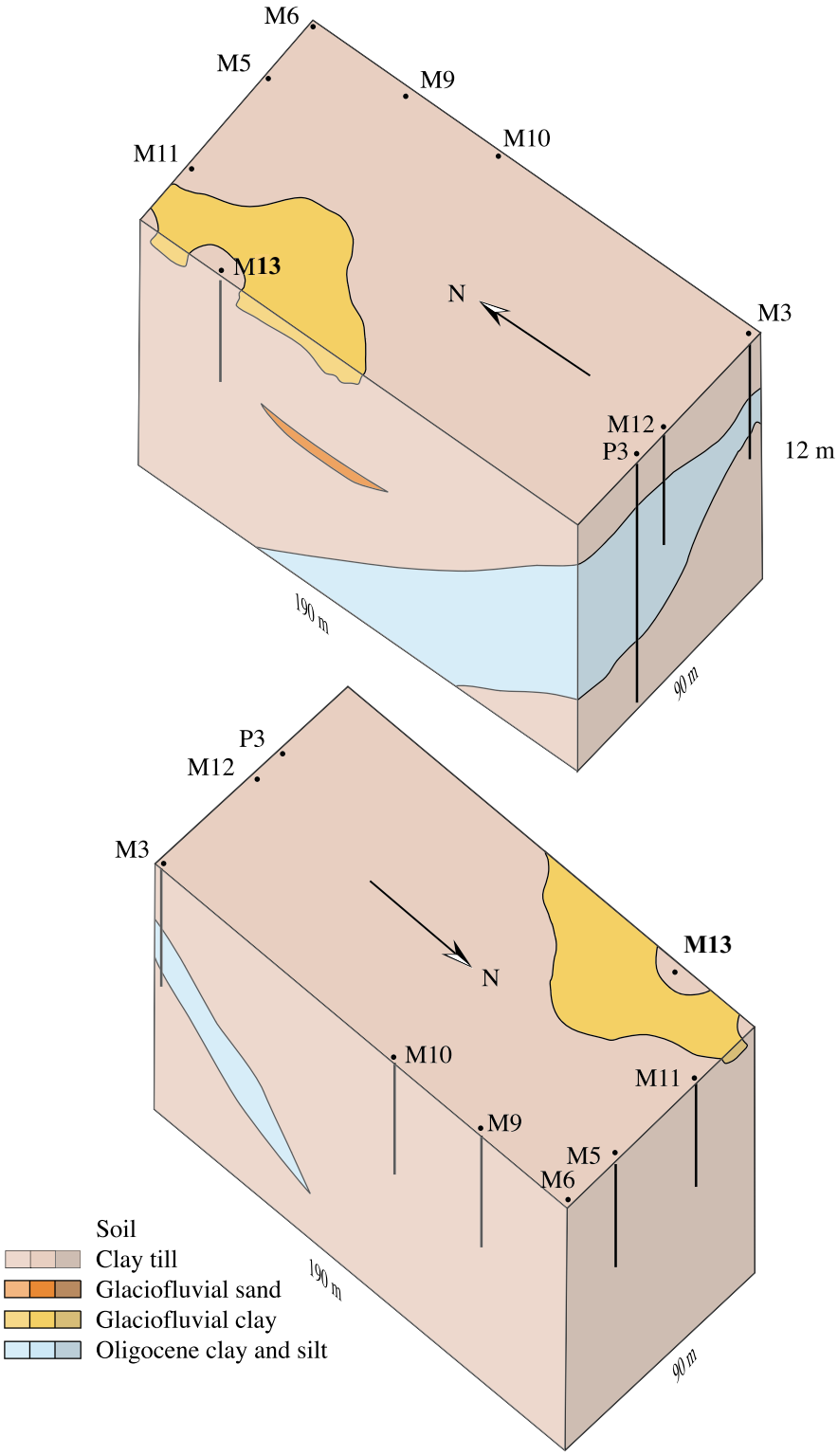


Figure 5.6. A geological model for the Silstrup site.

meltwater sand are present. Dislocated Oligocene clay and silt are present in the till along the southern rim of the test field. The site is situated in an area of glaciotectonic thrust faults and the coastal cliff east of the site contains dislocated Palaeocene and Oligocene deposits deformed by glaciers from the NNE and N.

The geophysical mapping is in good accordance with the well data and the field can be described as homogeneous.

A geological-pedological model comprised of the four units described below has been established on outcrop and borehole data and is illustrated in Figure 5.6.

Unit 1: Topsoil. 0–0.5 m b.g.s.

The dark grey brown to black sandy clayey topsoil (sandy clay loam/sandy loam) contains humus (1.9-2.4 % TOC) and numerous burrows and roots. The unit is also heavily fractured by vertical desiccation fractures. It is an Ap horizon and the material is noncalcareous. The saturated hydraulic conductivity ranged from 10^{-6}–10^{-4} m/s.

Unit 2: Noncalcareous oxidized clay till. 0.5–1.3m b.g.s.

The oxidized yellow brown clay till is penetrated by roots and burrows mainly in the upper part. The till is generally noncalcareous but some spots at the site are calcareous. Several horizontal-subhorizontal fractures are present. The till is weathered and the B horizon consists of Bv and Bt with clay illuviation in the lower part. The saturated hydraulic conductivity ranges from approx. 10^{-5}–10^{-4} m/s.

Unit 3: Calcareous oxidized clay till. 1.3–3.5 m b.g.s.

The brown and light yellow brown clay till is oxidized and calcareous (C- horizon). The till contains small vertical and subvertical fractures which decreases in amount with increasing depth. Additional sparse horizontal to subhorizontal fractures occur in this unit. Dislocated Oligocene clay and silt are included along the southern rim of the site. Saturated hydraulic conductivity values range from 10^{-7}–10^{-5} m/s

Unit 4: Calcareous reduced clay till. 3.5–13 m b.g.s.

The olive grey clay till is calcareous and contains chalk and chert gravel. Only very few vertical fractures exist at this depth while horizontal and subhorizontal fractures are more abundant.

Other deposits

At the southern end of the field, dislocated Oligocene clay and silt layers are found interbedded in the clay till. Since the clast fabric in the clay till indicates a deformation from the north, it is likely that the dislocated Oligocene layers strike approx. 90° and dip

towards the north. The clay content of these layers ranges from 20–30% and the silt content from 40–80%. The TOC content is 1.0–2.1%.

Regional aquifer

The sparse well data available for the area reflect the fact that there is no primary aquifer below the Silstrup site. However, the chalk is found at a depth of at least 100 m.

5.4 Site 4: Estrup

This test field is situated west of Vejen in central Jutland. It covers an area of 1.26 ha and the width of the buffer zone is 10 m towards the north and west, 5 m towards the south (where the railroad is) and 15 m towards the east. All installations are shown in Figure 5.7.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 1.5–21.9 m b.g.s. Based on the groundwater potential in the piezometers in autumn 1999 it was concluded that the direction of groundwater flow is to the northeast. The monitoring wells were therefore placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 1.5–5.5 m b.g.s.

The drainage system was established in 1965. It is thought to be constructed of 6.5 cm drains. To prevent water outside the test field from entering the drainpipes in the test field, a cut-off drain was installed along the south and east boundary of the site. The monitoring chamber was placed in the northeastern corner of the site. A 85 m long pipe running 1–2 m from the edge of the ditch collected discharge from the two 8 cm pipes that originally led to the ditch. Water from the main drainage system was conveyed to the monitoring chamber by a 5 m long pipe. The two branches join as a T-junction right outside the chamber.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northeastern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Due to the prevailing geological conditions, only one of two planned horizontal wells were installed. Three 18 m screen sections and four 1 m bentonite seals were installed

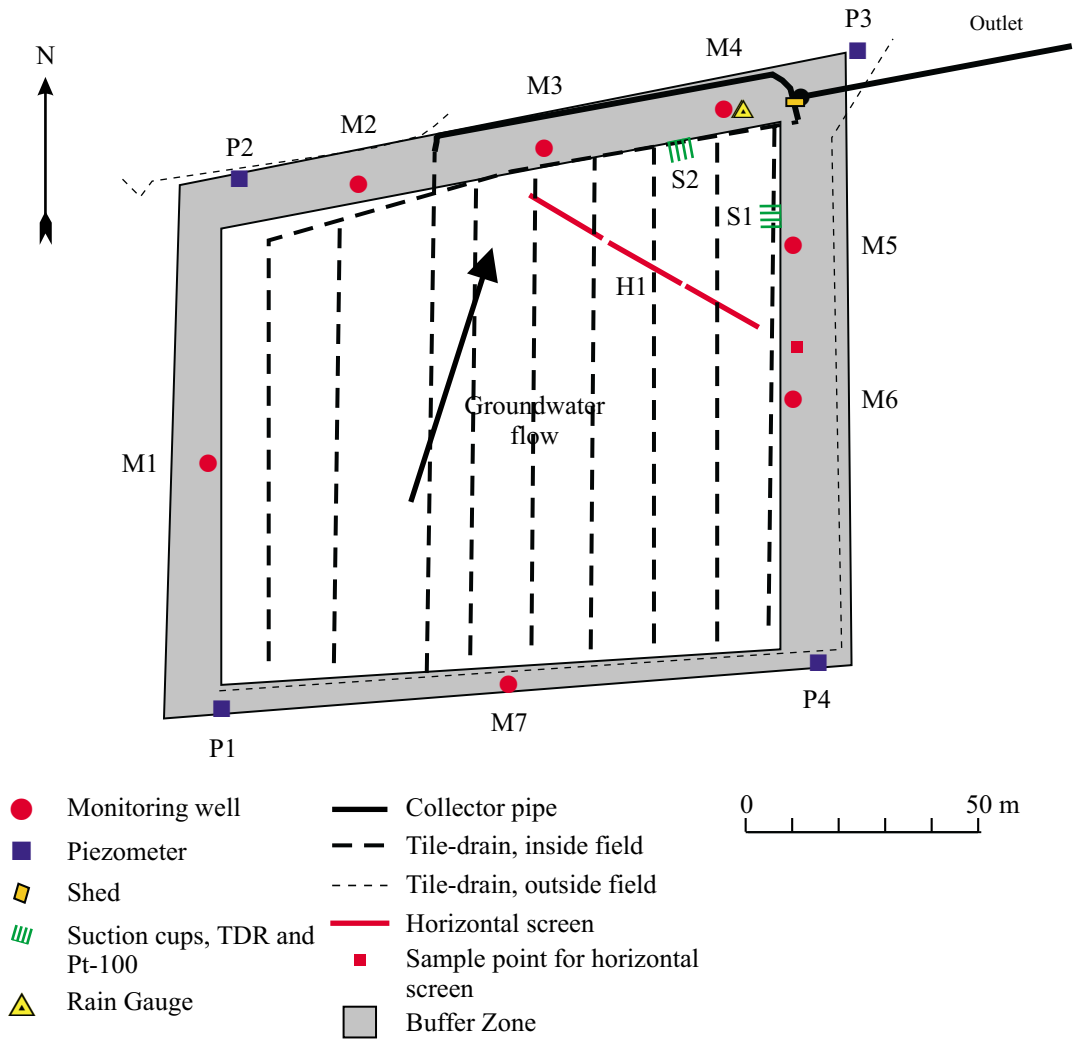


Figure 5.7. Sketch of the Estrup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

3.5 m b.g.s. beneath the northeastern corner (H1). The samples are collected from the southern end of the well. A second attempt was made to drill a horizontal well from a position 7 m west of M2 to 13 m north of M6, but the borehole had to be abandoned after 15 m of drilling in sand.

Geology

The Estrup site is located west of the Main Stationary Line of the Weichselian Glaciation and the clay till that dominates the site is therefore Saalian. The site has a complex geological structure comprising a clay till core with deposits of different age and com-

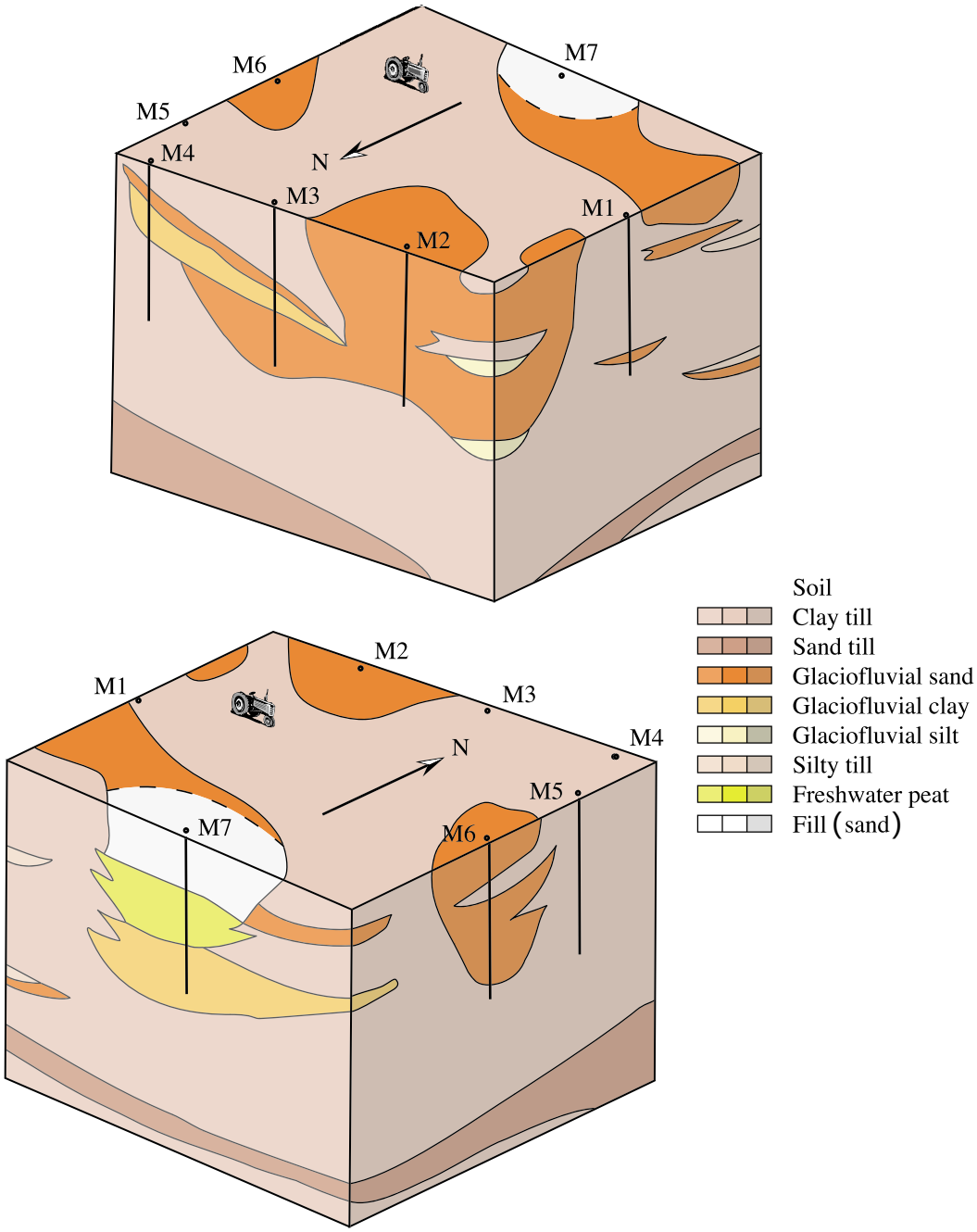


Figure 5.8. A geological model for the Estrup site.

position (Figure 5.8). At the southern rim of the site, shallow Post-Glacial peat is depositedupon a meltwater clay above the till. In the northwestern corner, a Saalian meltwater sand basin with intercalation of till and silt layers is present. Along the eastern rim of the area there is a small meltwater sand body. In the northeastern corner, a small lacustrine basin filled with clay and gyttja rests on the clay till. The age of the deposits could be Weichselian Interstadial or Eemian Interglacial. Small bodies of black mica-

ceous clay (not shown on Figure 5.8) with a high content of organic material are considered to be glacially dislocated Miocene sediments.

The soil profiles developed in the clay till at the site are classified as Pseudogleytypilessive, whereas the soil profiles in the meltwater sand are classified as Lessive Pseudogleytypipodsol.

The Estrup site is heterogeneous with different lithologies of Saalian, Weichselian and Post-Glacial ages. The long exposure of the sediments to weathering during the glacial-interglacial-glacial cycle has resulted in pedological development of acidification, decalcification and transport of fines and organic matter resulting in leached upper horizons.

The clay and sand till body is the most important lithology as regards the geological model. It is difficult to incorporate all the lithologies in one single model, and a geological-pedological clay till model has therefore been established and relationships to the other sediments are mentioned. The four units of the model are described below and a conceptual 3-D model is illustrated in Figure 5.8.

Unit 1: Topsoil. 0-0.4 m b.g.s.

The topsoil consists of very dark greyish brown clay and clayey sand (sandy loam) with a TOC content between 1.7 and 7.3%. It is an Ap horizon and is noncalcareous. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-4} m/s.

Unit 2: Noncalcareous clay till. 0.4–1.0 to 4.0 m b.g.s.

The yellow brown clay till is noncalcareous and oxidized. Root channels reach down to a depth of 2 m in this zone and occur together with randomly oriented small desiccation fractures. From 2.0 to 4.0 m the fractures are still randomly oriented, but systems of small vertical fractures and horizontal-subhorizontal fractures also occur. A few large fractures are found. The till is heavily weathered and has an upper BE-horizon with clay evaluation , a middle Bt horizon with clay and Fe and Mn oxide illuviation, and a lower C horizon. The saturated hydraulic conductivity is 10^{-7}–10^{-5} m/s. Other sediment bodies present at the site are in contact with unit 2 and may influence the upper part of the hydraulic system of the Estrup site.

Unit 3: Non calcareous/calcareous clay till. 4– approx. 12 m b.g.s.

The light yellow to brown grey sandy clay till is oxidized. The calcareous content varies through the unit due to the occurrence of chalk rafts. Abundant large vertical fractures and horizontal fractures occur and form a three-dimensional pattern. The saturated hy-

draulic conductivity ranges from 10^{-9}–10^{-7} m/s. The meltwater sand bodies are in contact with unit 3.

Unit 4: Calcareous clay and sand till. >12 m b.g.s.

This unit consists of alternating reduced calcareous grey clay till and sandy till beds with some sand veins.

Other deposits

In addition to the deposits included in the clay till model, the site also includes the following:

- Noncalcareous Saalian meltwater sand in the northeastern corner of the site. A glacial raft of Miocene micaceous clay with a TOC content of 10% is found in the southeastern corner at a depth of approx. 2 m.
- South of the site 2 m of Post-Glacial peat was found with a TOC content of 50% and no $CaCO_3$. East of the site there is a 5 m thick glaciofluvial sand body with a clay till bed. Northwest of the site there is a 7 m thick sequence of glaciofluvial sand with clay till and silt beds.

Regional aquifer

The regional aquifer is located approx. 20 m b.g.s. and consists of meltwater sand.

5.5 Site 5: Faardrup

This test field is situated at Faardrup south of Slagelse on Zealand. It covers an area of 2.33 ha and the width of the buffer zone is >11 m towards the north, 12 m towards the west (where the road adds another 4 m to the buffer zone), 17 m towards the east and >11 m towards the south. All installations are shown in Figure 5.9.

Instrumentation

Four clusters of piezometers were installed in each corner of the test field, in the buffer zone. Each cluster consisted of three 0.5 m long screens distributed over the depth interval 1.5–13.2 m b.g.s. Based on the ground water potential in the piezometers during summer 1999 it was concluded that the direction of groundwater flow was towards the west. The monitoring wells were then placed such that 6 of the 7 monitoring well

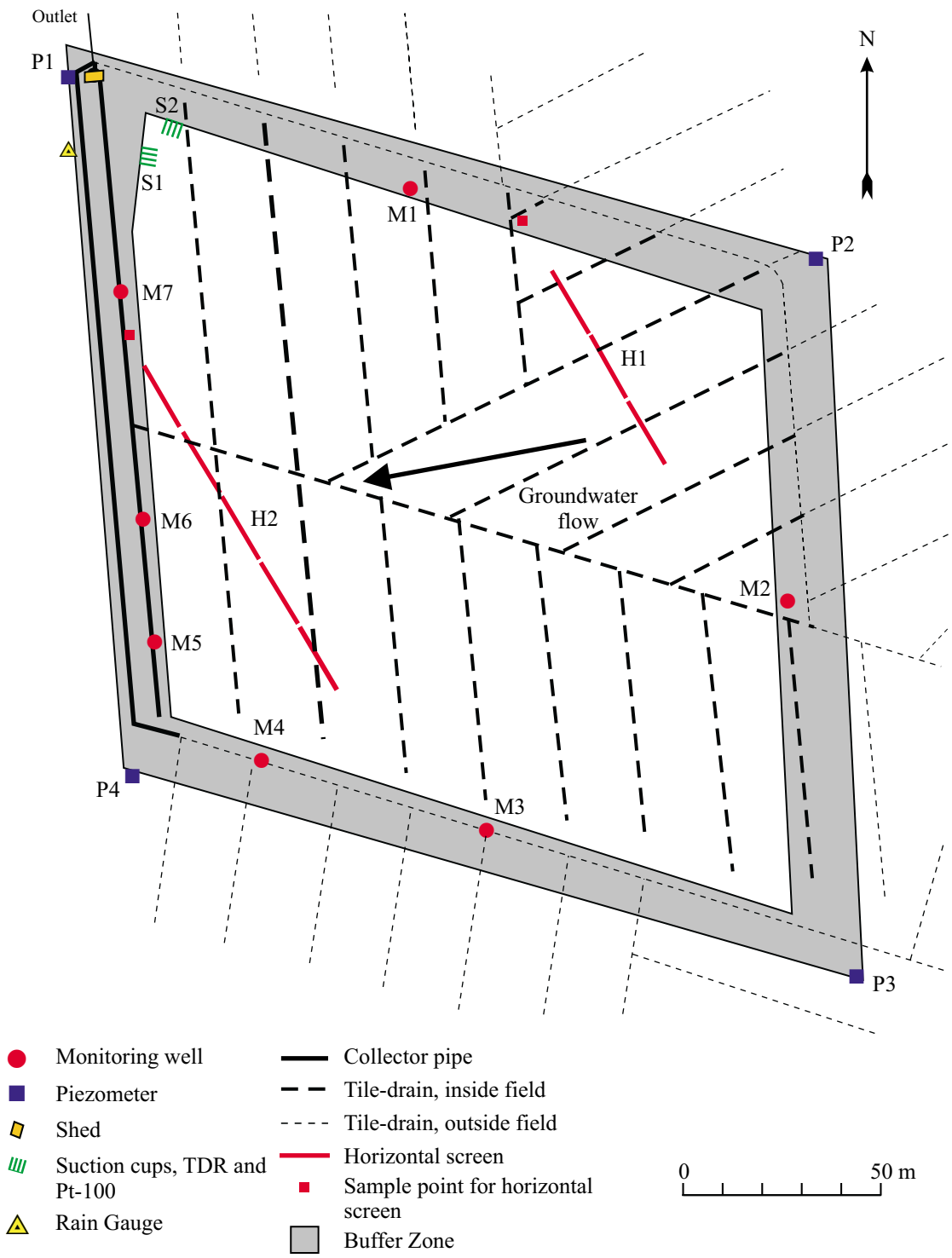


Figure 5.9. Sketch of the Faardrup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

clusters were located downstream of the test field. Each cluster contained four separate 1 m screens covering the depth interval 1.5–5.5 m b.g.s.

The drainage system at Faardrup was installed in 1944. The map from 1944 shows a traditional systematic drainage system. The drainage water from the test field and the adjacent fields is collected in a 15 cm main drain that runs along the western side of the area. The drainage system in the test field is a "herringbone system" with a collector drain that runs down westwards from the hills to the east, crosses the middle of the field and ends in the 15 cm main drain. All the drainpipes are clayware – 5.5 cm i.d. laterals and 6.5 cm and 10 cm i.d. collector drains. The monitoring chamber was placed in the northwestern corner of the site.

To isolate the test field drainage system, two cut-off drainpipes were installed. South of the test field there is a smaller, independent drainage system which also exited at the top end of the 15 cm main in the southwestern corner of the experimental field. This system was disconnected at this point and the water lead downstream via a new watertight pipe installed along the western boundary, parallel to the old main. A second cut-off drain made of perforated, corrugated pipes with an envelope of gravel was installed to the north and the east of the test field to prevent water from running into the test field from its upstream side. All the existing drains intersected were closed off with a brick towards the experimental field, and their upstream parts were connected to the new drainpipe via a T-junction.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northwestern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Two horizontal sampling wells were installed at Faardrup. Both wells were planned to consist of five 18 m screens separated by 1 m long bentonite seals, total length 96 m, including a 1 m bentonite seal at each end. Due to technical difficulties, however, H1 only consists of three 18 m long screens separated by 1 m bentonite seals.

H1 was drilled under the northeastern corner of the field. The overall drilled length is 160 m, of which 120 m lie beneath the test field. The screens are positioned from 3.35 to 3.70 m b.g.s. The samples are collected from the northern end of H1. Well H2 intersects the southwestern corner of the field. The overall drilled length is 158 m, of which 110 m lies beneath the test field. The screens are positioned from 3.2 to 3.7 m b.g.s. The samples are collected from the northern end of H2.

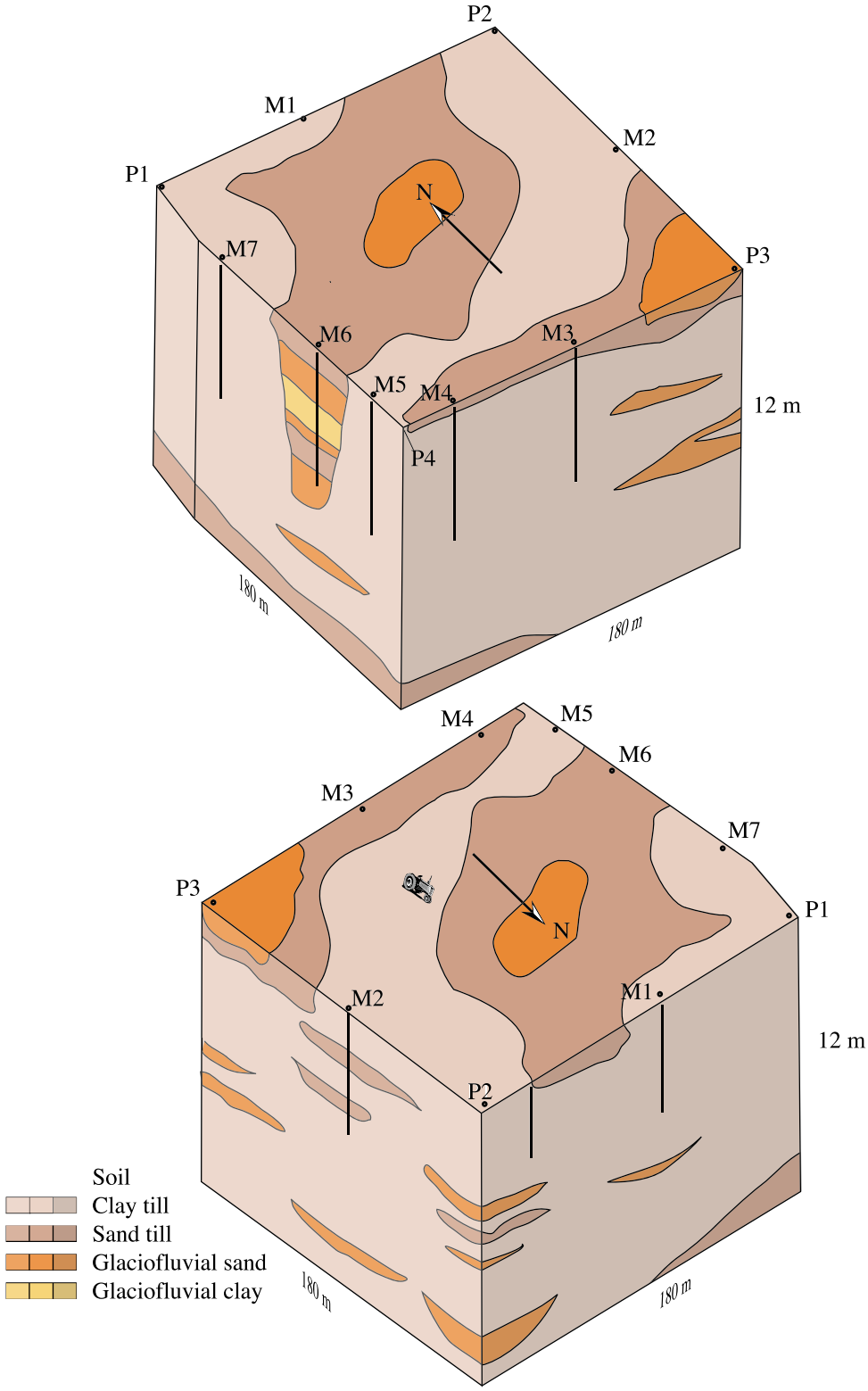


Figure 5.10. A geological model for the Faardurp site.

Geology

The Faardrup site is dominated by Weichselian clay till deposits more than 18 m thick and overlying a regional meltwater sand aquifer. The till deposits are covered by a clayey topsoil 0.3-0.4 m thick. The upper part of the till is classified as sandy-clayey till as the clay content is about 12%. This part is heavily weathered, bioturbated and fractured. The underlying clay till consists of an upper oxidized unit down to 4.1 m b.g.s. and below a reduced unit. Borehole information shows that the clay till body contains small channels or basins consisting of meltwater clay and sand (Figure 5.10).

The two of the soil profiles developed in the more or less clay-rich till are classified as Pseudogleytypilessive and one as Degralessive.

The geophysical data are in accordance with the well and outcrop data and the test field can be described as relatively homogenous representing the variability of the till plain. A geological-pedological model for the clay till has been established consisting of the 4 units described below. A conceptual 3-D model is illustrated in Figure 5.10. The meltwater sand and clay layers are not included in the model.

Unit 1: Topsoil. 0–0.4 m b.g.s.

The dark brown topsoil consists of clay and sand (loam/sandy loam) with TOC content between 1.2-1.8% and is an Ap horizon, of sandy loam. The material is noncalcareous. The deposits contain numerous wormholes and root channels. Saturated hydraulic conductivity ranges from 10^{-6}–10^{-3} m/s.

Unit 2: Noncalcareous sandy clay till. 1.1–1.8 m b.g.s.

The yellow brown sandy-clayey till with sand lenses is oxidized and noncalcareous. Numerous burrows and roots are present but decrease in number with increasing depth. Vertical fractures (desiccation cracks) occur through the whole unit. The till is heavily weathered, often with an upper BE horizon showing eluviation of clay and a lower Bvt horizon showing illuviation of clay and Fe and Mn oxides. The saturated hydraulic conductivity of the till is relatively high (compared to till deposits), ranging from 10^{-5}–10^{-3} m/s.

Unit 3: Calcareous clay till. 2–4.2 m b.g.s.

The olive brown and yellow clay till is oxidized and calcareous. Few deep roots penetrate down into this unit. The unit is dominated by a network of fractures: Numerous horizontal to subhorizontal fractures, many small fractures and few large fractures penetrating down to at least 5 m b.g.s., i.e. into Unit 4. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-5} m/s in the upper part (1.5m) and 10^{-9} m/s in the lower part.

Unit 4: Reduced clay till. 4–>18 m b.g.s.

The olive grey reduced clay till with sand lenses and layers of sandy till is calcareous. The till contains few large subhorizontal fractures crossed by few large vertical fractures that can be followed into unit 3. The saturated hydraulic conductivity is 10^{-9} m/s at 5.0 m b.g.s.

Other deposits

Well M6 contains a sequence of glaciofluvial sand, silt and clay 5 m thick that appears to be an infilled erosive channel. There is good reason to believe that glaciofluvial sediments of the same origin can be found under the topographic depression in the eastern part of the field.

Regional aquifer

The regional aquifer is located approx. 15–25 m b.g.s. beneath the clay till. According to local water well data, it consists of meltwater sand and gravel.

5.6 Site 6: Slaeggerup

This site is situated at Slaeggerup northeast of Roskilde on Zealand. It covers an area of 2.17 ha and the width of the buffer zone is >12m towards the northwest and northeast, and >10 m towards the southwest and southeast. All installations are shown in Figure 5.11.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 2.0–13.5 m b.g.s. Based on the groundwater potential in the piezometers in summer 1999 it was concluded that the direction of the shallow groundwater flow is towards the northwest, following the topography. The monitoring wells were thus placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 1.5–5.5 m b.g.s.

The exact age of the drainage system is unknown, but the system is shown on a map of several other drainage systems dated 1963. The systems exit to a ditch, a small stream running 30-40 meters from the eastern boundary of the experimental field. The drainage materials used are traditional clayware – 5.5 cm i.d. laterals and 8 cm and 10 cm i.d. main drains. The field is systematically drained. The spacing between the field drains

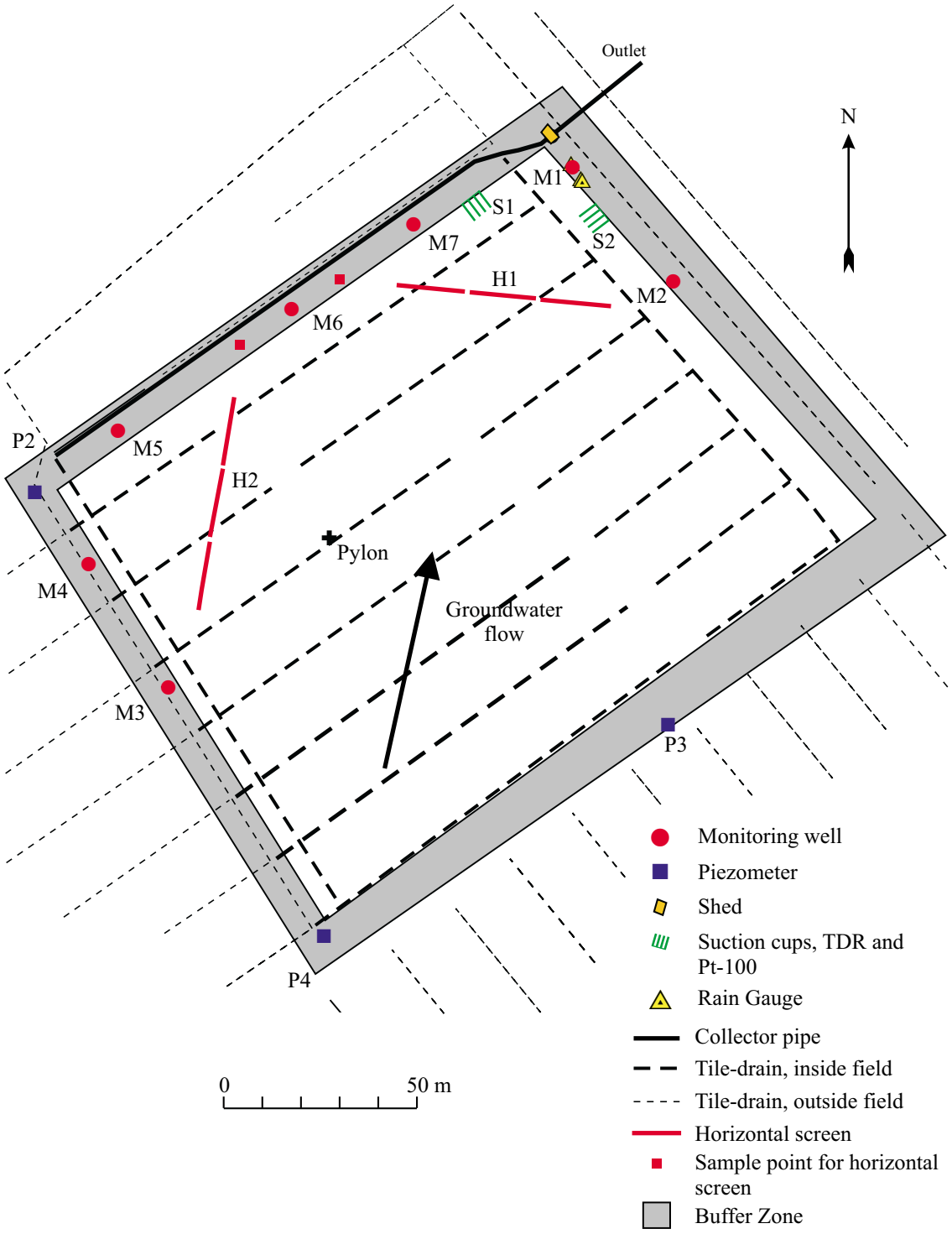


Figure 5.11. Sketch of the Slaeggerup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

(laterals) is 20 m. Since the field has a hilltop on the middle, the field drains are connected to a main drain on either side of the hill.

The monitoring chamber was placed in the northeastern corner of the site. Along the northwestern side of the test field a new PE pipe was installed to connect the two main drains to the monitoring chamber. The main pipe on the southwestern side of the hill has side drains attached from both sides. Eight drains approaching from the west were cut off along the western border of the field by a new main drain laid parallel to the old main drain at a distance of 8 m.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northeastern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Two horizontal monitoring wells were installed at the site each containing three 18 m screens separated by 1.0 m bentonite seals. Well H1, which intersects the northern corner of the field, was installed 3.5 m b.g.s. Well H2 was installed in the western corner. During the process of drilling the well, upward transport of drill water was recorded in two places, one approx. 32 m from the southwestern boundary and 5 m east of the well trajectory and the other approx. 48 m from the southwestern boundary and 9 m east of the well trajectory. When the PVC liner was drawn out of the well, a far larger force than usual was needed, thus indicating the presence of a gravel/boulder bed in the well path with hydraulic contact to the surface in the well path. The screens of well H2 were also installed 3.5 m b.g.s.

Geology

The Slaeggerup site consists of Weichselian glacial deposits. Layers of clay and sand till dominate. Meltwater clay, sand and gravel cover the till in the main part of the area and clay till is only present just below the topsoil in the southeastern corner of the site. A meltwater lacustrine basin on the top of the tills is filled lowermost with a sand-gravel body having an erosive base, and uppermost by a clay veneer that is only missing to the east (Figure 5.12).

The three soil profiles at the site are classified as Brunjordstypilessive.

A geological-pedological model has been established consisting of the six units described below. A conceptual 3-D model is illustrated in Figure 5.12.

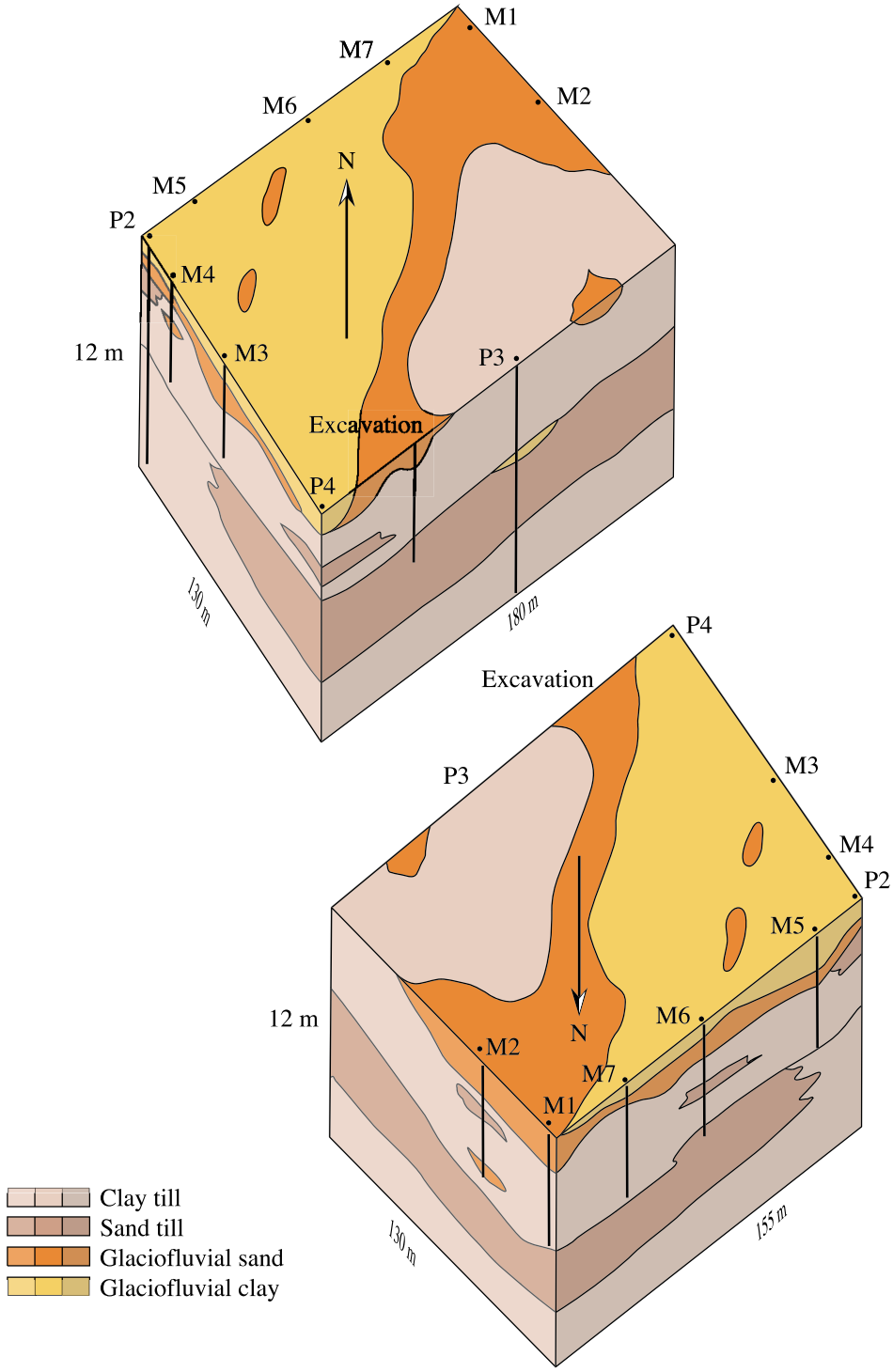


Figure 5.12. A geological model for the Slaeggerup site.

Unit 1: Topsoil. 0–0.3 m b.g.s.

The topsoil is a very dark grey brown clay (loam and sandy loam) containing 1.0-1.7% TOC. It is noncalcareous and contains small roots and burrows. It is an Ap horizon. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-4} m/s.

Unit 2: Meltwater clay. 0.3–1.8 m b.g.s.

The meltwater clay is up to 1.8 m thick and overlies meltwater sand and gravel (unit 3, below) with a gradational boundary. The clay content is 40-55%. In the lower part of unit 2 the clay is commonly sandy and strongly silty whereas it is weakly sandy and silty in the upper part. Small roots, wormholes and vertical desiccation fractures are common. The clay is strongly calcareous except down to approx. 0.7 m b.g.s. where it is noncalcareous. Down to approx. 0.7 m b.g.s. the clay has a yellow brown colour indicating oxidized conditions whereas greyish colours in deeper levels indicate reduced conditions. The soil horizon consists of a Bv or a Bvt with clay illuviation and Fe and Mn oxide nodules. The saturated hydraulic conductivity in the horizons ranges from 10^{-5}- 10^{-4} m/s.

Unit 3: Meltwater sand and gravel. 0.3–2.5 m b.g.s.

The meltwater sand and gravel erosively overlies a clay till (unit 4, below). The deposits are up to 1.8 m thick and consists of gravelly sand with scattered stones overlaid by alternating beds of sand, silt and clay. The sand beds are commonly cross laminated whereas the clay and silt beds are horizontally laminated. Small vertical and horizontal fractures are abundant in the clay and silt beds. The colours of the sediments are generally yellow brown and light yellow brown indicating oxidized conditions. The soil horizon is a Cc with unweathered sediments. The unsaturated hydraulic conductivity ranges from 10^{-7}- 10^{-5} m/s.

Unit 4: Oxidized/reduced clay till.0.3–7 m b.g.s

The calcareous, sandy clay till contains lenses of silt and sand. The clay till is yellow brown and oxidized down to 3.5 m, where it gradually changes into a reduced environment. The clay till has large vertical tectonic fractures and some horizontal-subhorizontal fractures. The $CaCO_3$ content is 20–30% and the TOC content ranges from 0.06-0.6%. The saturated hydraulic conductivity is approx. 10^{-8}-10^{-9}m/s.

Unit 5: Reduced sand and clay till. 4.7–>14 m b.g.s.

The unit is at least 8.5 m thick. It consists of a strongly sandy clay till overlaid by a sand till. Lenses of meltwater sand and clay are common. The till deposits are calcareous and have greyish colours indicating reduced conditions. However, locally the sand till has a light yellowish brown colour in its uppermost part indicating oxidized conditions. The

TOC content in the till deposits ranges from 0.08-0.13%. The saturated hydraulic conductivity is approx. 10^{-8} m/s in the sand till. Based on water well data the till deposits rest directly upon Danian limestone, which forms the regional aquifer at a depth of approx. 15-20 m b.g.s.

5.7 Comparison of the sites

The six sites were selected on the basis of the available information on the pedology and geology of the sites. The key data on the six sites is summarized in Table 5.1.

The total organic carbon (TOC) content of the topsoil at the sites ranges from 1.5 to 2% except at Estrup, where it varies markedly from 1.7 to 7.3% within the test field.

The sandy sites – Tylstrup and Jyndevad – represent two different types of sandy soil. The soil at Jyndevad is coarse-grained sand, with a low content of clay and silt, whereas that at Tylstrup is fine-grained sand with some silt and hence is characterized as a loamy sand. The two soils also different as regards pH. Thus the pH is 4-4.5 at Tylstrup but around 6 at Jyndevad. The saturated hydraulic conductivity is one order of magnitude higher at Jyndevad than at Tylstrup. The upper part of the groundwater is aerobic at both sites.

Of the four sites dominated by clay till, the clay content of the topsoil is lowest at Faardrup (14–15%) and highest at Silstrup and Slaeggerup (18–26%). Soil texture varies considerably within each site, both horizontally and vertically. The clay content is shown versus depth for two to three profiles per site in Figure 5.13. Considerable variation with depth is seen at Estrup and Silstrup. In some parts of the Estrup site the clay content is as much as 50%.

The saturated hydraulic conductivity in the C horizon is approx. 10^{-5}–10^{-6} m/s at the three clay sites (Silstrup, Faardrup and Slaeggerup), but two orders of magnitude lower at Estrup.

At Silstrup, Faardrup and Slaeggerup the calcareous matrix is located 1 m b.g.s., and the reduced matrix occurs 4 to 5 m b.g.s. At Estrup the calcareous matrix is located from 1–4 m b.g.s., and the reduced matrix occurs at more than 5 m b.g.s.

The fracture intensity at 3–4 m b.g.s. is 0–4 fractures m^{-1} at Silstrup and Faardrup compared with the much higher figure of 11–12 fractures m^{-1} at Estrup and Slaeggerup. The

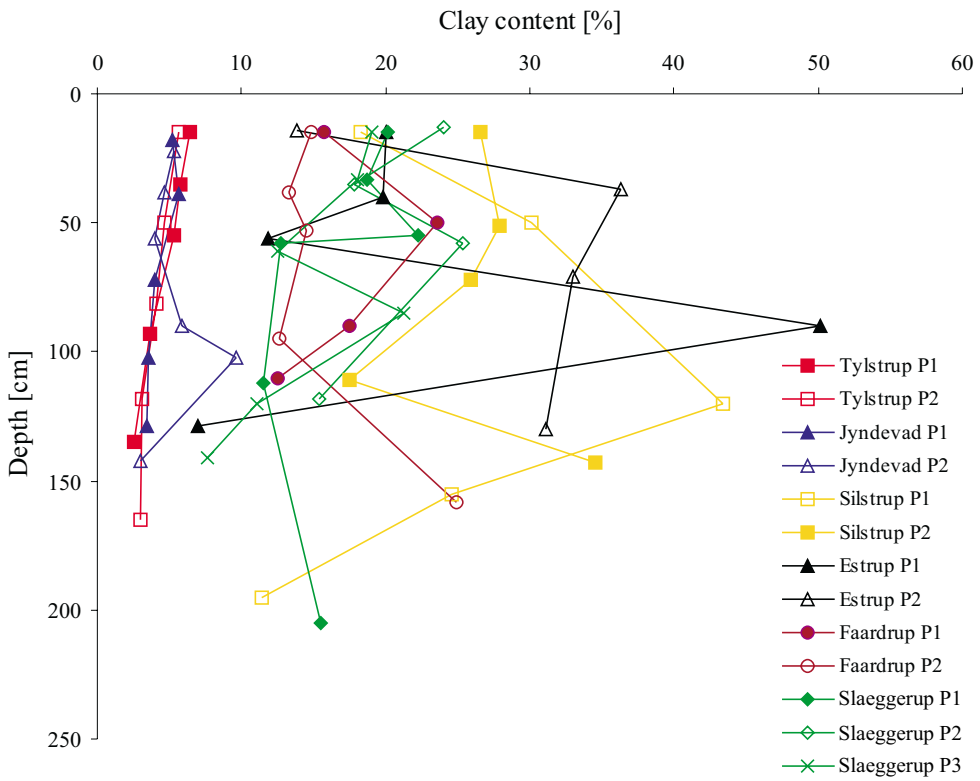


Figure 5.13 Clay content versus depth for two to three profiles per site.

maximum depth of the fractures is 4–5 m b.g.s. at Silstrup and Slaeggerup, but more than 5.5 m b.g.s. at Estrup and 8 m b.g.s. at Faardrup.

Table 5.1. Key data for the six selected sites encompassed by the Danish Pesticide Leaching Assessment Programme.

Name Location	**Tylstrup** Brønderslev	**Jyndevad** Tinglev	**Silstrup** Thisted	**Estrup** Vejen	**Faardrup** Slagelse	**Slaeggerup** Roskilde
Precipitation, mm/y[a]	668	858	866	862	558	585
Potential evaporation, mm/y	741	742			785	
B x L, m	70 x166	135 x 184	91 x 185	120 x 105	160 x 150	165 x 130
Area, ha	1.1	2.4	1.7	1.3	2.3	2.2
Tile drain	no	no	yes	yes	yes	yes
Depth to ground water, m	3-4	1-2				
Deposited by	Saltwater	Meltwater	Glacier	Glacier/ meltwater	Glacier	Glacier
Soil type	Fine sand	Coarse sand	Clayey till	Clayey till	Clayey till	Clayey till
DGU-symbol	YS	TS	ML	ML	ML	ML
Topsoil characteristics						
–USDA-classification	Loamy sand	Sand	Sandy clay loam/sandy loam	Sandy loam	Sandy loam	Loam/sandy loam
– DK-classification	JB2	JB1	JB7	JB5/6	JB5/6	JB7
– Clay content, %	6	5	18–26	10–20	14–15	20–24
– Silt content, %	13	4	27	20–27	25	25–33
– Sand content, %	78	88	8	50–65	57	41–54
– pH	4–4.5	5.6–6.2	6.7–7	6.5–7.8	6.4–6.6	6–6.3
– TOC, %	2.0	1.8	2.2	1.7–7.3	1.4	1.4
Subsoil characteristics						
K_s, in C horiz., m/s[b]	$2.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$3.4 \cdot 10^{-6}$	$8.0 \cdot 10^{-8}$	$7.2 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$
Depth to the calcareous matrix, m b.g.s.	6	5–9	1.3	1–4[c]	1.5	0.7
Depth to the reduced matrix, m b.g.s.	>12	10–12	5	>5[c)]	4.2	3.7
Max. fracture depth in excavation and wells m b.g.s.	–	–	4	>6.5	8	4.7
Fracture intensity 3–4 m depth (fractures m^{-1})	–	–	<1	11	4	11

a) Mean precipitation for the period 1961–90 in the region where each site is located.

b) Determined on large soil samples (6,280 cm^3).

c) Large variation within the field

6. Pesticide selection

The purpose of the Danish Pesticide Leaching Assessment Programme is to assess the risk of leaching among pesticides approved for use in Denmark. In 1998, 72 pesticides were approved for use in the cultivation of plants, not counting fungicides for use on seed corn. Pesticides used in forestry, fruit growing and horticulture are not encompassed by the programme. As it is not possible to include all 72 of these pesticides in the programme, 18 of the 72 pesticides have been selected for study during the first three growing seasons by the Danish Environmental Protection Agency on the basis of expert judgement.

Based on the 18 selected pesticides, four different crop rotations were established involving three crops. Two of the crop rotations were for sandy soils and two for clayey soils (Table 6.1).

Table 6.1. Crop rotations.

	Clayey soil		Sandy soil	
Year	C1	C2	S1	S2
1	Beets	Spring barley 1	Potatoes	Winter rye
2	Spring barley 1	Peas	Spring barley 2	Maize
3	Winter wheat	Winter wheat	Winter rye	Spring barley

To run these four crop rotations it was necessary to add a further six pesticides to the programme to give 24 pesticides in all (Table 6.2 and Figure 6.1). The sorption coefficient K_{oc} and degradation rate DT_{50} given for each pesticide in Table 6.2 are median values where possible or otherwise the midpoint between the minimum and the maximum value.

The reasons for selecting the specific pesticides are explained below.

Bentazone

Bentazone is considered to be highly mobile in the soil under Danish conditions. For this reason the permitted dose was reduced to 300 g active ingredient per ha in 1996. Bentazone was included in the programme to evaluate whether the reduction in the permitted dose is adequate.

Table 6.2. Pesticides encompassed by the Danish Pesticide Leaching Assessment Programme.

Pesticides, common names	Type[1]	Product name in Denmark	Selected by DEPA[2]	GRUMO[3]	Consumption in 1998, tonnes[4]	Treated area in 1998, 1,000 ha[5]	K_{oc} l/kg	DT_{50} days
Bentazone	H	Basagran 480	x	X	69	11	13[6]	52[6]
Bromoxynil	H	Oxitril	x	X	80	200	371[10]	10[8]
Desmedipham	H	Betanal Optima			0.9	1.3	370[7]	49[7]
Dimethoate	I	Dimethoat 400	x	X	37	82	30[7]	16[7]
Ethofumesate	H	Betanal Optima		0	22	54	150[7]	37[7]
Fenpropimorph	F	Tilt Top	x	X	219	292	3,700[7]	67[7]
Flamprop-M-isopropyl	H	Barnon Plus	x		12	20	400[8]	116[9]
Fluazifop-P-butyl	H	Fusilade X-tra	x		6.2	23	30[8]	5[8,9]
Fluroxypyr	H	Starane 180	x		31	222	62[7]	27[7]
Glyphosate	H	Roundup	x	X	618	491	3.400[6]	16[6]
Ioxynil	H	Oxitril	x	0	81	202	278[10]	38[10]
Linuron	H	Afalon			8.0	7.3	233[7]	131[7]
Mancozeb	F	Dithane DG	x	(X)	294	196	>2.000[9]	11[8]
Metamitron	H	Goltix WG	x	X	189	54	207[6]	14[6]
Metribuzin	H	Sencor WG		X	5.3	22	16[8]	83[8]
Metsulfuron-methyl	H	Ally	x		0,8	132.	56[6,8]	45[6]
Pendimethalin	H	Stromp SC	x	X	374	294	725[6]	34[6]
Phenmedipham	H	Betanal Optima			31	43	826[7]	45[7]
Pirimicarb	I	Pirimor G	x	X	5.7	44	821[7]	108[7]
Propiconazole	F	Tilt Top	x	0	41	324	688[6]	96[7]
Pyridate	H	Lentagran			13	15		5[7]
Terbuthylazine	H	Gardoprim 500W	x	X	42	52	220[8]	73[8,9]
Triasulfuron	H	Logran 20 WG	x		0,3	64	9[6]	19[9]
Tribenuron-methyl	H	Express	x		1.5	207	67[8]	7[8,9]

1) H: herbicide, I: insecticide, F: fungicide.
2) Pesticide selected by the Danish Environmental Protection Agency (DEPA).
3) Pesticide included in the Danish National Ground Water Monitoring Programme (GRUMO), X: detected in Danish groundwater, 0: Not detected (GEUS, 2000).
4) Amount used in Denmark in 1998 in the cultivation of plants expressed in 1,000 kg active ingredient (Miljøstyrelsen, 1999).
5) Estimated area treaed in 1998 with the pesticide, 1,000 ha (Miljøstyrelsen, 1999).
6) Lindhardt *et al*., 1998
7) Linders *et al*., 1994
8) Roberts, 1998
9) Tomlin, 1997
10) Miljøstyrelsen

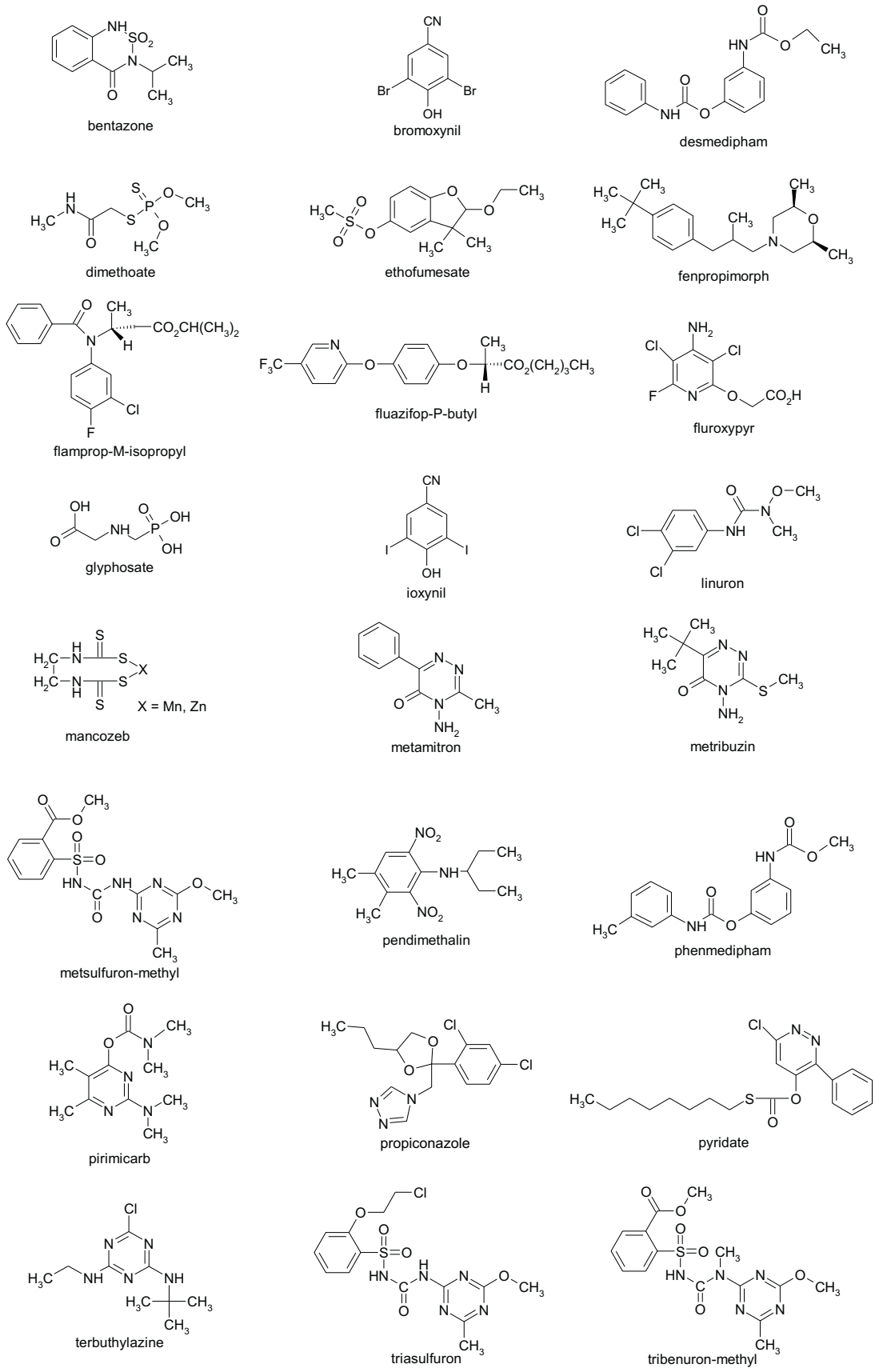


Figure 6.1. Structure of the selected pesticides.

Bromoxynil

Based on the sorption and degradation properties, the pesticide is considered to be immobile. It was selected for inclusion in the programme because it is used on large areas and primarily in autumn, which increases the risk of leaching in Denmark.

Desmedipham

Desmedipham is one of the active ingredients of the product Betanal Optima, which is used to control weeds in beet crops. The compound itself is not expected to leach because of hydrolysis. Knowledge of the fate of the degradation products is insufficient, however.

Dimethoate

Dimethoate was the most used insecticide in Denmark in 1998 in terms of quantity, and the second most used in terms of treated area. The compound was selected for inclusion in the programme because it is considered to be mobile.

Ethofumesate

Ethofumesate is also an active ingredient of the product Betanal Optima, and is considered to be reasonably mobile in soil under Danish conditions.

Fenpropimorph

Fenpropimorph was the second most used fungicide in Denmark in 1998. The compound is expected to sorb strongly to the soil and hence is not considered to be mobile. Some studies indicate that fenpropimorph is degraded in soil by oxidation of the tertiary butyl group to *cis*-4-[3-[4-(2-carboxypropyl)-phenyl]-2-methylpropyl]-2,6-dimethylmorpholine, called "fenpropimorph acid". This degradation product is expected to be mobile in soil under Danish conditions.

Flamprop-M-isopropyl

Flamprop-M-isopropyl is considered to be reasonably mobile in soil under Danish conditions because of its low degradation rate. The major degradation product is expected to be the carboxylic acid flamprop-M, which is also considered to be mobile in soil under Danish conditions.

Fluazifop-P-butyl

Degradation of fluazifop-P-butyl occurs rapidly in soil, the major transformation product being fluazifop-P. Fluazifop-P is considered to be mobile in soil under Danish conditions.

Fluroxypyr

Fluroxypyr is used on relatively large areas in low dose. It was selected for inclusion in the programme because it is considered to be mobile, which is the reason for selecting it to the programme.

Glyphosate

Glyphosate is expected to be immobile based on its sorption and degradation properties. It was selected for inclusion in the programme because of the large amount used. It is the most used pesticide in crop production in Denmark in terms of both quantity and applied area.

Ioxynil

Based on the sorption and degradation properties ioxynil is considered to be relatively immobile. It was selected for inclusion in the programme because it is used on large areas and primarily in autumn, which increases the risk of leaching in Denmark.

Linuron

Linuron was included in the programme because it is used for weed control in potatoes. Consumption in Denmark only amounts to a few thousand kg per year. Based on its properties and low degradation rate it is expected to leach out of the root zone.

Mancozeb

Mancozeb is a dithiocarbamate that is readily hydrolysed in neutral and alkaline soil and further degraded into ETU (ethylenethiourea). ETU is highly mobile. It is uncertain whether ETU is persistent in subsoil. The dose of mancozeb used in potatoes is extremely high compared to other pesticides, as much as 20 kg per ha per year being used in some years. Mancozeb was included in the programme because of the high dosage and uncertainty as to whether ETU is persistent in subsoil.

Metamitron

Metamitron was the fourth most used herbicide in Denmark in 1998 in terms of quantity used. It is applied in relatively high doses and is considered to have "medium" mobility in soil. Metamitron is very rapidly degraded on the soil surface and in water by photodecomposition, resulting in desamination to desamino-metamitron (3-methyl-6-phenyl-1,2,4-triazin-5-one).

Metribuzin

Metribuzin is used in relatively small quantities in Denmark. Based on its properties it is expected to leach out of the root zone. Metribuzin is degraded by desamination to form

desamino-metribuzin (6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-5-one) or diketo-metribuzin (4-Amino-6-tert-butyl-4,5-dihydro-1,2,4-triazin-3,5-dione). This are further transformed to desamino-diketo-metribuzin (6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-3,5-dione). All of these degradation products are expected to be mobile.

Metsulfuron-methyl

Even though the total amount used in Denmark is low, the area treated with metsulfuron-methyl is relatively high because the compound, like the other sulfonylureas, is applied in low doses (10–20 g per ha). Metsulfuron-methyl degrades in soil by cleavage of the sulfonylurea linkage to yield methyl 2-(aminosulfonyl)benzoate and 4-methoxy-6-methyl-2-amino-1,3,5-triazine as the major degradation products. The latter is called triaziamin. Laboratory tests indicate that triazinamin can be persistent in soil. It is for this reason that metsulfuron-methyl was included in the programme.

Pendimethalin

Pendimethalin sorbs strongly to soil, for which reason it is not considered to be mobile. It was included in the programme because of its extensive use. It was the third most used herbicide in 1998 in terms of both quantity used and treated area.

Phenmedipham

Phenmedipham is also an active ingredient of the product Betanal Optima. The compound itself is not expected to leach because of relatively rapid hydrolysis. In alkaline soils, hydrolytic degradation of phenmedipham results in MHPC (*N*-(3hydroxyphenyl)carbamate) as an intermediate and 3-aminophenol as the end product. Knowledge of the fate of these degradation products is insufficient.

Pirimicarb

Pirimicarb was the second most used insecticide in 1998 in Denmark. Pirimicarb is expected to be moderately mobile, but the documentation is considered to be incomplete. When slow degradation occurs in soil, the major degradation product is dimethylpirimicarb (2-(methylamino)-5,6-dimethyl-4-pyrimidinyl-dimethylcarbamate).

Propiconazole

Propiconazole was the most used fungicide based on treated area in 1998. The compound is considered to be moderately mobile. The degradation product 1,2,4-triazole is mobile.

Pyridate

Pyridate was selected for the programme because of uncertainty of the mobility of the principal degradation product, 3-phenyl-4-hydroxy-6-chloropyridazine.

Terbuthylazine

Based on the sorption and degradation properties of terbuthylazine it is expected to be mobile. Lysimeter studies indicate leaching of a number of degradation products.

Triasulfuron

See metsulfuron-methyl.

Tribenuron-methyl

Tribenuron-methyl is included in the programme for the same reasons as metsulfuron-methyl and triasulfuron. Tribenuron-methyl is the most used sulfonylurea. Tribenuron-methyl degrades rapidly in acidic soil by hydrolysis and forms triazine-methyl (4-methoxy-6-methyl-2-methylamino-1,3,5-triazine).

References

Andersen, S. & Sjørrring, S. (1992): Det nordlige Jylland, Geologisk set, En beskrivelse af områder af national geologisk interesse – Geografforlaget, Miljøministeriet, Skov- og Naturstyrelsen.

Bos, M.G. (1976): Discharge Measurement Structures. International Institute for Land Reclamation and Improvement, Publication no. 20. Wageningen, Netherlands

DS 405.9 (1978): Testing of sand, gravel and stone materials, sieve analysis. Dansk Standardiseringsråd

Duchafour, P. (1979): Pedology – George Allen & Unwin, London.

Durlesser, H. (1999): Bestimmung der Variation bodenphysikalischer Parameter in Raum und Zeit mit elektromagnetischen Induktionsverfahren – FAM-Bericht, Technische Universität München, Shaker Verlag.

Ehlers, J. (1978): Fine Gravel Analysis after the Dutch method as tested out on Ristinge Klint, Denmark. Bulletin Geological Society of Denmark, 27, 157 – 165.

Ernstsen, V. (1998): Clay minerals of clayey subsoils of Weichselian Age in the Zealand –Funen area, Denmark. Bulletin of the geological Society of Denmark, 45, 39 – 51.

Ernstsen, V., Binnerup, S.J., & Sørensen, J. (1998): Reduction of Nitrate in Clayey Subsoils Controled by Geochemical and Microbial Barriers. Geomicrobiology, 15, 195-207.

Eyles, N. (1983): Glacial Geology for Engineers and Earth Scientists, Pergamon, New York.

Eyles, N. (1984): Glacial Geology - University of Toronto, Canada. Pergamon Press, Toronto.

Fetter, C.W. (1999): Contaminant hydrogeology. Prentice Hall. New York.

Flury, M. (1996): Experimental evidence of transport of pesticides through field soils – a review. Journal of Environmental Quality, 25, 25-45.

Frich, P. Rosenørn, S., Madsen, H. & Jensen, J.J. (1997): Observed precipitation in Denmark 1961-90. DMI, Techical report 97-8

GEUS (2000): Grundvandsovervågning 2000. Danmarks og Grønlands Geologiske Undersøgelse, København, Danmark.

Greve, M. Helweg, A., Yli-Halla, M.. Eklo, O.M., Nyborg, Å.A., Solbakken, E., Øborn, I., & Stenstrøm J.(1998): Nordic Reference Soils - In: E. Tiberg (Ed.) 1998: Nordic Reference Soils – Nordic Council of Ministers, TemaNord 1998: 537, Environment.

Gry, H. (1940): De istektoniske forhold i moleområder. Med bemærkninger om vore dislocerede klinters dannelse og om den negative askeserie. Medd. Dansk Geol. Foren., 9.

Hansen B. & Sørensen, N. K. (1996): Metodereferencer til Centrallaboratoriets analyser – Centrallaboratoriet, intern rapport fra Statens Husdyrbrugsforsøg Nr. 96.

Hansen, J.M. & Håkansson, E. (1980): Thisted strukturen et neotektonisk skoleeksempel. Dansk geol. Foren. Årsskrift for 1979.

Hansen, L. (1976): Soil types at the Danish Experimental Stations – Særtryk af Tidskrift for Planteavl 80, 742-758.

Hansen, S. (1989): Geologisk kort over Danmark. Geological map of Denmark. 1:100 000. Kortbladet/Mapsheet Tinglev. Jordarts kort & Glacial-morfologiske kort/Soil map & Glacial morphological map. Danmarks Geologiske Undersøgelse, Kortserie 9 & 10.

Harremoës, P., Moust Jacobsen, H. & Krebs Ovesen, N., (1984): Lærebog i Geoteknik, 5. udg. Polyteknisk Forlag. Copenhagen.

Heidmann, T. (1989): Startkarakterisering af arealer til systemforskning IV. Resultater fra arealet ved Jyndevad – Statens Planteavlsforsøg, Beretning nr. S 2021.

Henriksen, H.J., Christiansen Barlebo, H., Ernstsen, V., Hansen, M., Harrar, B., Jakobsen P. R., Klint, K. E. & Troldborg, L (2000): Anvendelse af regionale pesticidmodeller som prognoseværktøj Pesticider og Grundvand - Temanummer fra Grundvandsgruppen. Miljøforskning 42, April 2000, Det Strategiske Miljøforskningsprogram, 40-42.

Hermansen, B. & Jacobsen, P.R. (1998): Danmarks digitale Jordartskort 1:25.000. Version 1.0 GEUS.

Houmark-Nielsen, M. (1987): Pleistocene stratigraphy and glacial history of the central part of Denmark. Bull. geol. Soc. Denmark, 36, 1-189.

Iversen, B.V., Schjønning, P., Poulsen, T. G. & Moldrup, P. (2001): In situ, on-site and laboratory measurements of soil air permeability: Boundary conditions and measurement scale. Soil Science, 166, 97-106.

Jacobsen, E.M.(1984): En råstofgeologisk kortlægning omkring Roskilde. Dansk geol. Foren., Årskrift for 1984, 65-78.

Jacobsen, O.H. (1989): Unsaturated hydraulic conductivity for some Danish soils, metods and characterization of soils – Statens Planteavlsforsøg, Afdeling for Kulturteknik, Jyndevad, Beretning nr. S 2030.

Jessen, K. & Milthers,V. (1928): Stratigraphical and Paleontological Studies of Interglacial Freshwater-deposits in Jutland and Northwest Germany. D.G.U. II Række, nr 48, 1-379 + Atlas.

Klint K.E.S. & Pedersen, S.A.S. (1995): The Hanklit Glaciotectonic Thrust Fault Complex, Mors, Denmark. Danmarks Geologiske Undersøgelse, DGU serie A, 35, 1-30.

Klint, K.E.S. & Gravesen, P. (1999): Fractures and Biopores in Weichselian Clay Till Aquitards at Flakkebjerg, Denmark. Nordic Hydrology, 30, 267-284.

Klute, A. & Dirksen, C. (1986): Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd edition, Amer. Soc. Agron., Madison, WI, 687-734.

Klute, A. (1986): Water retention: Laboratory methods. In: Klute, A. (ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd edition, Amer. Soc. Agron., Madison, WI, 635-656.

Langohr, R. (1993): Types of Tree Windthrow, their impact on the Environment and their importance for the understanding of Archeological Excavating Data – Helinium, XXXIII/1, 36-49.

Larsen, G., Frederiksen, J, Villumsen, A., Fredericia; J., Gravesen, P., Foged, N., Knudsen, B. & Baumann, J. (1995): Vejledning i Ingeniøgeologisk prøvebeskrivelse. Danish Geotechnical Society Bull. 1, rev. 1.

Linders, J.B.H.J., Jansma, J.W., Mensink, B.J.W.G. & Otermann, K (1994): Pesticides: Benefaction or pandora's box ? National institute of public health and environmental protection, The Netherlands. Report no. 679101014.

Lindhardt, B., Brüsch, W., Fomsgaard, I. S. & Bossi, R (1998): Vurdering af pesticiders udvaskelighed på grundlag af tilgængelige data for sorption og nedbrydning. 15th Danish Plant Protection Conference, 1998, 43-52.

Madsen, H.B. (1983): Himmerlands jordbundsforhold – Landbrugsministeriet, Arealdata-kontoret, Vejle.

Madsen, H.B. (1988): Geografiske forskelle i landbrugsjordens reaktionstal – Agrologisk Tidsskrift 12/88.

Madsen, H. B. & Jensen, W.H. (1983): Et pedologisk jordbundklassifikationssystem baseret på danske jorde, manual – Landbrugsministeriet, Arealdatakontoret, Vejle.

Madsen, H.B. & Jensen, N.H. (1985): Jordprofilundersøgelsen – Landbrugsministeriet, Arealdatakontoret Vejle.

Madsen, H.B. & Jensen, N. (1988): Vejledning til beskrivelse af jordbundsprofiler – Landbrugsministeriet, Arealdatakontoret, Vejle..

Mertz, E.L. (1924): Oversigt over de sen- og postglaciale niveauforandringer i Danmark. Danmarks Geologiske Undersøgelse, II. Rk., 41.

Miljøstyrelsen (1999): Bekæmpelsesmiddelstatistik 1998. Orientering fra Miljøstyrelsen nr. 5 1999. København, Danmark.

Nehmdahl, H. (2000): Kortlægning af jordbundsvariation – geoelektriske målinger med EM38. GeologiskNyt 2/00, 18-19.

Nielsen, J.D. & Møberg, J.P. (1985): Klassificering af jordprofiler fra forsøgsstationer i Danmark – Tidsskr. for Planteavl 89, 157-167.

Pedersen, S.A.S. (1989): Glacitectonite: Brecciated sediments and cataclastic sedimentary rocks formed subglacially. In Genetic Classification of Glacigenic Deposits,(Goldthwait and Matsch (eds.)) Balkema, Rotterdam.

Rasmussen, H.W. (1968): Danmarks geologi – Gjellerups liniebøger, Gjellerup.

Rhoades, J.D. & Corwin, D.L. (1981): Determining Soil Electrical Conductivity-Depth Relations Using an Inductive Electromagnetic Soil Conductivity Meter – Soil Sci. Soc. Am. J., 45, 255-260.

Roberts, T (1998): Metabolic pathways of agrochemicals. The Royal Society of chemistry, Cambrige, UK.

Rosenbom, A.E., Klint, K.E.S. & Fredericia, J. (2000): Pore-to-core scale-up studies of the transport properties of organic pollutants with natural attenuation. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2000/79. Copenhagen: GEUS.

Skov- og Naturstyrelsen (1987): Geofysik og råstofkortlægning. Råstofkontorets kortlægningsserie 5, pp 7-207. Skov- og Naturstyrelsen.

Soil Survey Staff (1999): Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Agriculture Handbook Number 436. Second Edition, United States Department of Agriculture, New York.

Stamp, L.D. (1966): A glossary of geographical terms. New York Wiley.

Statens Planteavlsforsøg (1996): Geographic data at the Department of Landuse – Ministry of Agriculture and Fisheries, SP report, No. 6.

Tabatabai, M.A. & Bremner, J.M., (1970): Use of Leco Automatic 70-Record Carbon Analyser for total carbon analysis of soils. Soil Sci. Soc. Amer. Proc., 34, 608-610.

Tomlin, C.D.S. (1997): The pesticide manual. British Crop Protection Council, Surrey, UK.

US-EPA (1998): Guidance for prospective ground water monitoring studies. Environmental fate and effects division, Office of Pesticide Programs. U.S. Environmental Protection Agency.

van den Elsen, E., Stolte, J. & Veerman, G. (1999): Three automated laboratory systems for determining the hydraulic properties of soils. In: Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media, Part 1. M. Th. Van Genuchten, F. J. Leij, and L. Wu (Eds.). Riverside, CA. U.S. Salinity Laboratory, USDA, ARS. Department of Environmental Sciences, University of California. pp. 329-340.

Washburn, A.L. (1979): Geocryology, A survey of periglacial processes and environments 2nd ed. Edward Arnold (Publishers) Ltd.

Site Characterization and Monitoring Design

Annexe 1.

Site 1: Tylstrup

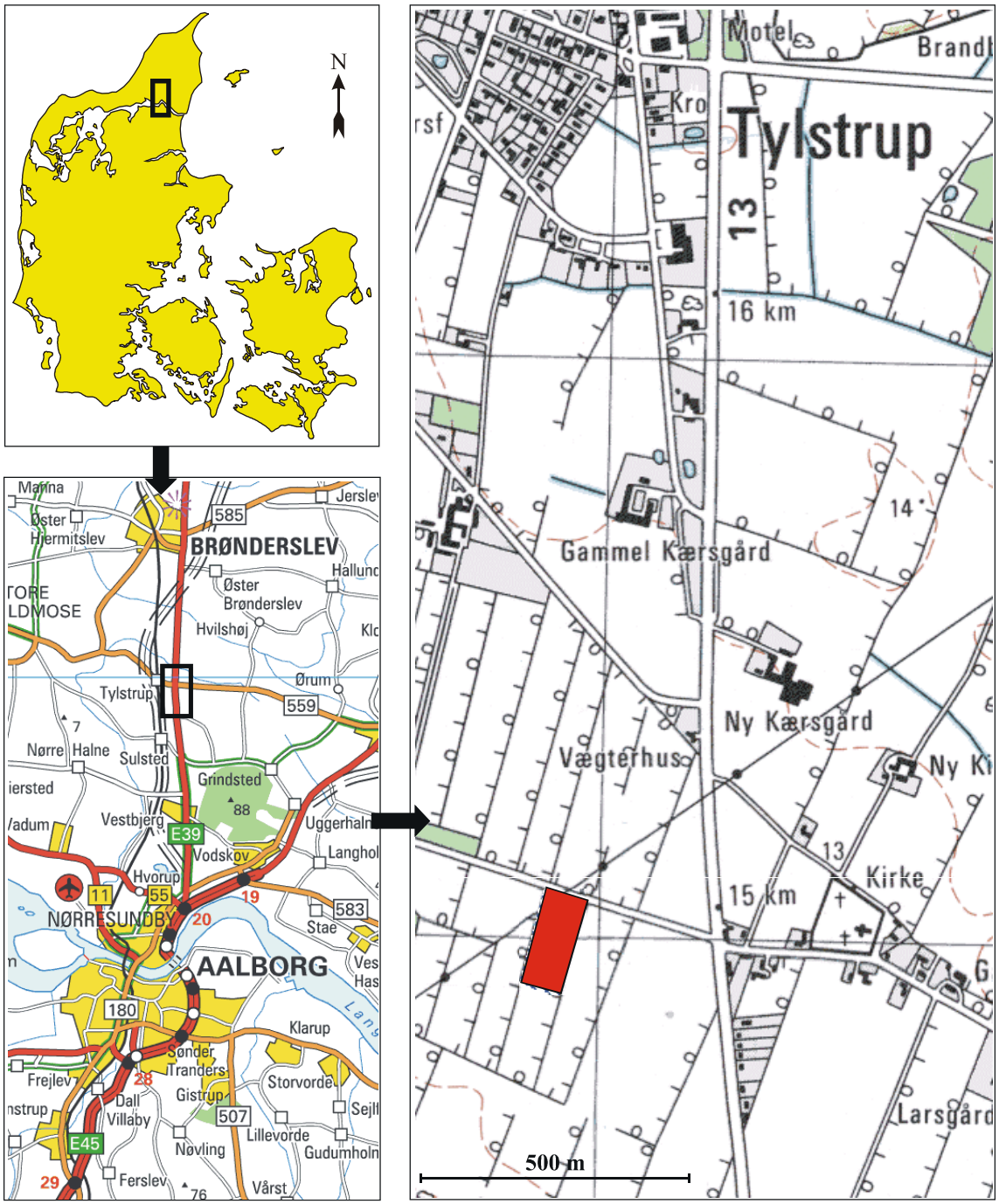


Figure A1.1. Location of the test field.

A1.1 Location, ownership and earlier cultivation and use

The test field is located at Tylstrup in Vendsyssel, northern Jutland (Figure A1.1). It is owned by the Danish Institute of Agricultural Sciences (DIAS) which has an experimental station 1 km northwest of the area. The site characteristics are summarized in Table A1.1.

Table A1.1. Site characteristics.

Length and width of the test field	166 m x 70 m
Total area of the site, incl. buffer zone	3.3 ha
Area of the test field	1.08 ha
Municipality	Aalborg
County	Nordjylland
Land registry no.	3a, Tylstrup, Ajstrup
Ownership	DIAS, Tylstrup Experimental Station Forsøgsvej 30 9382 Tylstrup

Earlier use

As is apparent from Figure A1.2, the field has been farmland at least since 1942. Since 1991 the site has been farmed as one whole field. Previously it consisted of four equal parcels , Kj1..Kj4 (Figure A1.3). Cultivation and pesticide application history of the field during the 10 years prior to the present investigations are summarized in Appendix A1.1.

A1.2 Technical installations

All installations at Tylstrup are numbered according to the code described in Section 3. In the present description, however, the site-specific code for Tylstrup, i.e. “1”, has been omitted for the sake of simplicity. The locations of all the installations were selected on the basis of the groundwater flow pattern (Figure A1.3) and are shown in Figure A1.4.

Buffer zone

The width of the buffer zone at Tylstrup is approx. 2 m along the northeastern border, 3 m along the southeastern border, 22 m along the southwestern border and 4.5 m along the northwestern border (Figure A1.4). A windbreak runs along the southeastern and the northwestern borders.

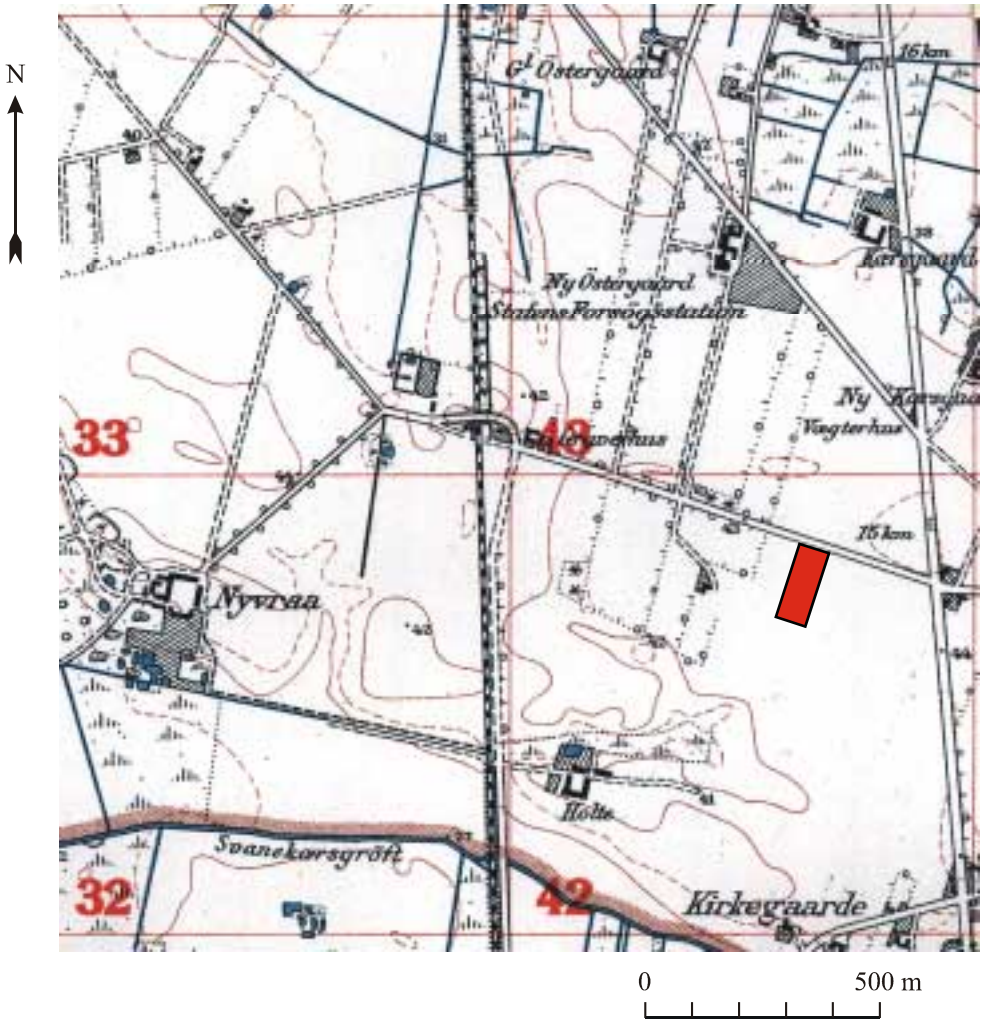


Figure A1.2. Topographic map 1:20.000 from 1942. The test field is marked as a red square.

Suction cups, TDR and Pt-100 sensors

The suction cups, TDR and Pt-100 sensors at Tylstrup were installed in excavations S1 and S2 shown in Figure A1.4. The instruments were installed as described in Section 3.3 except that installation of the suction cups deviated as follows:

- The suction cups installed 1 m b.g.s. were placed at a horizontal distance of 1 m from the edge of the field rather than 2 m as described in Section 3.3.
- The suction cups installed 2 m b.g.s. were placed at a horizontal distance of 1.5 m from the edge of the field rather than 2.5 m as described in Section 3.3.
- The installation holes were drilled manually with a hand auger.
- A ¾" garden hose was sliced open and used as cable duct.

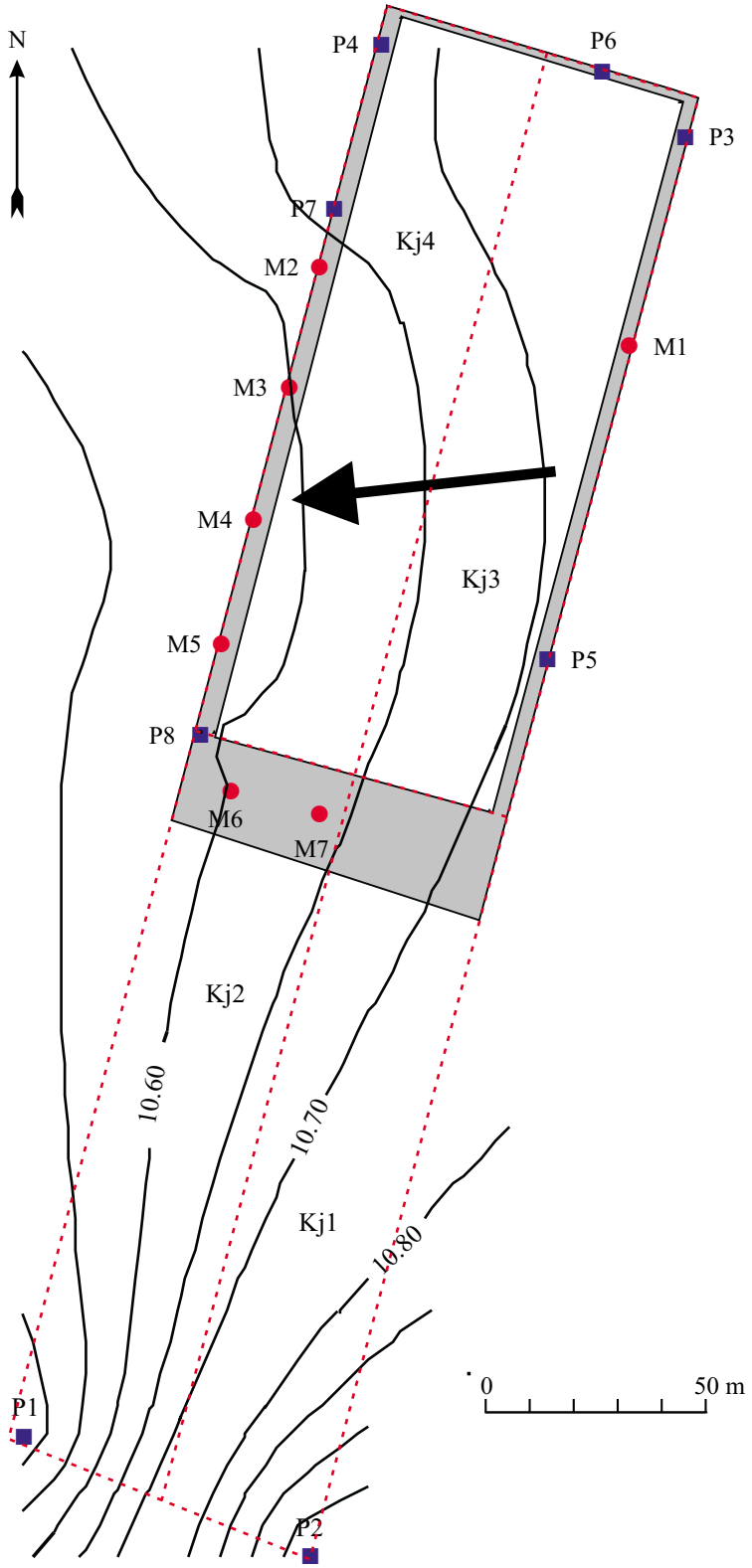


Figure A1.3. Potential head (m a.s.l.) at the site measured in November 1999 and the direction of the ground water flow. The red broken line indicates the border of the parcels before 1991.

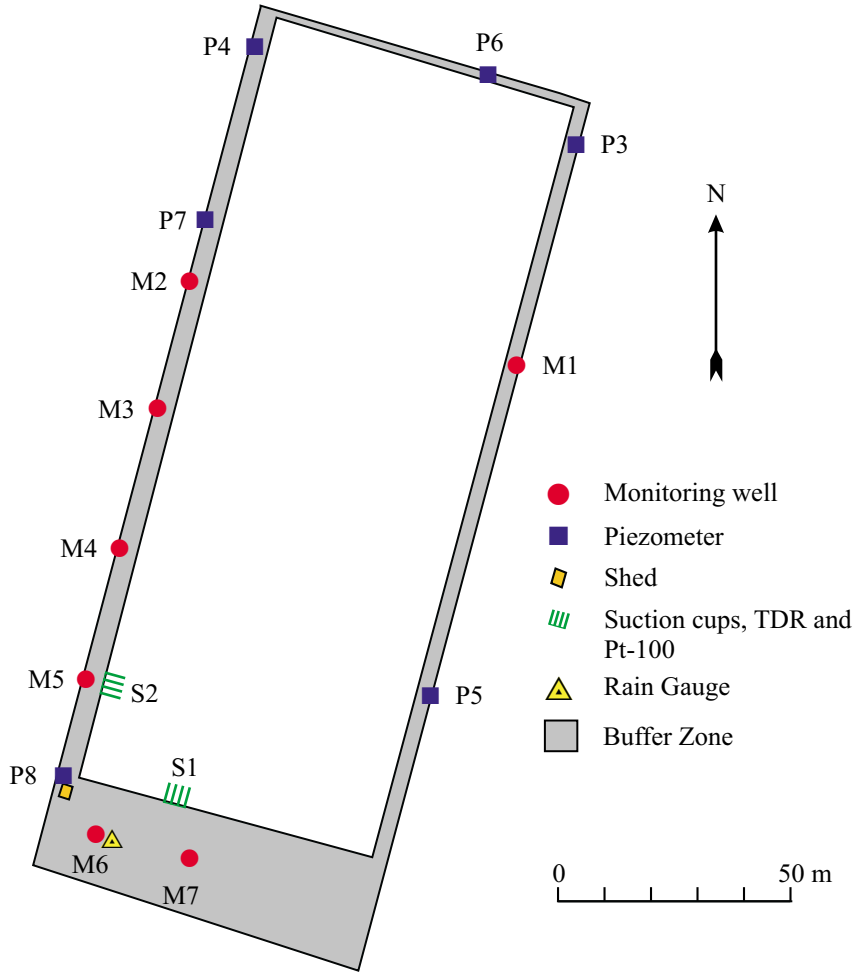


Figure A1.4. Sketch of the field showing the test and buffer zones and location of installations.

Wells

Piezometers

Piezometers P1-P4 consisted of ¾" electroplated pipes hammered into the ground. The remaining piezometers were drilled with a 6" (152 mm) solid stem auger down to around 3.5 m b.g.s. At deeper levels, below the groundwater table, the wells were drilled as cased wells using a bailer.

Piezometers P1–P4 were installed at the end of January 1999 in order to estimate the flow direction of the groundwater. Piezometers P5–P8 were drilled on February 15–18 1999. The piezometers were placed at various depths in accordance with Table A1.2.

Table A1.2. Depth of the piezometer screens.

Well no.	DGU no.	Upper screen m b.g.s.	Middle screen m b.g.s.	Lower screen m b.g.s.
P1	–	6.3 –6.4	–	–
P2	–	5.8–5.9	–	–
P3	–	6.1–6.2	–	–
P4	–	4.6–4.7	–	–
P5	16. 795	4.6–5.1	8.3–8.8	11.1 –11.6
P6	16. 798	5.3–5.8	8.7–9.2	11.6–12.1
P7	16. 797	4.4–4.9	8.4–8.9	11.4–11.9
P8	16. 796	4.6–5.1	8.2–8.7	11.1–11.6

Vertical monitoring wells

A total of seven monitoring well clusters (M1–M7) each consisting of four individual wells were installed at Tylstrup in March 15–19 1999. The technical specifications are described in Section 3.1.2.

The top of the upper screen from each monitoring cluster was placed above the highest seasonal water table. The screens of one monitoring cluster were not necessary placed at the same depths as the screens of other monitoring clusters (Table A1.3) due to minor variations in the topography within the buffer zone resulting in differences in the distances between the ground surface and the groundwater table.

Table A1.3. Depths of the monitoring well screens.

Monitoring well cluster	Screen Mx.1 m b.g.s.	Screen Mx.2 m b.g.s.	Screen Mx.3 m b.g.s.	Screen Mx.4 m b.g.s.
M1	2.1–3.1	3.1–4.1	4.0–5.0	4.9–5.9
M2	2.4–3.4	3.3–4.3	4.3–5.3	5.1–6.1
M3	2.3–3.3	3.2–4.2	4.1–5.1	5.1–6.1
M4	2.4–3.4	3.5–4.5	4.4–5.4	5.2–6.2
M5	2.3–3.3	3.2–4.2	4.1–5.1	5.0–6.0
M6	2.2–3.2	3.2–4.2	4.0–5.0	4.8–5.8
M7	2.5–3.5	3.5–4.5	4.5–5.5	5.4–6.4

A1.3 Geology

Regional geology

In Vendsyssel, northern Denmark, the Quaternary deposits are mainly 125–200 m thick and rest on Cretaceous chalk. Three landscapes are represented: glacial highland, marine plain of the Yoldia Sea and marine plain of the lower-lying Lithorina Sea (Andersen and Sjørring, 1992). The field site is located on the marine plain of the Yoldia Sea. The glacial highland was formed in the Weichselian by glacial movement and a stationary period during deglaciation. The marine plains are the result of interplay between isostatic uplift and eustatic sea level rise caused by melting of the local and global ice-caps, respectively.

The Yoldia Sea flooded northern Jutland approx. 15,000 years BP during deglaciation of the Weichselian Scandinavian ice sheet. The sea was limited towards the north and east by ice caps and towards the south by a land area consisting of large meltwater plains. Towards the west it was connected to the North Sea (Andersen and Sjørring, 1992). Hills and ranges of hills produced by glaciers prior to the area becoming flooded formed islands in the sea. The marine deposits of the Yoldia Sea consist of Lower Saxicava sand overlain by Younger Yoldia clay and Upper Saxicava sand. The Lower Saxicava sand is rarely more than a few meters thick and is only found exposed at a few localities. It consists of grey, clayey sand with shells and is horizontally bedded. The Younger Yoldia clay is up to 30 m thick, but the thickness varies considerably. In some places the clay is sandy and contains gravel. The Upper Saxicava sand is up to 30 m thick. The sand is mostly fine-grained and clayey in the lower part and furthest away from the glacial hills. Along the hill slopes, in contrast, it commonly contains gravel or turns into beach gravel. Burrows made by bivalves are common whereas shells only occur locally.

About 13,000 years BP the rate of isostatic uplift overwhelmed the eustatic sea level rise and the Yoldia Sea consequently withdrew from Vendsyssel. A period of riverine erosion into the glacial and marine Late-Glacial deposits followed.

The marine plain of the Lithorina Sea and its deposits were formed approx. 8,000–7,500 years BP when Vendsyssel was again flooded as a result of enhanced eustatic sea level rise due to melting of the ice sheets on the North American continent. The Lithorina Sea deposits vary markedly and consist of sand, gravel, clay and marine gyttja. The sea subsequently withdrew as a result of the renewed dominance of isostatic uplift and the coast gradually moved into its present position.

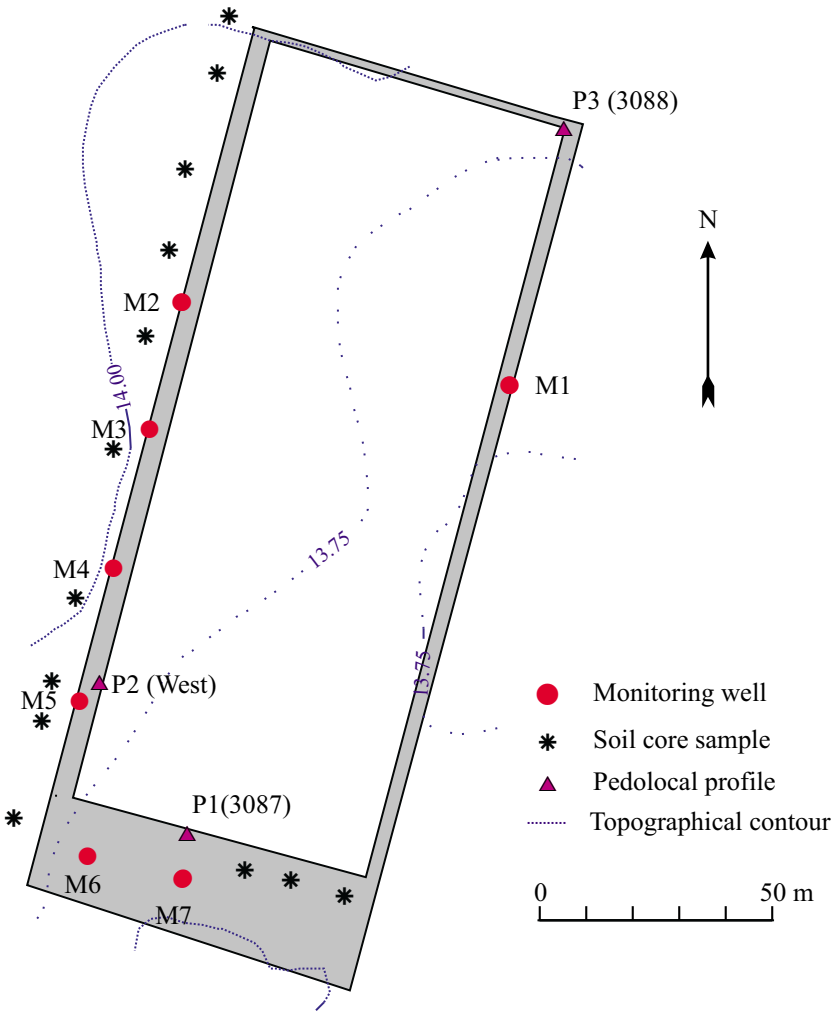


Figure A1.5. Topography at the site and location of soil cores, test pit and monitoring wells.

As a result of continued isostatic uplift the sediments of the Yoldia and Lithorina Seas presently occur as raised seafloor deposits. Because the uplift has been greatest towards the northeast, the position of shorelines from both seas falls from the northeast towards the southwest (Mertz,1924).

Well logs in the Tylstrup region shows that the Late-Glacial marine sediments are up to 20 m thick and rest on an uneven surface of glacial deposits dominated by meltwater sand. The marine sediments are thickest in areas where depressions occur in the underlying glacial deposits. The depressions are filled with clay and silt (Younger Yoldia clay) overlain by sand (Upper Saxicava sand). Outside the depressions the Late-Glacial sediments mainly consist of sand (Upper Saxicava sand) which becomes thinner towards the glacial highland.

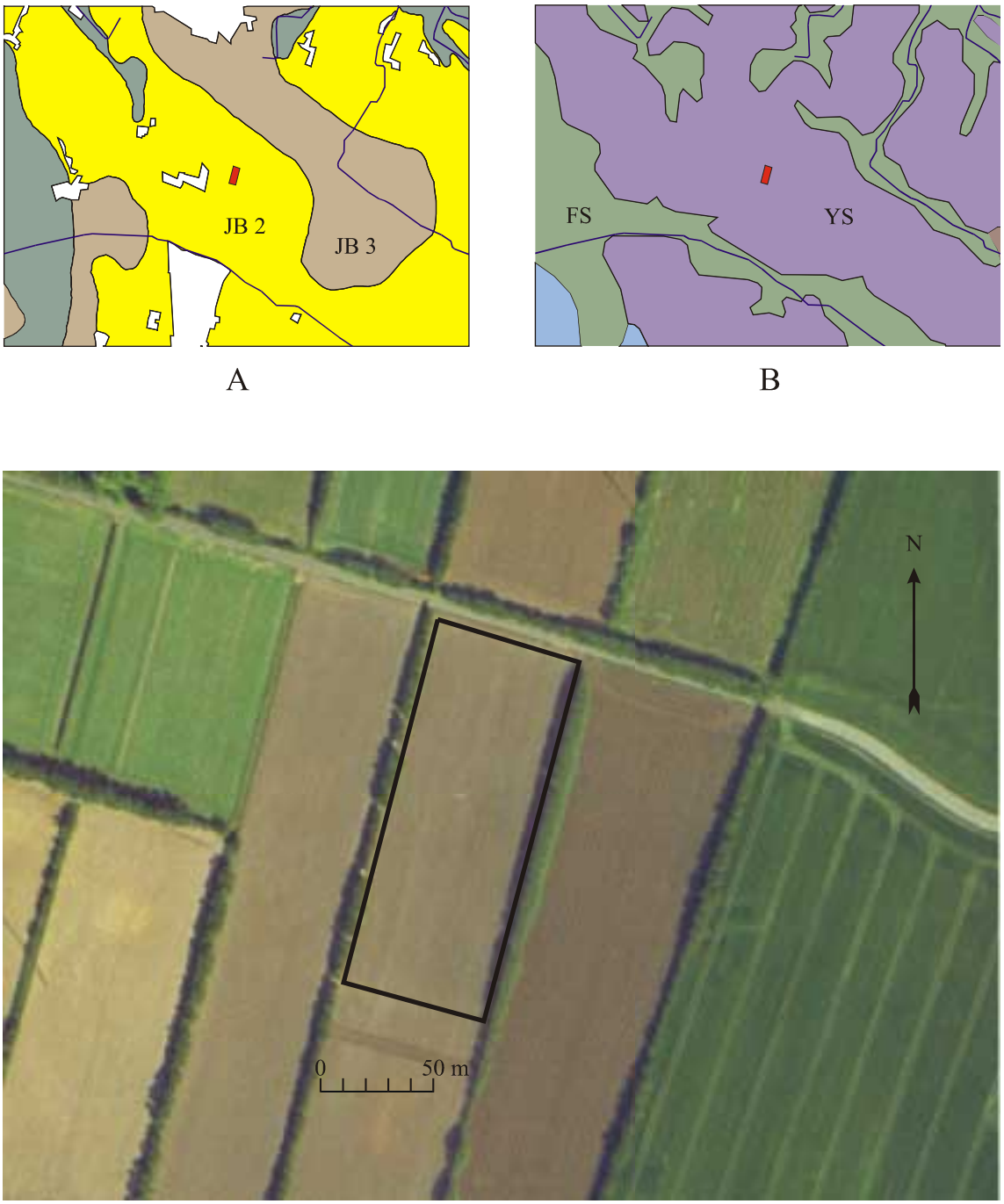


Figure A1.6. Location of the test field (red square) superimposed on: A) The soil type map. JB 2: Fine Sandy Soil, JB 3: Loamy Sandy Soil. B) Map of Quaternary sediments in Denmark, YS: Late-Glacial saltwater sand, FS: Post-Glacial freshwater sand. C) An aerial orthophotograph (Kampsax Geoplan, DDO1999).

Geomorphology

In the Tylstrup region, the marine plain of the Yoldia Sea lies approx. 14 m a.s.l. (Figure A1.5). Glacial deposits occur in a topographically higher level towards the northeast and southeast. These formed land areas in the Late-Glacial period. In the other directions, the lower-lying marine plain of the Lithorina Sea, which is commonly covered by Post-Glacial peat deposits, limits the marine plain.

The test field is shown superimposed on the map of Quaternary sediments in Denmark (Hermansen and Jacobsen, 1998), the Soil Classification map and a 1999 aerial orthophotograph in Figure A1.6. As can be seen, the field lies on a soil type consisting of fine sandy soil (JB2). This is in agreement with the map of the Quaternary deposits of Denmark, which places the field in an area of Late-Glacial saltwater sand (YS). Based on the orthophotograph the field appears to be homogenous.

Geology of the monitoring wells and piezometer wells

The geological layers were described down to 12 m b.g.s. and 6 m b.g.s. during drilling of piezometers P5–P8 and monitoring wells M1–M7, respectively. Piezometers P1–P4 consisted of ¾" pipes hammered into the ground and no description of the penetrated layers is therefore available for these. The location of the wells is shown in Figure A1.3.

In the wells situated in the southern part of the test field the sediment consists almost entirely of sand, whereas beds and clasts of silt and clay are abundant within the uppermost 5 m in some of the remaining wells situated further to the north (wells M1–2, M5, M6 and P7 in Figures A1.3 and A1.7). Gravel occurs in the sand locally. It is difficult to see sedimentary structures in the drilled material but horizontal bedding can be recognized locally. The depth to which carbonate is dissolved varies from approx. 5.3–8.5 m b.g.s.

The colour generally changes with increasing depth from very dark greyish brown in the topsoil layer to yellowish brown, brownish yellow or dark olive brown below the topsoil layer and finally to light yellowish brown in the deepest parts. This shows that conditions are oxic down to at least 12 m b.g.s.

Geology of the test pit and ditch

Sediments and especially the pedology were studied in three excavations up to 1.5 m deep (Figure A1.5) and in a ditch up to 1.4 m deep and approx. 160 m long situated along the eastern side of the test field. The ditch was dug for a telephone cable from the road to the shed situated in the southwestern corner of the test field (Figure A1.4). The

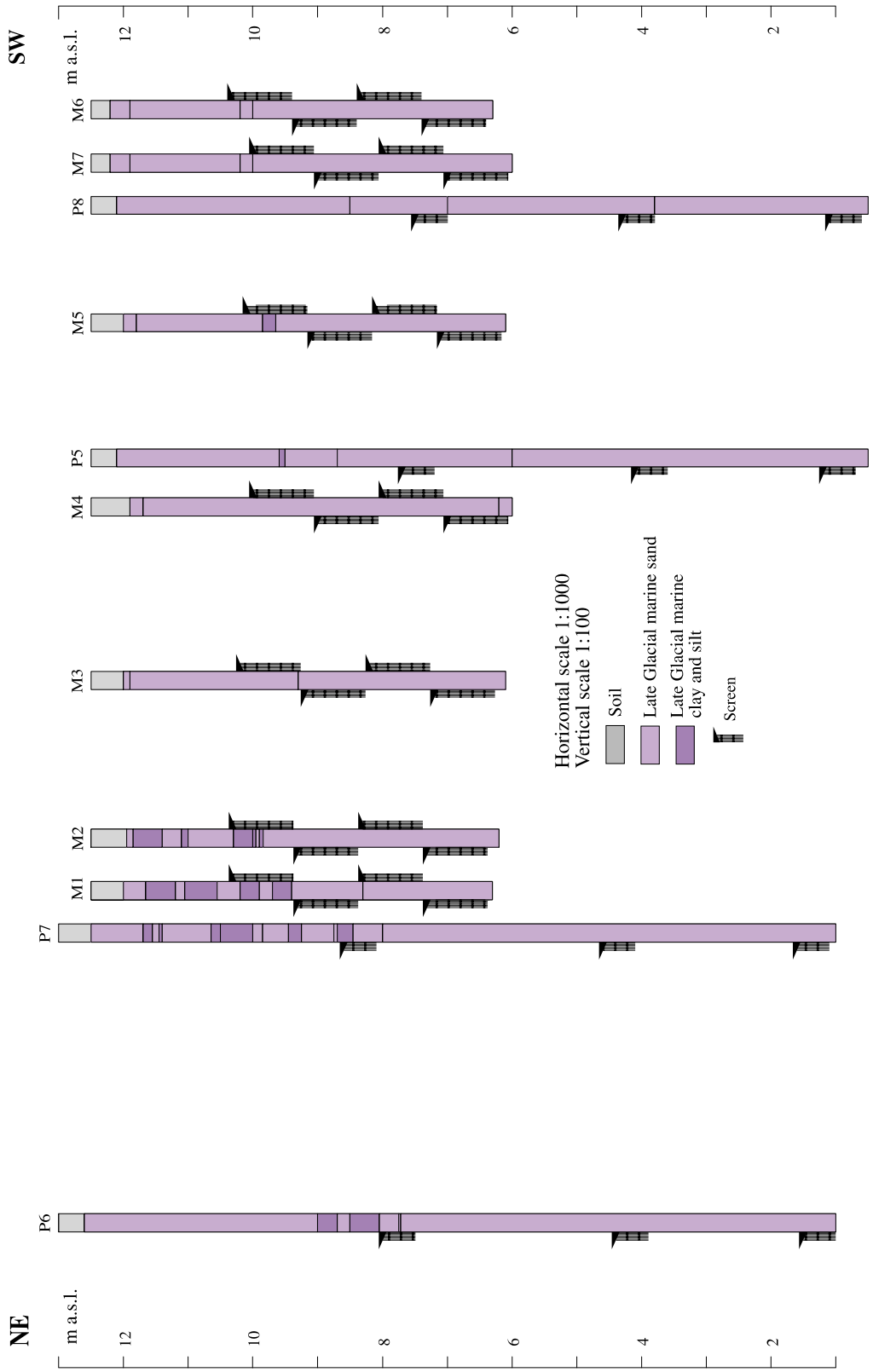


Figure A1.7. NE-SW cross section based on wells at the site. The location of the wells is shown in Figure A1.4.

following description focuses on the lithology and primary sedimentary structures as a basis for interpreting the depositional environment. The pedology itself is described in detail in Section A1.4. Generally, soil formation has destroyed primary sedimentary structures in the uppermost 0.5 m of the excavations.

In excavations P1 and P2 and in the southern part of the ditch the sediments consist from below of structureless fine-grained sand overlain by cross-laminated or cross-bedded sand with sets up to 0.3 m thick. Locally the sand contains vertical burrows made by bivalves. The sand is topped by an erosive surface at 0.8 m b.g.s. in excavation P1 and 1.3 m b.g.s. in excavation P2 and the nearby ditch. In the ditch the erosive surface dips towards north and hence can only be followed over a short distance before it disappears below the bottom of the ditch. A thin bed of gravely sand overlies the surface locally punctuated with stones up to 15 cm in diameter. In places where the erosive surface forms depressions, it may be overlain by a thin sandy silt layer. In the upper part of excavations P1 and P2 and the ditch the sediments generally consist of yellow brown, slightly silty, fine-grained sand which is without structures.

In excavation P3, which is situated in the northern part of the field site (Figure A1.5), the sediment consists of slightly silty, fine-grained sand with a few horizons of scattered pebbles. In the lower part, 1.7–1.8 m b.g.s., the sand is weakly laminated. In the upper part, though, the primary sedimentary structure has been destroyed due to soil development. In the northern part of the ditch the sediments consist of fine-grained sand with abundant sandy silt layers. The silt layers are commonly separated from the sand by erosive boundaries, which have lateral extensions of up to 10 m. Locally the erosive surfaces are draped with gravel.

Interpretation of the depositional environment

The sediments within the field area are dominated by fine-grained sand interpreted as being Upper Saxicava sand based on knowledge of the regional geology and the occurrence of burrows indicating a marine environment. The generally fine grain size of the sediments reflects deposition under low-energy conditions. The cross-bedded sandstone in excavations S1 and S2 and the southern part of the ditch attributed to the migration of bars in a coastal environment. The overlying erosive boundary and the gravel above it reflect high-energy conditions attributable to wave winnowing and scour and fill processes in the near shore zone or perhaps to a minor fall in relative sea level. Low-energy conditions occurred towards the north as evidenced by data from the cores and excavations and the iso-ohm maps, which indicate an overall fall in grain size from south towards north. The silt and clay layers observed in wells and excavations in the northern end of the test field were formed by suspension fallout during fair-weather conditions. Some of the layers may have a large lateral extent as indicated by the up to 50 m long

continuous reflectors visible on the ground-penetrating radar sections. Erosive events also took place in the northern end of the field site, however, as evidenced by the presence of minor erosive surfaces overlain by gravel or silt in excavation S3 and the ditch

Laboratory analyses

Grain size analysis

Grain size analysis has been carried out on nine samples from the deeper levels of the site (Table A1.4). The grain size distribution within the silt and clay fractions has only been analysed in one sample. Those fractions only form a minor component of the sand samples and it has generally been impossible to obtain enough material from the thin silt and clay layers for the analysis.

The grain size analyses show that the sand is mainly fine-grained. In a few of the sand samples the <0.63 mm fraction accounts for up to 40%. These samples were in the field described as being strongly silty. A sample from a clay layer shows a clay content of 14% and a silt content of 62%.

Table A1.4. Texture analysis of selected well sediment samples expressed as percentage by weight**.**

	Grain size in mm								
Depth and location m b.g.s.	<0.002	0.002–0.020	0.02–0.63	<0.063	0.63–0.125	0.125–0.200	0.20–0.5	0.5–2.0	Sediment
P6(2.9)				16.9	71.0	12.0	0.17	0	Fine-grained sand
P6(6.0)				8.2	44.3	42.6	4.6	0.3	Fine-grained sand
P6(11.5)				5.8	26.7	48.4	19.0	0.1	Fine-grained sand
P7(2.0)				42.4	43.3	9.2	4.9	0	Silty, fine-grained sand
P7(3.6)	14.0	51.8	10.6	76.4	9.1	10.0	4.8	0.3	Silty clay
P7(7.0)				7.5	28.8	44.6	15.5	1.5	Fine-grained sand
P7(10.0)				9.8	51.6	32.3	5.9	0.2	Fine-grained sand
P8(1.8)				6.5	51.1	31.4	10.6	0.1	Fine-grained sand
P8(10.0)				3.8	37.0	49.7	9.4	0.1	Fine-grained sand

Data from GEUS Sediment Laboratory. Some of the fractions were determined by linear interpolation.

Total organic carbon (TOC) and $CaCO_3$ content

The TOC and $CaCO_3$ data are shown in Figure A1.8 and Table A1.5. In sediments containing carbonate, the carbonate content is up to 2.0%. The total organic carbon content is about 1.6% in the topsoil layer in the test pits. Below the topsoil layer it decreases with increasing depth from about 0.1% to 0.02% in the deepest part.

Table A1.5. $CaCO_3$ and total organic carbon (TOC) in selected well sediment samples.

Locality	Depth m b.g.s.	TOC %	$CaCO_3$ %	Sediment
P6	2.9	0.03	<0.1	Fine-grained sand
P6	6.0	0.04	2.0	Fine-grained sand
P6	11.5	0.03	1.8	Fine-grained sand
P7	1.4	0.16	Not analysed	Clay
P7	2.0	0.04	Not analysed	Silty, fine-grained sand
P7	2.5	0.11	Not analysed	Silty clay
P7	3.6	0.07	<0.1	Silty clay
P7	5.5	0.11	<0.1	Silty, fine-grained sand
P7	6.5	0.09	<0.1	Silty, fine-grained sand
P7	7.0	0.06	<0.1	Fine-grained sand
P7	7.5	0.08	<0.1	Silty, fine-grained sand
P7	8.0	0.04	<0.1	Silty, fine-grained sand
P7	10.0	0.03	1.9	Fine-grained sand
P7	12.0	0.02	1.4	Fine-grained sand
P8	1.8	0.08	<0.1	Fine-grained sand
P8	10.0	0.03	0.6	Fine-grained sand

Data from GEUS Sediment Laboratory.

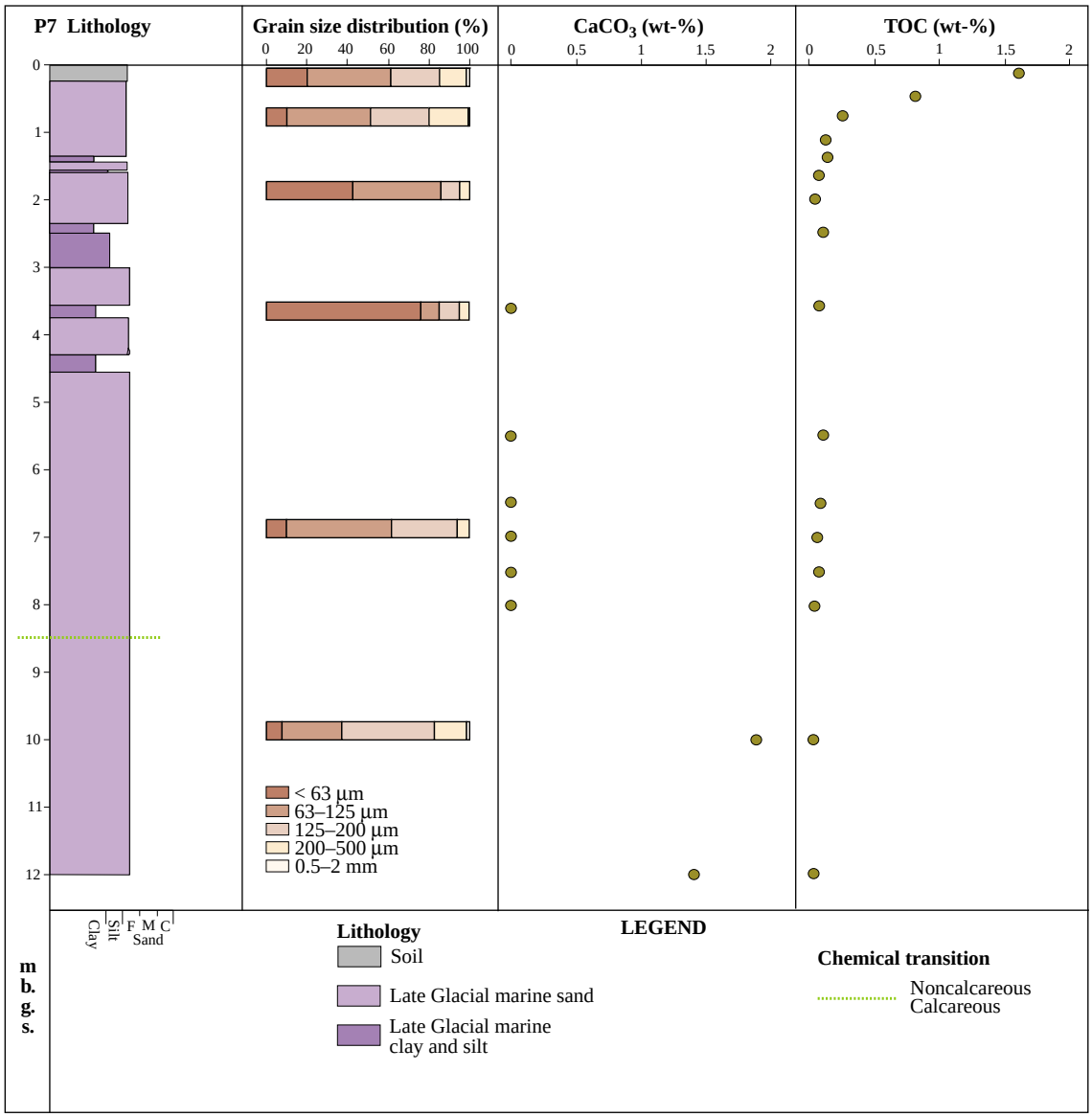


Figure A1.8. Lithology of well P7, grain size distribution and $CaCO_3$ and total organic carbon (TOC) content in the test pits. Grain size fractions larger than 2.0 mm are not included in the grain size analysis.

A1.4 Pedology

The pedological fieldwork at Tylstrup was carried out from March 22 to March 24 1999. Three soil profiles were excavated and described (Figure A1.5). Two of them were located beside each of the two groups of suction cups. In the buffer zone to the west and south, 12 soil cores were collected to a depth of 120 cm (Figure A1.5). Inside the field, 21 soil samples were collected from the topsoil (0–25 cm).

Table A1.6. Description of profile 1 (3087 Tylstrup South).

Soil classification, DK	Typibrunsol	**Soil classification, USDA**	Humic Psammentic Dystrudept
Parent material	Fine sand Marine sand	**Profile depth**	160 cm
UTM	32V NJ Easting 557893 Northing 6337909	**Drainage class**	Well drained
Landform	Yoldia plain	**Groundwater level**	>160 cm
Map sheet	1317 III NV	**Vegetation**	Stuble
Elevation	14 m DNN	**Maximum rooting**	105 cm
Topography	Flat	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	23.03.99

Profile description

Ap (0–32 cm)
Very dark greyish brown (10YR 3/2 f) clayey silty sand, containing humus, structure-less, moist non-sticky consistency, artificial liming mainly as lumps, a few small, mainly rounded stones of mixed form, type and degree of weathering, some small roots, clear smooth boundary.

Ap2 (32–40 cm)
Very dark brown (10YR 2/2 f) light clayey silty sand, containing humus, weak within angular structure, moist non-sticky consistency, a few small mainly rounded stones of mixed form, type and degree of weathering, 10–40 wormholes and root channels per dm^2, some small roots, very small mottles of thin coatings of clay minerals, sesquioxides and humus in root channels, gradual wavy boundary.

Bv (40–60 cm)
Very dark brown (10YR 2/2 f) light clayey silty sand, humus poor, weak angular structure, moist non-sticky consistency, a few small, mainly rounded stones of mixed form, type and degree of weathering, some small roots, very small mottles of thin coatings of clay minerals, sesquioxides and humus in root channels, gradual irregular boundary.

BC (60–105 cm)
Brownish yellow (10YR 6/6 f) with many horizontal stripes, clear spots of brownish yellow (10YR 6/8 f) silty sand, humus poor, very weak within granular structure, moist non-sticky consistency, a few small, mainly rounded stones of mixed form, type and degree of weathering, a few small roots, very small mottles of thin coatings of clay minerals, sesquioxides and humus in root channels, diffuse smooth boundary.

C (105–160 cm)
Light yellowish brown (10YR 6/4 f) silty sand, humus poor, very weak structure, moist non-sticky consistency, a few small, mainly rounded stones of mixed form, type and degree of weathering, no roots.

Remarks	Vertical wormholes until 85 cm. The Bv horizon: Contains brittle clay/humus concretions 1–3 mm in size. The BC horizon: The chimney/funnel contains more roots than the surrounding matrix. The upper part is cut by a wavy abrupt horizontal 0.5–2 cm thick undulating brittle/hard Placic horizon.

Table A1.7. Description of profile 2 (Tylstrup West).

Soil classification, DK	Typibrunsol	**Soil classification, USDA**	Humic Psammentic Dystrudept
Parent material	Marine sand	**Profile depth**	170 cm
UTM	32V NJ Easting 557875 Northing 6337939	**Drainage class**	Well drained
Landform	Yoldia plain	**Groundwater level**	> 160 cm
Map sheet	KM 1317 III NV	**Vegetation**	Stuble
Elevation	14 m DNN	**Maximum rooting**	90 cm
Topography	Flat	**Authors**	Søren Torp
Slope	0 – 1°	**Date of description**	23.03.99

Profile description

Ap (0–33 cm)
Very dark greyish brown (10YR 3/2 f) light clayey sand with some stones 1–7 cm in size, homogeneous topsoil with down-ploughed straw/manure, artificial liming, smooth sharp boundary.

Bh (33–44 cm)
Black (5YR 2.5/1 f) sand with 1–5% humus, many tree roots 1–2 cm in size and many fine roots, abrupt boundary.

Bv (33–50 cm)
Black (7.5YR 2.5/1 f) silty sand, many tree roots and many fine roots, light mottled look, boundary down is very smooth and relatively sharp. Seems to be an old plough layer boundary.

BC (50–87 cm)
Dark yellowish brown (10YR 3/4 f) sand, tree roots, mottled look and lighter downwards.

C (87–132 cm)
Yellowish brown (10YR 5/6 f) sand, reddish hydromorphic character in the bottom (10YR 5/8 f), the texture is coarser downwards with stones in the bottom, sharp smooth boundary.

2C (132–160 cm)
Brownish yellow (10YR 6/6 f) sand, finely laminated.

Remarks	The Bh horizon is located as an incoherent horizon, perhaps as a result of soil handling.

Table A1.8. Description of profile 3 (3088 Tylstrup North).

Soil classification, DK	Typibrunsol	**Soil classification, USDA**	Humic Pachic Dys-trudept
Parent material	Marine sand	**Profile depth**	160 cm
UTM	32V NJ Easting 557974 Northing 6338057	**Drainage class**	Well drained
Landform	Yoldia plain	**Groundwater level**	>160 cm
Map sheet	1317 III NV	**Vegetation**	Stuble
Elevation	14 m DNN	**Maximum rooting**	120 cm
Topography	Flat	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	24.03.99

Profile description

Ap (0–32 cm)
Very dark brown (10YR 2/2 f) light clayey sand, containing humus, a few small, mainly rounded stones, frequent small roots, 1–10 wormholes and root channels per dm^2, very weak structure, non-sticky consistency, clear smooth boundary.

Ap2 (32–72 cm)
Dark brown (10YR 3/3 f) sand, a few horizontal stripes of thin weak brown spots (10YR 4/3 f) containing humus, a few small, mainly rounded stones, frequent small roots, 1–10 wormholes and root channels per dm^2, very weak structure, non-sticky consistency, clear smooth boundary.

Bv (72–87 cm)
Dark yellowish brown (10YR 4/4 f) sand, a few rounded, large dark yellowish brown spots (10YR 3/4 f), humus poor, some mainly rounded stones, some small roots, 1–10 wormholes and root channels per dm^2, very weak structure, weak strongly discontinuous cemented Placic horizon, gradual irregular boundary.

C (87–155 cm)
Brownish yellow (10YR 6/4 f) sand, a few vertical stripes of large strongly brown spots (7.5YR 5/8 f), humus poor, no stones, a few small roots, 1–10 wormholes and root channels per dm^2, very weak structure, gradual irregular boundary.

Cg (155–160 cm)
Light yellowish brown (2.5Y 6/3 f) sand, humus poor, no stones, without structure.

Remarks	The Ap horizon contained down-ploughed dung and straw.

Table A1.9. Soil texture analysis from the pedological profiles.

Pro. no	Hor. no	Horizon	Depth cm	Soil texture (mm) % <0.002	0.002–0.02	0.02–0.63	0.63–0.125	0.125–0.2	0.2–0.5	0.5–2	$CaCO_3$ %	OM[1] %
1	1	Ap	10–20	6.4	3.6	9.3	36.0	25.3	15.6	1.1	–	2.7
1	2	Ap2	30–40	5.8	4.2	15.0	46.2	18.4	7.2	0.7	–	2.5
1	3	Bv	45–55	5.3	3.7	14.1	45.4	23.1	5.3	1.1	–	2
1	4	BC	87–97	3.6	0.9	13.7	67.8	13.3	0.3	0.1	–	0.3
1	5	C	130–140	2.5	0.5	12.5	62.1	21.8	0.4	0.1	–	0.1
3	1	Ap	10–20	5.7	4.3	9.5	40.0	23.3	12.8	1.6	–	2.7
3	2	Ap2	45–55	4.7	4.3	9.4	37.7	28.7	12.9	0.9	–	1.4
3	3	Bv	76–86	4.1	0.9	5.0	41.0	28.7	19.2	0.7	–	0.4
3	4	C	113–123	3.1	0.9	9.9	72.6	13.0	0.2	0.1	–	0.2
3	5	Cg	160–170	3.0	0.5	11.8	67.0	17.2	0.3	0.1	–	0.1

1) OM: Organic matter, OM = 1.72 x TOC. Analysed by DIAS.

Table A1.10. Soil chemistry of samples from the pedological profiles.

Pro. no.	Hor. no.	N_{total} %	C/N	P_{total} mg/kg	pH[1]	K	Na	Ca	Mg cmol/kg	Total bases	H^+	CEC	Base sat. %	Fe (Ox) mg/kg	Al (Ox) mg/kg
1	1	0.12	13	796	4.49	0.18	0.02	2.52	0.21	2.93	4.67	7.6	39	1660	1034
1	2	0.1	15	453	4.63	0.11	0.01	2.4	0.21	2.73	5.67	8.4	33	2272	2160
1	3	0.09	13	–	4.52	0.07	0.02	1.02	0.1	1.21	7.19	8.4	14	2432	3660
1	4	0.03	6	–	4.72	0.04	–	0.2	0.02	0.26	2.94	3.2	8	1516	1520
1	5	0.03	2	–	4.76	0.04	–	0.13	0.01	0.18	4.92	5.1	4	340	1008
3	1	0.13	12	784	4.0	0.38	0.07	3.3	0.5	4.25	5.65	9.9	43	1460	994
3	2	0.05	16	485	4.8	0.12	0.13	1.91	0.13	2.29	4.11	6.4	36	1228	856
3	3	0.03	8	–	4.8	0.06	0.06	0.59	0.04	0.75	3.15	3.9	19	411	1456
3	4	0.02	6	–	4.8	0.05	0.05	0.31	0.02	0.43	2.87	3.3	13	317	1278
3	5	0.01	6	–	4.8	0.05	0.1	0.22	0.02	0.39	2.01	2.4	16	328	1052

1) pH determined in $CaCl_2$ solution. Analysed by DIAS.

Profile description

The pedological descriptions of the three profiles are summarized in Tables A1.6 to A1.8. The profile horizons are shown in Figure A1.9. The profile laboratory data (grain size, texture, organic matter, nutrients and major cations) are summarized in Table A1.9 and Table A1.10.

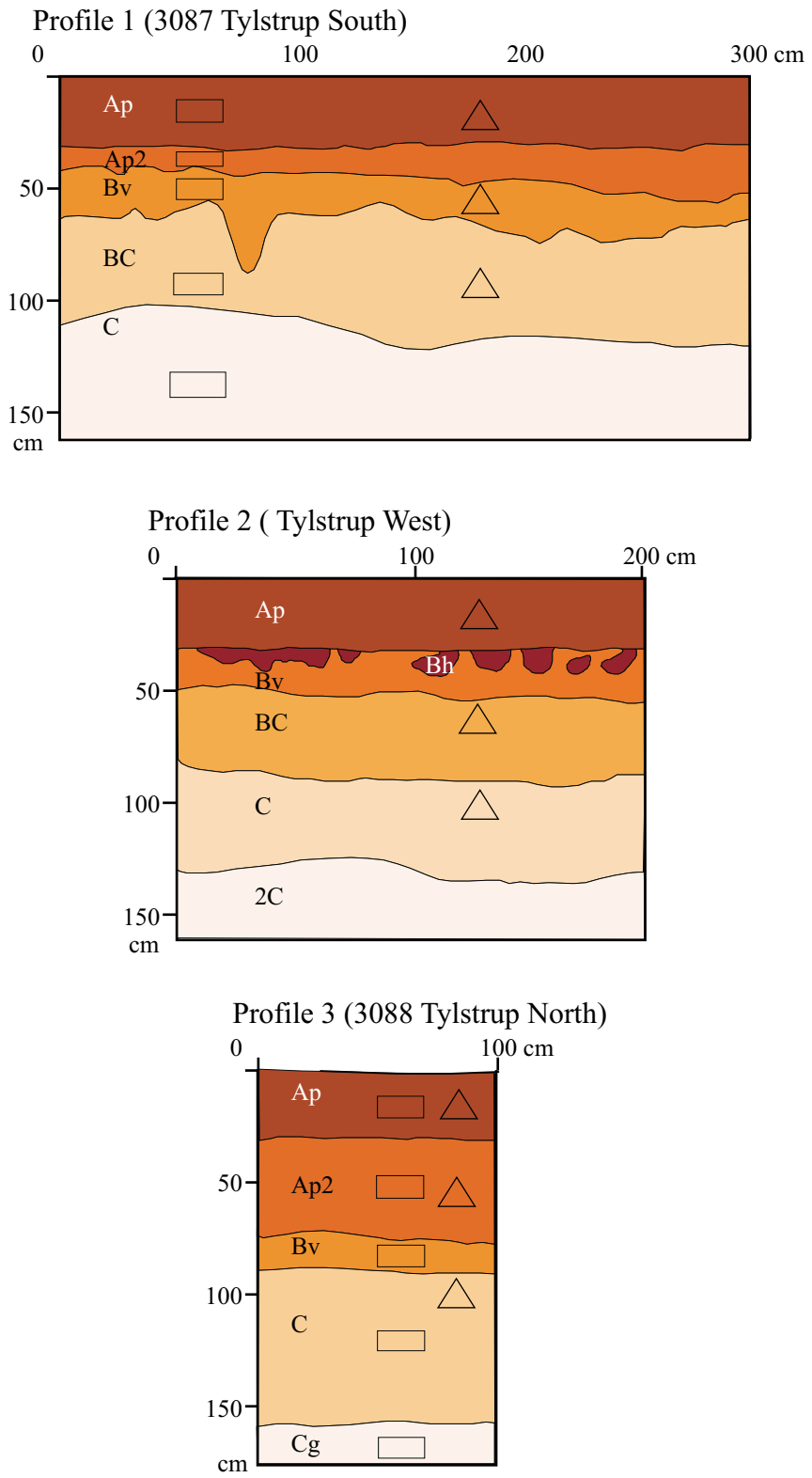


Figure A1.9. Schematic drawings of profiles showing horizon distribution. Rectangular boxes indicate sampling points for soil texture and soil chemistry. Triangular boxes indicate sampling points for hydrological analysis.

Table A1.11. Classification of the profiles.

Profile no.	Danish Soil Classification	USDA Soil Taxonomy
1 (3087 South)	Because the profile contains <8% clay and <30% silt, and because there is only a Bv horizon, the classification leads to Brunsols. On the 1st group level, all three profiles go as **Typibrunsols**.	The epipedons Ap and Bh become Umbric, as their base saturations are too low to become Antropic, even if they are thick. The B horizon is Cambic, which means that the profile is an Inceptisol. With a Udic soil moisture regime and a sandy grain size the profile can be classified as a **Humic Psammentic Dystrudept**.
2 (West)	do.	The same arguments as for profile 1. Profile 2 could be used for the classification of Tylstrup West, **Humic Psammentic Dystrudept**.
3 (3088 North)	do	On the base saturation, the epipedon becomes Umbric. The B horizon is too thin to be Cambic and the profile is thus an Inceptisol. Because the soil moisture regime is Udic it can be classified as Udept, and because of the thick epipedon, the soil is a **Humic Pachic Dystrudept**.

In Table A1.11 the profiles are classified according to both "A Pedological Soil Classification System Based on Danish Soils" (Madsen and Jensen, 1985) and USDA Soil Taxonomy (Soil Survey Staff, 1999).

Soil cores from the buffer zone

The soil cores show that the variation in the horizons is small. The thickness of the A horizons lies between 30 and 35 cm, and 45 cm at maximum. The old plough layer Ap2 is found along the hedge and seems to be thickest in the southern part of the area. The boarder to the C horizon lies at a depth of between 60 cm in the northern part and 95 cm in the southwestern part of the area. The soil development within the area probably lies in this range too. Ap–Bv–C are the common horizons in the area. In the southwestern part, the soils are more mature or more deeply developed and an Ap2 horizon and occasionally also a Bh horizon are present.

Total carbon mapping

The samples from the topsoil inside the field were only analysed for total organic carbon (TOC), which varied between 1.7 and 2.3% (dry weight) with a mean of 2.0±0.1%.

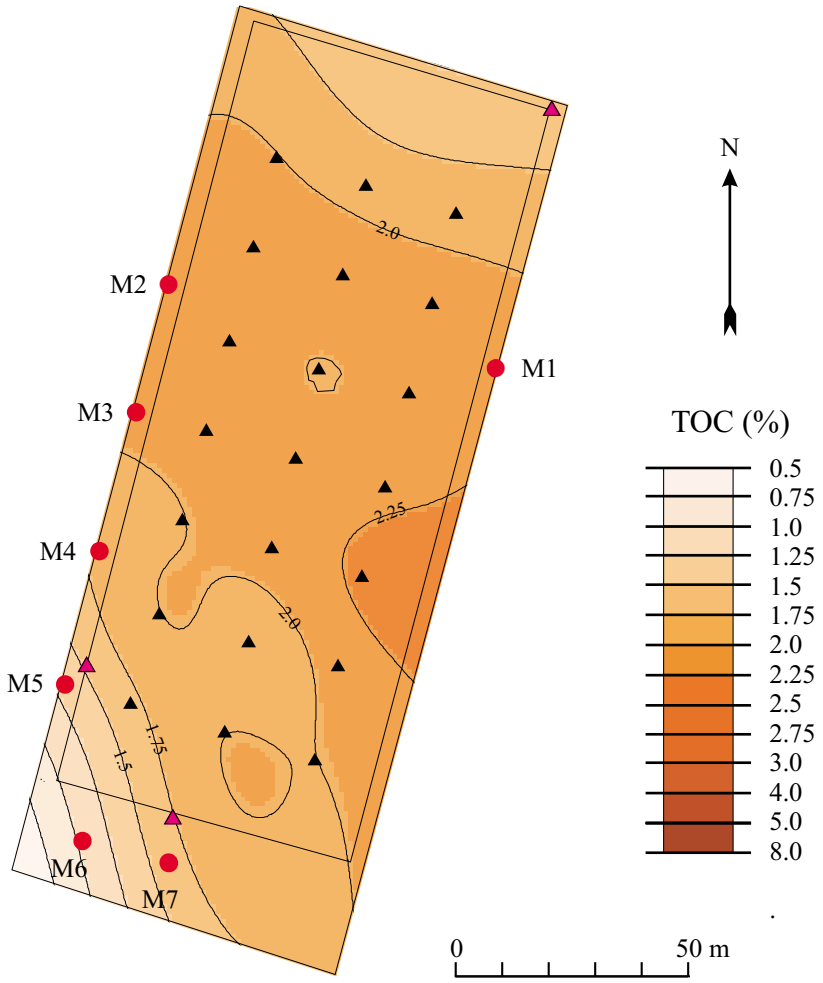


Figure A1.10. Map showing total organic carbon (TOC) content within the test field. Sampling points are indicated by ▲.

The concentration is lowest in the southwestern part of the field (Figure A1.10) and highest in the central part.

Pedological development

Hansen (1976), Jacobsen (1989) and Nielsen and Møberg (1985) have previously carried out thorough pedological investigations at the Tylstrup experimental station. Soil profiles no. 1989 and 1226 from the Danish Soil Profile Database are located 0.7 and 2.5 km, respectively, to the northwest of the test field and the reference profiles are located 0.8 and 3.5 km northwest of the monitoring area and 5.4 km east of it site.

The three investigated profiles have been developed from a parent material consisting of Late-Glacial marine sediments (Andersen and Sjørring, 1992). The only characteristics of marine origin in the profiles and trenches were traces of a bank structure and micro-laminated wave ribs in the C horizon.

The clay percentage decreased from about 5% in the upper horizon (clayey silty sand) to 2–3% in the C horizon (silty sand). The variation in soil texture was generally greatest in the upper soil layers. The dominant grain size fraction is 63–125 µm, i.e. fine sand, with the percentage varying from 25% at the top of the horizon to 70% at the bottom. Few pebbles are generally present. In a few places, stone layers are encountered in the C horizon. Soil texture at the test field are similar to those found with the reference profiles with the fine sand as the dominant fraction (Hansen 1976, Jacobsen 1989 and Nielsen and Møberg, 1985). Any original carbonate in the soil has been completely removed.

During the time the field was under cultivation, shifting sand from repeated earth drifts has superposed the entire area. A single superposition of up to 20–30 cm has occurred in some areas, as can be deduced from the thick plough layers along both sides of the fence and from the fact that the fence is situated on top of a bank. Investigations carried out by Nielsen and Møberg (1985) reach a similar conclusion. E horizons are thus present in the soils taken in the buffer zone that may be interpreted as reminiscences from previously buried less carbonaceous plough layers. In the middle of the field, the plough layer (Ap) is of a thickness more common for Danish sandy soils.

From the pedological point of view, the profiles consist of a thick homogeneous humus-containing plough layer (approx. 32 cm thick) with a C/N relation of 12–16 indicating good transformation of organic matter. The total organic carbon content of 2.0% is normal for cultivated Danish soil in sandy areas. The old buried plough layer seems to be widespread in the area since Nielsen and Møberg (1985) also found it and it is seen in the Square Grid Profiles (Larsen *et al*., 1995). The differences in colour and carbon content in the buried A horizons may reflect earlier cultivation practices entailing "in fields" and more extensively cultivated areas. This may also be true for the black Bh horizon in the profile 2 (Tylstrup West) (Figure A1.9).

The soils are generally poorly developed with brunified Bv horizons. The brown colour is the result of weathering of the primary minerals and is primarily due to oxidation of the iron content of the soil. Because iron is not very mobile, Fe is quickly deposited again in an oxide and a hydroxide form (Fe III) as micrometers thin layers on the matrix. The increased H^+ values of the Bv horizon are in part attributable to microbial oxidation of the biomass and cation absorption from plant roots.

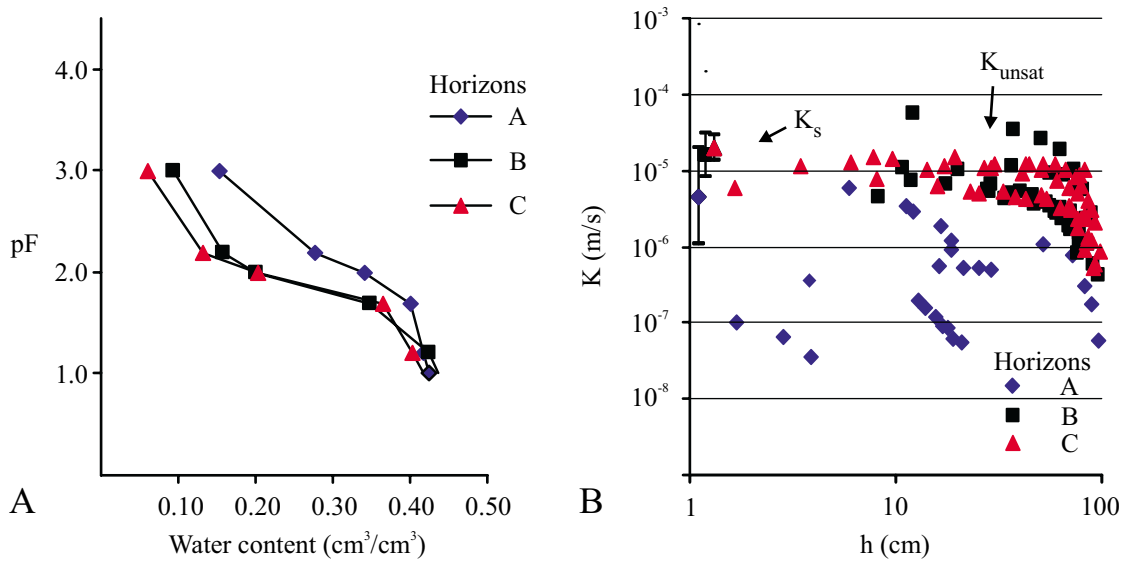


Figure A1.11. A) Retention curve based on values for the soil-water potential determined on the small soil core samples (100 cm^3). The data are the mean values from both profiles. B) The unsaturated hydraulic conductivity (K_{unsat}) as a function of soil water potential in cm H_2O and the saturated hydraulic conductivity (K_s) determined on the large soil cores (6,280 cm^3).

The thin dark-coloured Bh horizons found in the soil drillings may be signs of podsolization of the soil, but there was no evidence of enhanced Fe or Al levels in the B horizons. The colour of the soil is probably attributable to cultivation of the overlying soil. The application of ground chalk to the soil has equalized the pH yielding an almost homogeneous pH of between 4.5 and 5.0 down through the profile (Madsen, 1988). The reference profiles (Hansen, 1976; Nielsen and Møberg, 1985) exhibit slightly higher pH-values ranging from pH 6.2 in the plough layer to pH 4.7 in the C horizon. A high Ca^{2+} content is also seen in relation to the other bases in the upper approx. 60 cm. The degree of base saturation varies from 40% in the plough layer to 4–16% in the C horizon. The Square Grid Profile (Statens Planteavlsforsøg, 1996) near the experimental station differs as the base saturation is 59% and increases with increasing depth. CEC ranges from of 7–10 cmol/kg in the plough layer to 2–5 cmol/kg in the C horizon. The same is seen in the reference profiles for the area.

The area is generally well drained, but all three profiles have hydromorph characteristics visible as red deposits of iron in the form of through-going bands at a depth of 80–130 cm. The profiles are generally well drained, though, with small, fine roots descending 150–160 cm.

Soil hydrology

Soil cores (100 cm^3 and 6,280 cm^3) for the measurement of hydrological properties (soil water characteristics and hydraulic conductivity) were sampled at three levels corresponding to the A, B and C horizons.

The soil water characteristic of the nine small cores (100 cm^3) from each horizon are shown together with bulk density and porosity in Table A1.12 and Figure A1.11

Table A1.12. Soil water characteristics determined on the small soil cores, pF = $\log_{10}(-h)$

Profile no.	Horizon	Depth cm [3]	Water content at pF values cm^3/cm^3							Bulk density g/cm^3	Porosity[1] cm^3/cm^3
			1.0	1.2	1.7	2.0	2.2	3.0	4.2		
1 (3087)	Ap	15	0.44	0.43	0.41	0.33	0.28	0.15	0.04	1.33	0.50
	Bv	55	0.48	0.47	0.40	0.23	0.18	0.10	0.05	1.31	0.50
	BC	80	0.45	0.44	0.41	0.24	0.16	0.07	0.01	1.40	0.47
2 (West)	Ap	15	0.42	0.41	0.41	0.36	0.28	0.16	2)	1.45	0.45
	Bh	60	0.44	0.42	0.33	0.19	0.15	0.10	2)	1.39	0.48
	C	100	0.40	0.38	0.31	0.16	0.11	0.06	2)	1.51	0.43
3 (3088)	Ap1	15	0.41	0.41	0.38	0.33	0.27	0.15	0.05	1.45	0.45
	Ap2	50	0.39	0.38	0.31	0.18	0.14	0.08	0.03	1.50	0.44
	C	100	0.40	0.39	0.37	0.21	0.12	0.05	0.01	1.51	0.43

1) Assuming a particle density of 2.65 g/cm^3

2) Not measured

3) Mid- point of the soil core

The soil water characteristics show that the water-holding capacity of the soil is high until pF 1.7 (-50 cm H_2O), whereafter most of the water suddenly empties out of the soil pores. This reflects the fact that the well-sorted material contains a high number of equally sized pores, thus accounting for the distinct pore volume peaks in the horizons (Figure A1.12). In the Ap horizon the majority of pores are around 25 µm (tube-equivalent diameter) whereas the 40 µm pores dominate in the B and C horizons.

The saturated and unsaturated hydraulic conductivity determined on the large cores (6,280 cm^3) is shown in Figure A1.11. The hydraulic conductivity in the B and C horizons is high, ranging from saturation to a soil-water potential of about -70 cm H_2O whereafter the conductivity decreases rapidly, reflecting the well-sorted material. Compared to the more loamy soils at the Faardrup, Silstrup, Slæggerup and Estrup sites, the inter-measurement variability is low. The conductivity is lower and the variability higher in the A horizon than in the two other horizons.

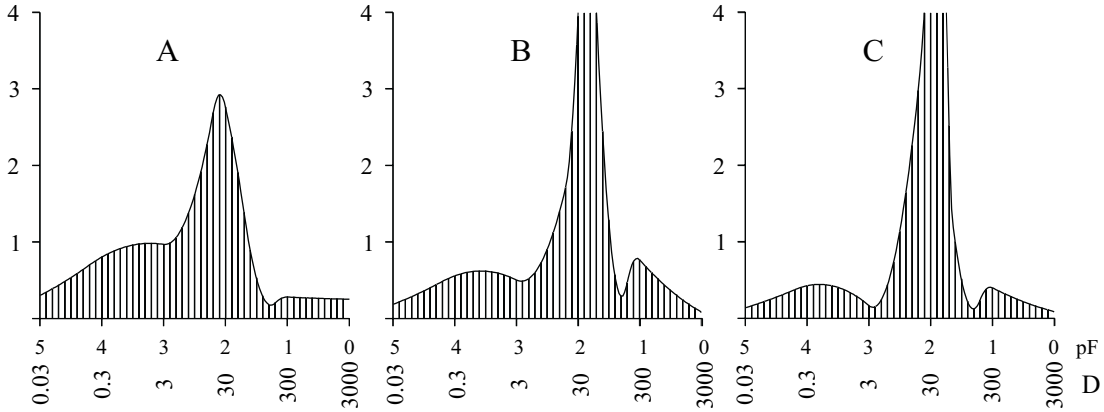


Figure A1.12. Pore size distribution measured (A, B, and C horizon) calculated from water retention data assuming the unity D=3000/10pF (D = pore diameter equivalent diameter, µm). A cubic spline interpolation procedure is used to yield discrete interpolate values on the sum curve obtained from the water retention curves. Abscissa: pF=log10(-h) in which h is the soil water potential in cm H_20. D = pore diameter, µm. Ordinate: percentage of pore volume per 1/10 pF-values, % v/v.

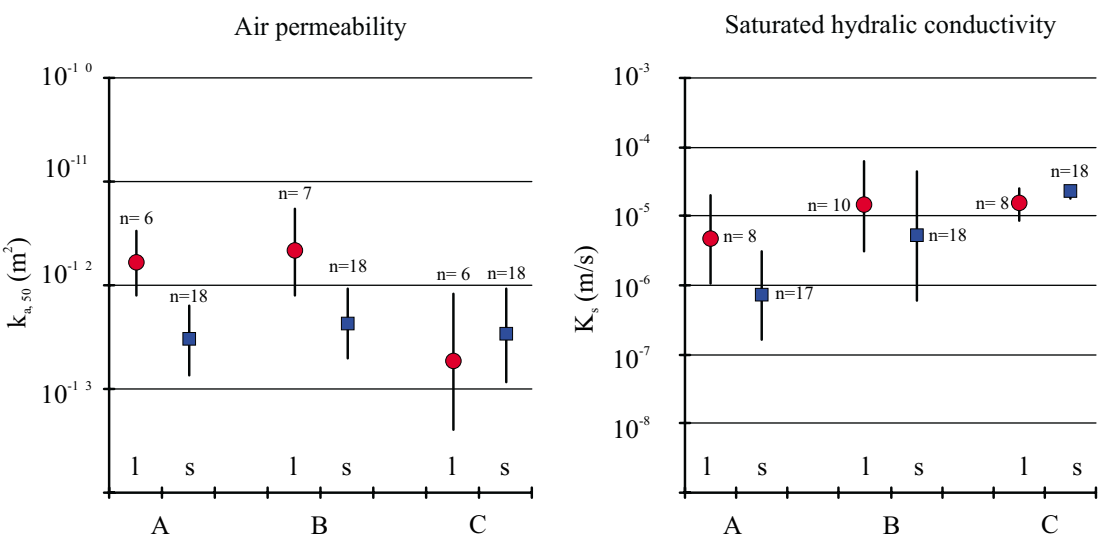


Figure A1.13. Air permeability at a water content of –50 cm H_20 ($k_{a,50}$) and saturated hydraulic conductivity (K_s) measured on large (6,280 cm^3) samples (●) and small (100 cm^3) samples (■).

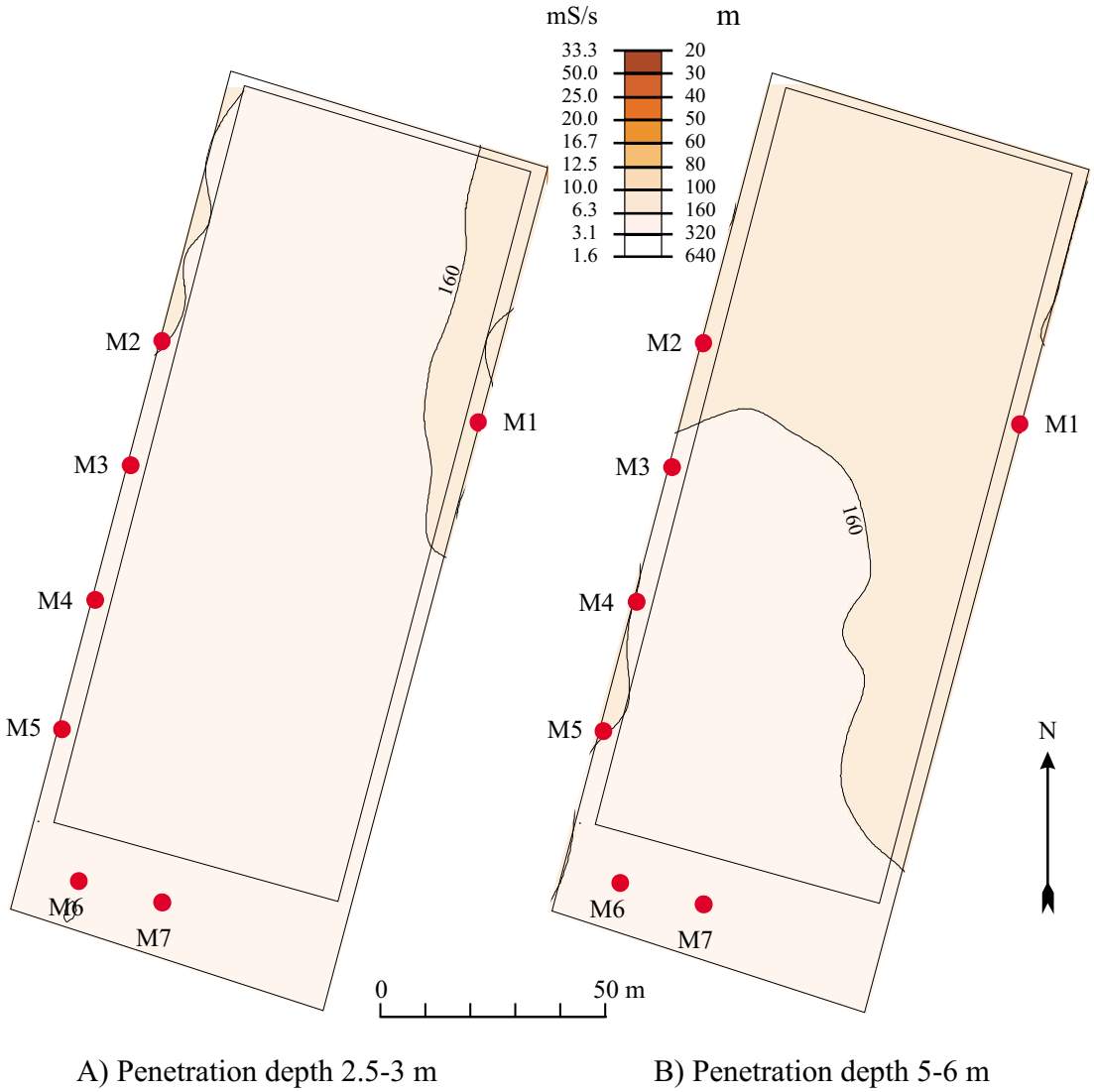


Figure A1.14. Resistivity map of the area.

Measurements of saturated hydraulic conductivity and air permeability using small (100 cm^3) or large (6,280 cm^3) soil samples did not reveal any significant differences, thus reflecting the weakly structured nature of the soil (Figure A1.13). The soil samples are thus representative irrespective of whether a small or large soil sample is used for the analysis.

A1.5 Geophysical mapping

Since destructive mapping methods are not accepted in the test field, it was decided to use EM-38, CM-031, and ground-penetrating radar (GPR). However, the high voltage

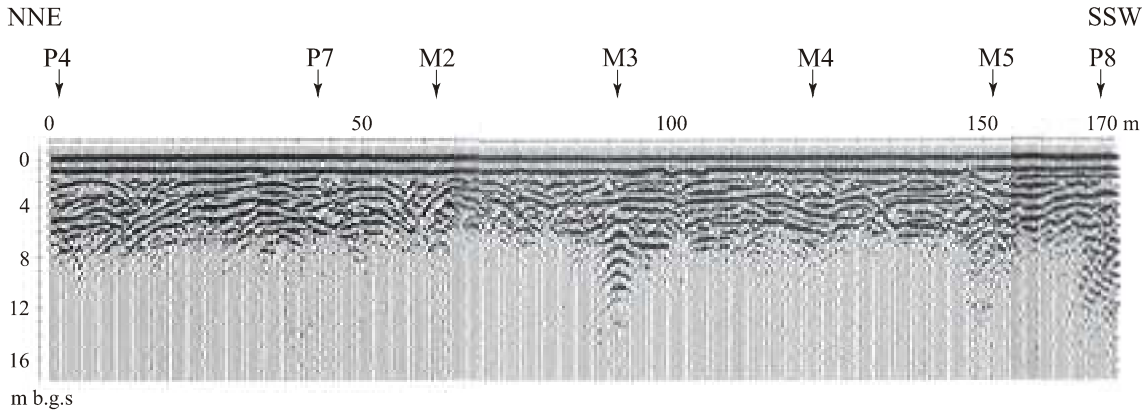


Figure A1.15. Ground penetrating radar profile.

overhead line that crosses the northern part of the area influenced the EM 38 measurements and as a consequence, no EM 38 data are available.

CM-031 mapping

Figure A1.14A shows the apparent resistivity determined with a horizontal magnetic field penetrating approx. 2.5–3 m b.g.s., while Figure A1.14B shows the apparent resistivity determined with a vertical magnetic field penetrating 5–6 m b.g.s. Both maps reveal the highest ohm reading in the southwestern part of the field site. From there the resistivity decreases towards north and northeast, reflecting an overall reduction in grain size in these directions.

Ground- penetrating radar (GPR)

The ground-penetrating radar mapping was conducted using 100 MHz aerials and a presumed wave velocity of 0.1 m/ns along a grid of approx. 20 m x 20 m. The penetration depth is 6–8 m and does not vary markedly within the test field. Several continuous reflectors up to 50 m long are present in the northern part of the cross sections, thus indicating the presence of large areas where surfaces separate different lithologies (Figure A1.15).

Appendix A1.1. Cultivation and pesticide application history at Tylstrup.

Year	Crop	Date	Pesticide brand	Dose per ha
1989	Spring barley, field 2, 3, 4	02.05.89	Shellprox, Super F	3.0 l
1989	Potatoes, field 1	09.05.89	Sencor	0.7 kg
		21.06.89	Cymbush	0.8 kg
		26/6, 5/7, 18/7, 2/8, 22/8, 2/9	Maneb	2.5 kg
		11.08.89	Ridomil	2.5 kg
1990	Field peas, field 1, 2, 3	May	Basagran 480	1.0 l
		May	Bladex 500 SC	1.0 l
1990	Potatoes, field 4	10.05.90	Sencor	0.7 kg
		12.06.90	Pirimor G	0.3 kg
		12/6, 26/6, 12/7, 24/7, 6/8	Maneb	4.0 l
		27.07.90	Ridomil	2.5 kg
		31.07.90	Reglone	0.8 l
1991	Winter rye		None	
1992	Potatoes	April	Thiram	2.5 kg
		May	Sencor	0.5 kg
		4 times	Daconil	2.5 kg
		August	Reglone	2.0 l
1993	Winter rye	May	CCC extra	2.0 l
1994	Potatoes	16.05.94	Reglone	1.0 l
		16.05.94	Sencor	0.3 kg
		29.07.94	Dithane	2.0 kg
		15.08.94	Dithane	2.0 kg
		30.08.94	Dithane	2.0 kg
		25.09.94	Dithane	2.0 kg

Year	Crop	Date	Pesticide brand	Dose per ha
1995	Field peas	08.05.95	Basagran	0.8 l
		08.05.95	Stomp SC	0.75 l
		05.08.95	Roundup	1.5 l
1996	Winter wheat	22.05.96	Activa	1.0 l
		22.05.96	Herbatox	0.6 l
		10.07.96	Tilt Turbo	0.4 l
		05.08.96	Roundup	1.5 l
1997	Winter rape	10.09.96	Benasalox	0.4 l
		10.09.96	Agil	0.25 l
		05.06.97	Agil	0.5 l
1998	Winter barley	18.09.97	Boxer	0.5 l
		18.09.97	Stomp	0.4 l
		18.09.97	IPU	0.25 l
		13.05.98	Express	0.0075 kg
		13.05.98	Starane 180	0.5 l
		13.05.98	Mangan	2.0 kg
		17.07.98	Roundup	2.0 l

Site Characterization and Monitoring Design

Annexe 2.

Site 2: Jyndevad

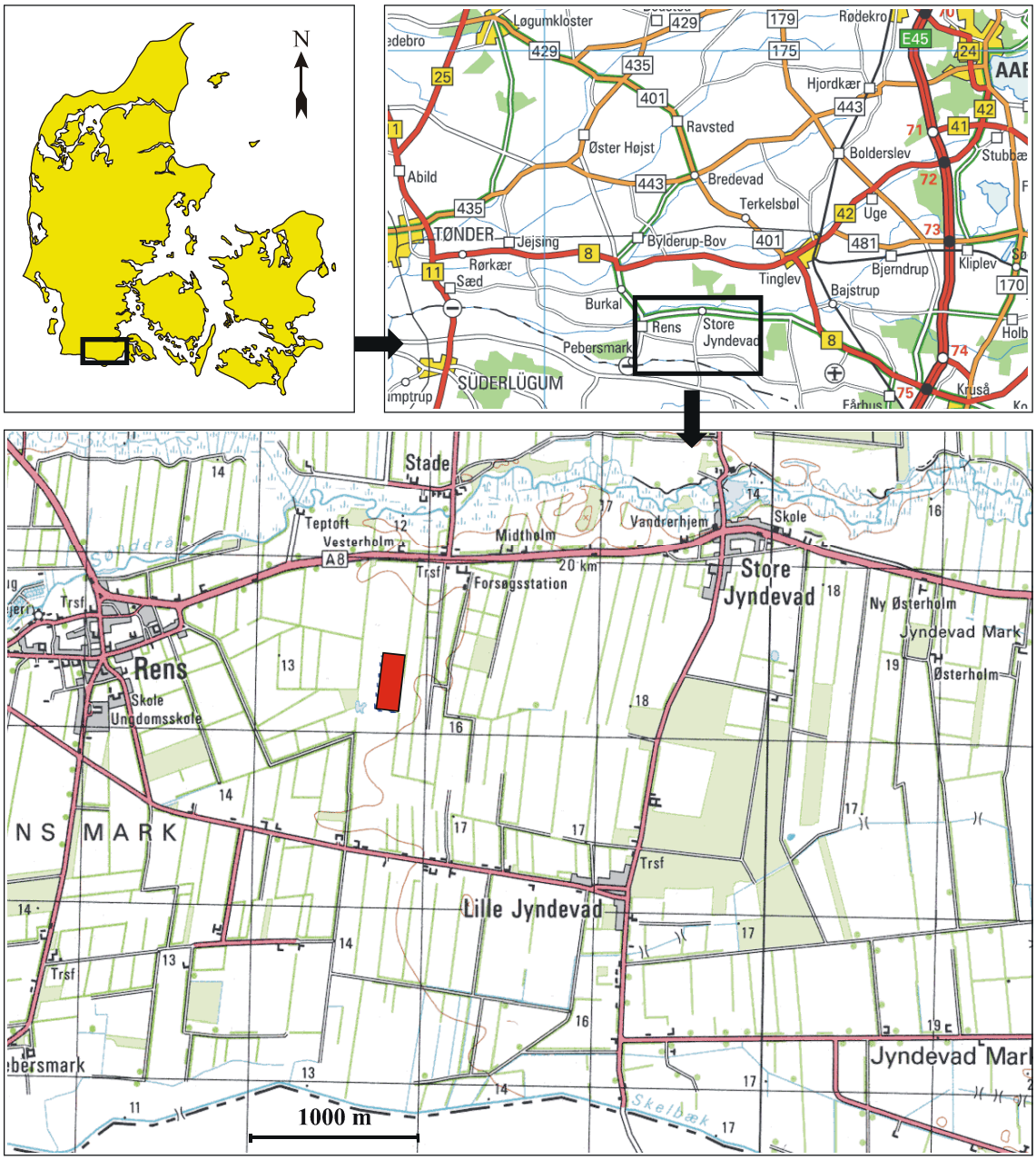


Figure A2.1. Location of the test field.

A2.1 Location, ownership and earlier cultivation and use

The test field is located at Store Jyndevad in southern Jutland (Figure A2.1). It is leased by the Danish Institute of Agricultural Sciences (DIAS), which has an experimental station 0.5 km NNE of the area. Site characteristics are summarized in Table A2.1.

Table A2.1. Site characteristics.

Length and width of the test field	184 x 135 m
Total area of the site, incl. buffer zone	3.3 ha
Area of the test field	2.39 ha
Municipality	Tinglev
County	Sønderjylland
Land registry no.	47, Burkal Sogn, Tinglev
Ownership	Private, leased by DIAS

Earlier use

The area is leased from a private farmer and has previously been farmed as a normal field. As is apparent from Figure A2.2, the field has been farmland since at least 1934. For the past few years it has been divided into a western part and an eastern part with different cropping histories. Cultivation and pesticide application history of the test field during the 4 years prior to the present investigations is summarized in Appendix 2.1.

A2.2 Technical installations

All installations at Jyndevad are numbered according to the code described in Section 3. In the present description, however, the site-specific code for Jyndevad, i.e. “2”, has been omitted for the sake of simplicity. The locations of all installations were selected on the basis of the groundwater flow pattern (Figure A2.3) and are shown in Figure A2.4.

Buffer zone

The width of the buffer zone at Jyndevad is 24 m along the northern border, 16 m along the western border, 14 m along the southern border and 3 m along the eastern border, where the wind break acts as an additional buffer zone (Figure A2.4).

Suction cups, TDR and Pt-100 sensors

The suction cups, TDR and Pt-100 sensors at Jyndevad were installed in excavations S1 and S2 shown in Figure A2.4. The instruments were installed as described in Section 3.3 except that installation of the suction cups deviated as follows:

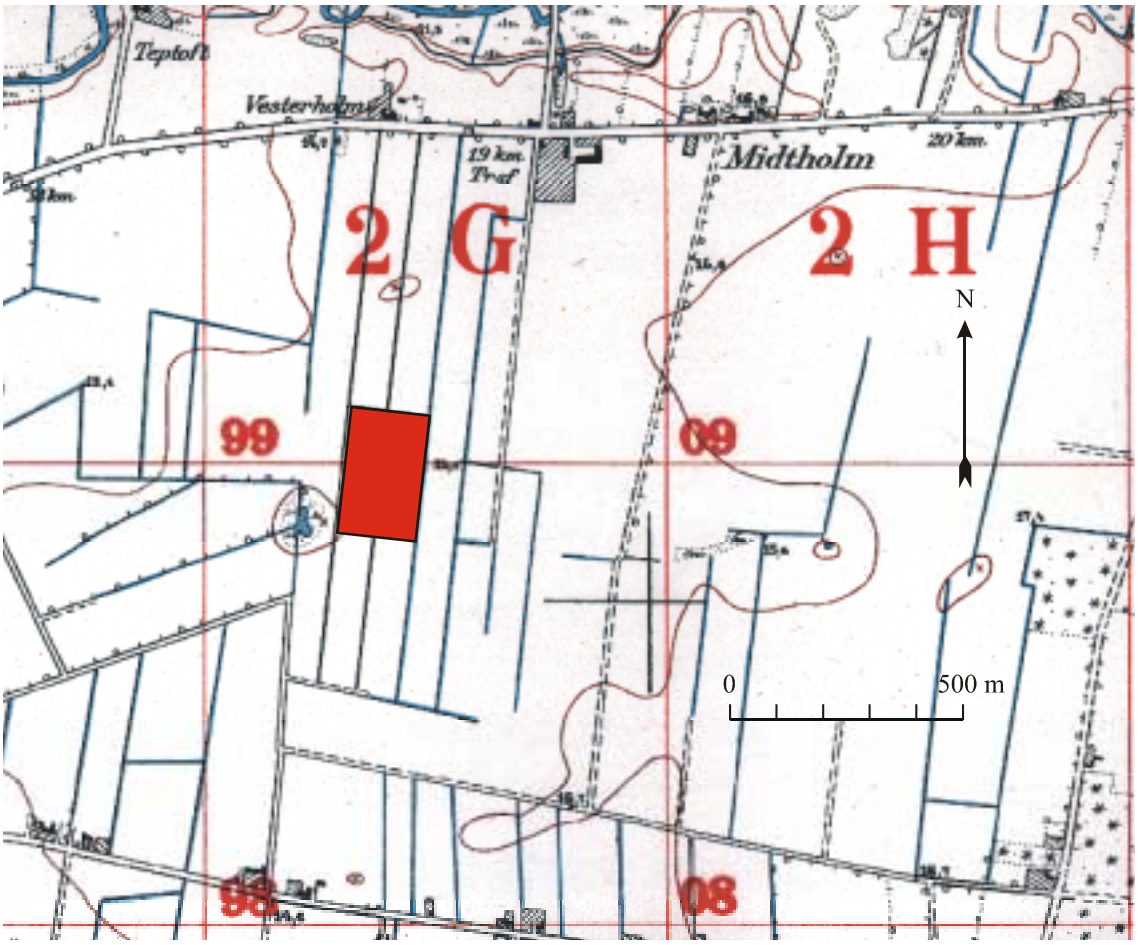


Figure A2.2. Topographic map 1:20.000 from 1934. The test field is marked as a red square.

- The suction cups installed 1 m b.g.s. were placed at a horizontal distance of 1.0 m from the edge of the field rather than 2 m as described in Section 3.3.
- The suction cups installed 2 m b.g.s. were placed at a horizontal distance of 1.5 m from the edge of the field rather than 2.5 m as described in Section 3.3.

Wells

Piezometers

Piezometers P1–P7 consist of ¾" electroplated pipes hammered into the ground. The remaining piezometers were drilled with a 6" (152 mm) solid stem auger down to around 4 m b.g.s. At deeper levels, below the groundwater table, the wells were drilled as cased wells using a bailer.

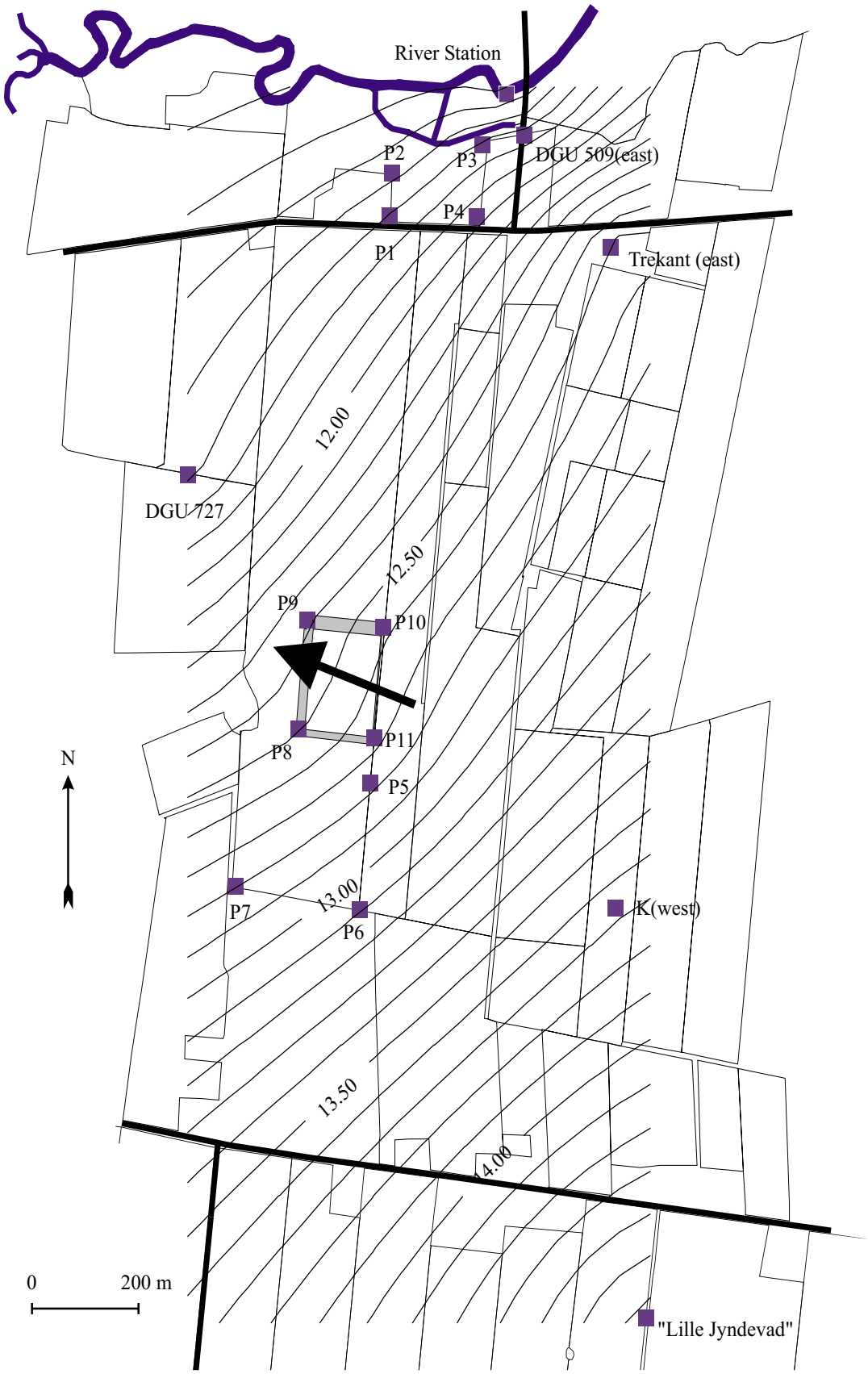


Figure A2.3. Potential head (m a.s.l.) at the site measured in September 1999, and the direction of the groundwater flow.

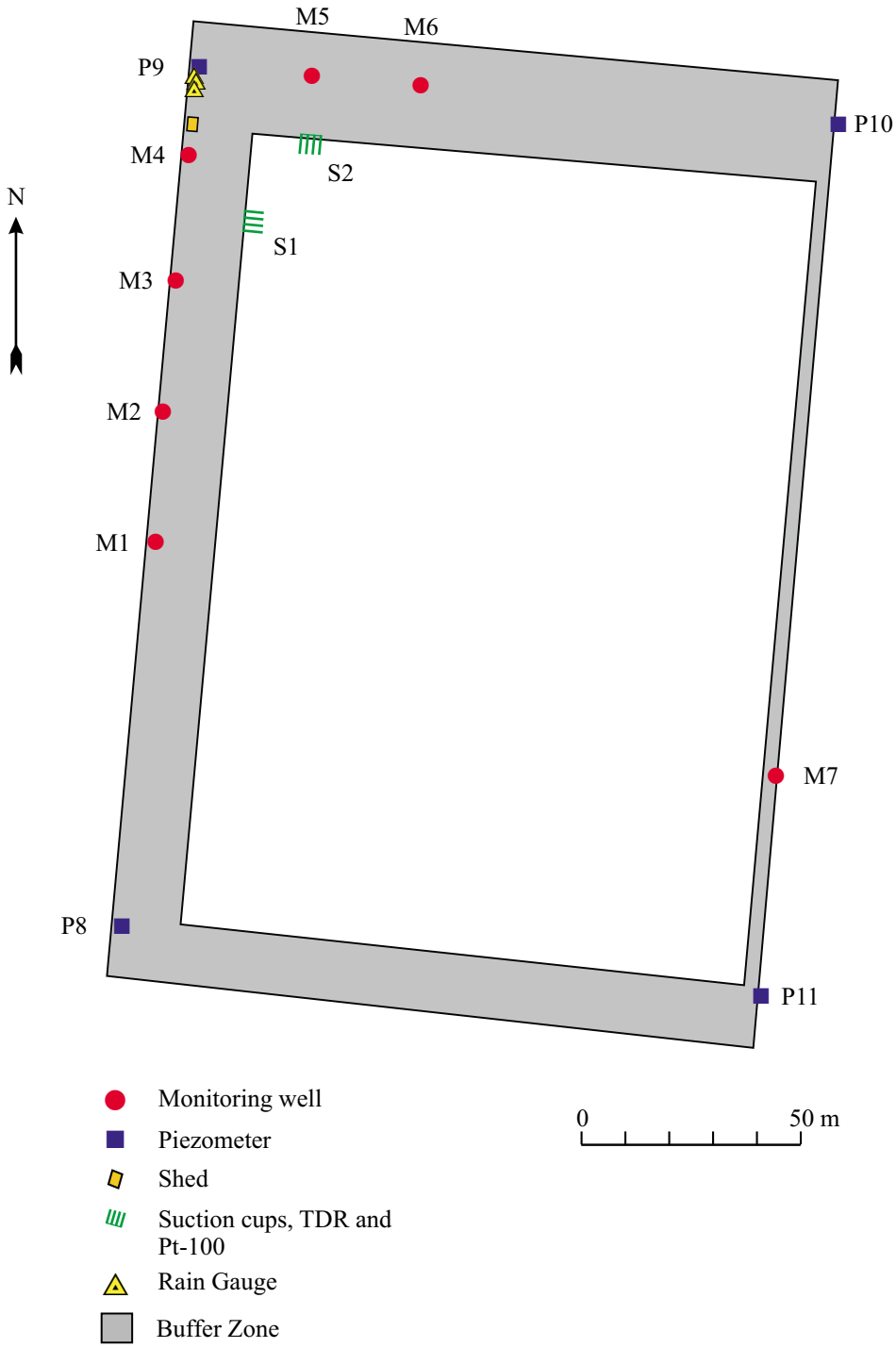


Figure A2.4. Sketch of the field showing the test and buffer zones and location of installations.

Piezometers P1–P7 were installed at the end of January 1999 in order to estimate the flow direction of the groundwater. In the area framed by piezometers P1–P4 (Figure A2.3), groundwater flow was highly influenced by the river immediately north of the area. An area further away from the river was thus selected instead (Figure A2.3). Piezometers P8–P11 were drilled on April 26–19 1999. The piezometers are placed at various depths in accordance with Table A2.2.

Table A2.2. Depth of the piezometer screens.

Well no.	DGU no.	Upper screen m b.g.s.	Middle screen m b.g.s.	Lower screen m b.g.s.
P1	–	6.5–6.6	–	–
P2	–	5.8–5.9	–	–
P3	–	6.7–6.8	–	–
P4	–	6.1–6.2	–	–
P5	–	5.2–5.3		
P6	–	4.7–4.8		
P7	–	4.7–4.8		
P8	167–1346	3.4–3.9	7.6–8.1	11.0–11.5
P9	167–1345	4.0–4.5	7.6–8.1	11.2–11.7
P10	167–1347	3.4–3.9	7.4–7.9	11.4–11.9
P11	167–1348	3.4–3.9	7.4–7.9	10.9–11.4

Vertical monitoring wells

A total of seven monitoring well clusters (M1–M7) each consisting of four individual wells were installed at Jyndevad in May 31–June 6 1999 (Figure A2.4). The top of the upper screen from each monitoring cluster was placed above the highest seasonal water table. The screens of one monitoring cluster were not necessarily placed at the same depths as the screens of other monitoring clusters (Table A2.3) due to minor variations in the topography within the buffer zone resulting in differences in the distances between the ground surface and the groundwater table.

Table A2.3. Depth of the monitoring well screens.

Monitoring well cluster	Screen Mx.1 m b.g.s.	Screen Mx.2 m b.g.s.	Screen Mx.3 m b.g.s.	Screen Mx.4 m b.g.s.
M1	0.6–1.6	1.6–2.6	2.6–3.6	3.6–4.6
M2	1.0–2.0	1.9–2.9	2.9–3.9	4.0–5.0
M3	0.9–1.9	2.1–3.1	3.2–4.2	4.1–5.1
M4	1.4–2.4	2.4–3.4	3.3–4.3	4.4–5.4
M5	1.6–2.6	2.7–3.7	3.7–4.7	4.7–5.7
M6	1.4–2.4	2.4–3.4	3.4–4.4	4.5–5.5
M7	1.6–2.6	2.6–3.6	3.6–4.6	4.6–5.6

A2.3 Geology

Regional geology

The following description of the regional geology is based on Hansen (1989). The Quaternary deposits in the region vary in thickness from about 10–125 m and rest on a rather flat surface of Tertiary marine clay from the Middle Miocene. Three landscapes are represented: Older Glacial landscapes, Younger Glacial landscapes, and Late-Glacial outwash plains. The test field is located on the outwash plain of Tinglev Hedeslette.

The older glacial landscapes occur like hilly islands on the outwash plain and have strongly eroded and smoothed surfaces. They consist of unsorted clayey, sandy or gravely till, deposited in Saalian time.

The Younger Glacial landscapes occur east of the Main Stationary Line, which marks the westernmost extension of the Weichselian ice sheet. The landscapes are characterized by undulating surfaces, tunnel valleys (subglacial erosion valleys), extramarginal meltwater valleys, eskers and iceborder areas.

The outwash plain consists of meltwater sand, locally draped by Post-Glacial aeolin sand and along streams by freshwater sand. In the eastern part of the outwash plain (east of the test field area) some low gravel ridges occur which represent crevasse fillings formed by meltwater deposits. These deposits together with a kettle hole field, which indicate the existence of a dead ice area, provide evidence of a final and short ice advance over the proximal part of the outwash plain. A well for Tinglev Waterworks (DGU no. 168.16B) contains deposits from 3 glaciations (Weichselian, Saalian and Elsterian) and 2 interglacial periods (Eemian and Holsteinian). Wells in the Jyndevad region show meltwater sand, a minimum of 35 m thick that locally contain meltwater gravel and clay.

Geomorphology

The outwash plain (Tinglev Hedeslette) on which the test field is situated slopes to the west and southwest with an average fall of about 1:1000. In the proximity of the Main Stationary Line the surface of the outwash plain occurs 60 m a.s.l. in the northern part of the outwash plain and 30–40 m a.s.l. in the southern part. In the western part of the outwash plain the surface is less than 5 m a.s.l. The surface of the outwash plain occurs approx. 14 m a.s.l. in the test field (Figure A2.5).

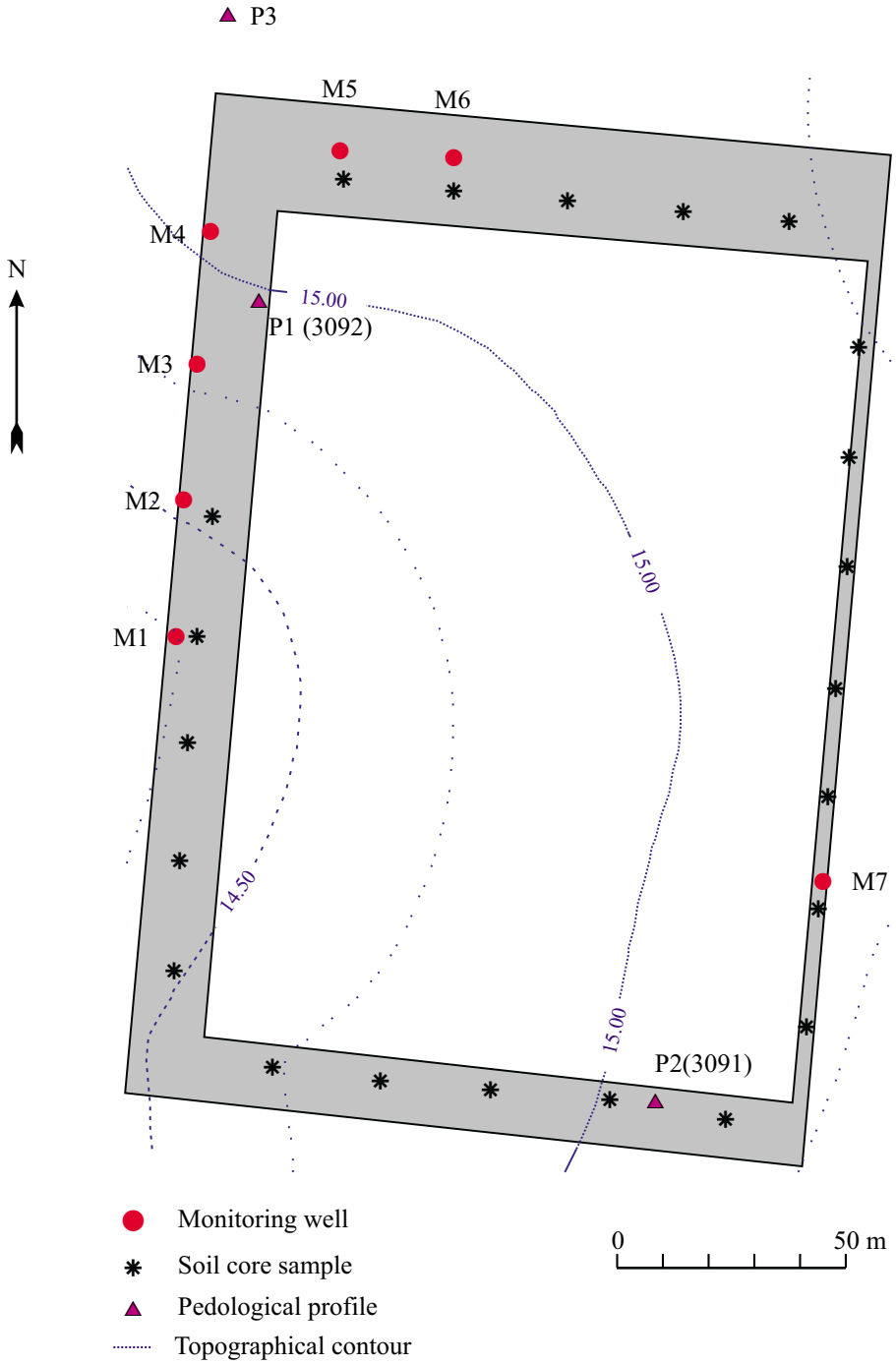


Figure A2.5. Topography at the site and location of soil cores, test pit and monitoring wells.

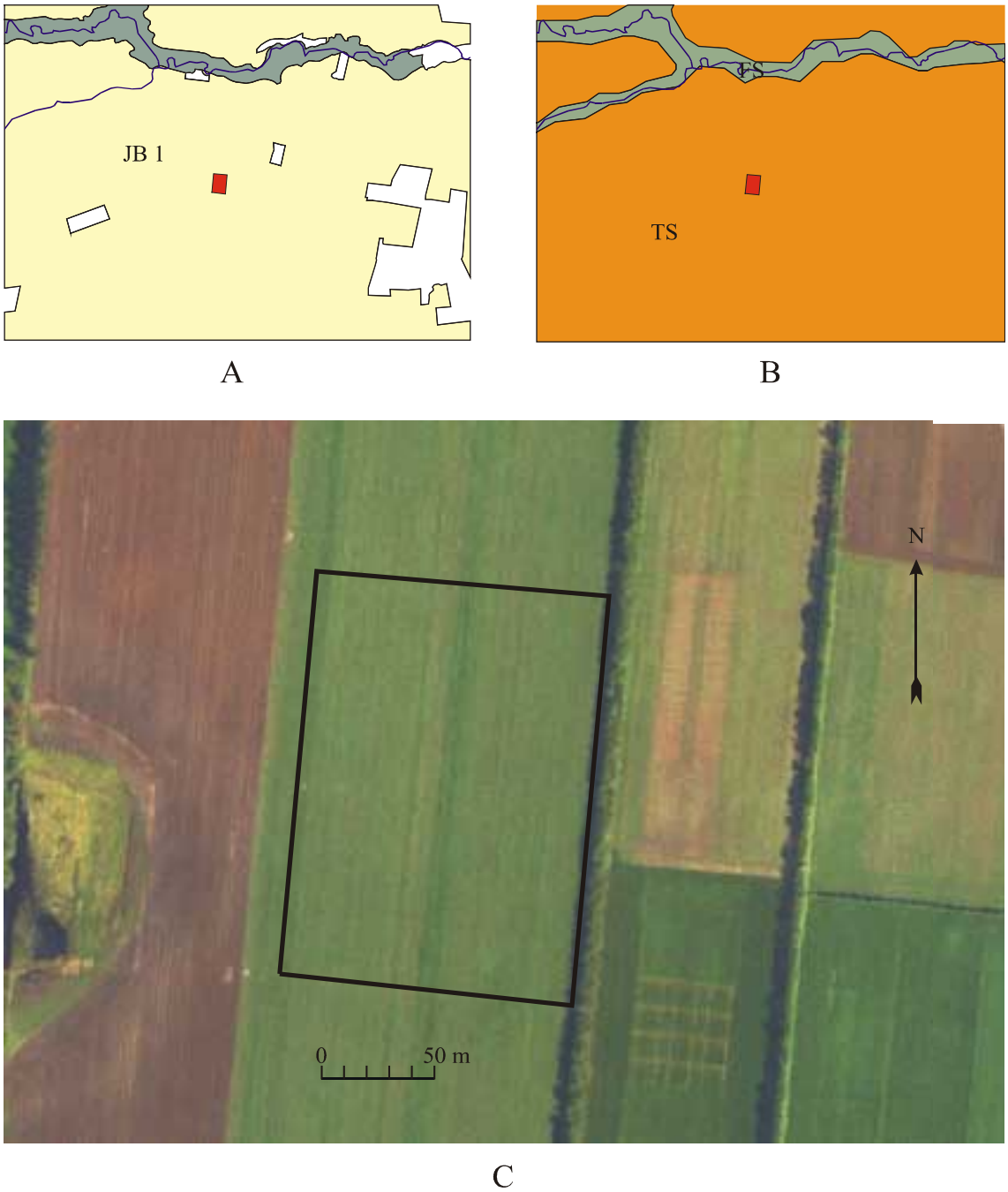


Figure A2.6. Location of the test field (red square) superimposed on: A) The soil type map. JB 1: Coarse sandy soil B) Map of Quaternary sediments in Denmark, TS: Late Glacial freshwater sand. C) An aerial orthophotograph (Kampsax Geoplan, DDO1999).

Figure A2.6 shows the test field superimposed on the map of Quaternary sediments in Denmark (Hermansen and Jacobsen,1998), the Soil Classification map and a 1999 aerial orthophotograph of the field. As is apparent from the figure, the field is located on a soil

type consisting of coarse sandy soil (JB1). The map of the Quaternary deposits of Denmark places the field in an area of Late-Glacial freshwater sand (TS) forming part of an outwash plain. Based on the orthophotograph, the field appears homogenous.

Geology of the monitoring wells and piezometer wells

The geological layers were described down to 12 m and about 5 m b.g.s., respectively, during the drilling of piezometers P8–P11 and monitoring wells M1–M7. The location of the wells is shown in Figure A2.4.

The wells drilled at Jyndevad show that the sediments are dominated by fine to coarse-grained sand, which in places contain gravel. Thin beds of clay and silt, generally 2–30 cm thick, occur locally (wells P9–10, M1, M3–4 and M6– M7 in Figure A2.7). The beds are thickest and most abundant in well M3 where a silt layer approx. 45 cm thick and two clay layers 20–30 cm thick occur within 1.15–3.2 m b.g.s. Fragments of charcoal occur in wells P8, P11 and M7. It is difficult to see sedimentary structures in the drilled sediments but horizontally bedding can be recognized locally.

Below the black topsoil layer the colour generally changes with increasing depth from dark yellowish brown followed by yellow brown and brownish yellow. In the deepest part the sediments have a light yellowish brown or light brownish grey colour. This shows that oxic conditions occur at least down to 12 m b.g.s. Piezometer P10 differs in that the sediments have a light olive grey colour from 10–12 m b.g.s. indicating suboxic conditions at this depth interval.

Geology of the test pits and ditch

Sediments and especially the pedology were studied in three excavations, approx. 1.7 m deep (P1,..P3, Figure A2.5). The following description focuses on the lithology and primary sedimentary structures as a basis for interpreting the depositional environment. The pedology is described in detail in Section A2.4. Generally soil formation has destroyed primary sedimentary structures in the uppermost 0.5 m of the excavations.

The sediments in the excavations consist of alternating beds of fine, medium and coarse-grained sand limited by erosional surfaces. The coarse-grained sand beds commonly contain gravel. The sand beds are structureless or trough cross-bedded with sets up to 30 cm thick. In excavation P1(3092) a clay layer, approx. 5 cm thick drapes an erosional depression approx. 2 m b.g.s.

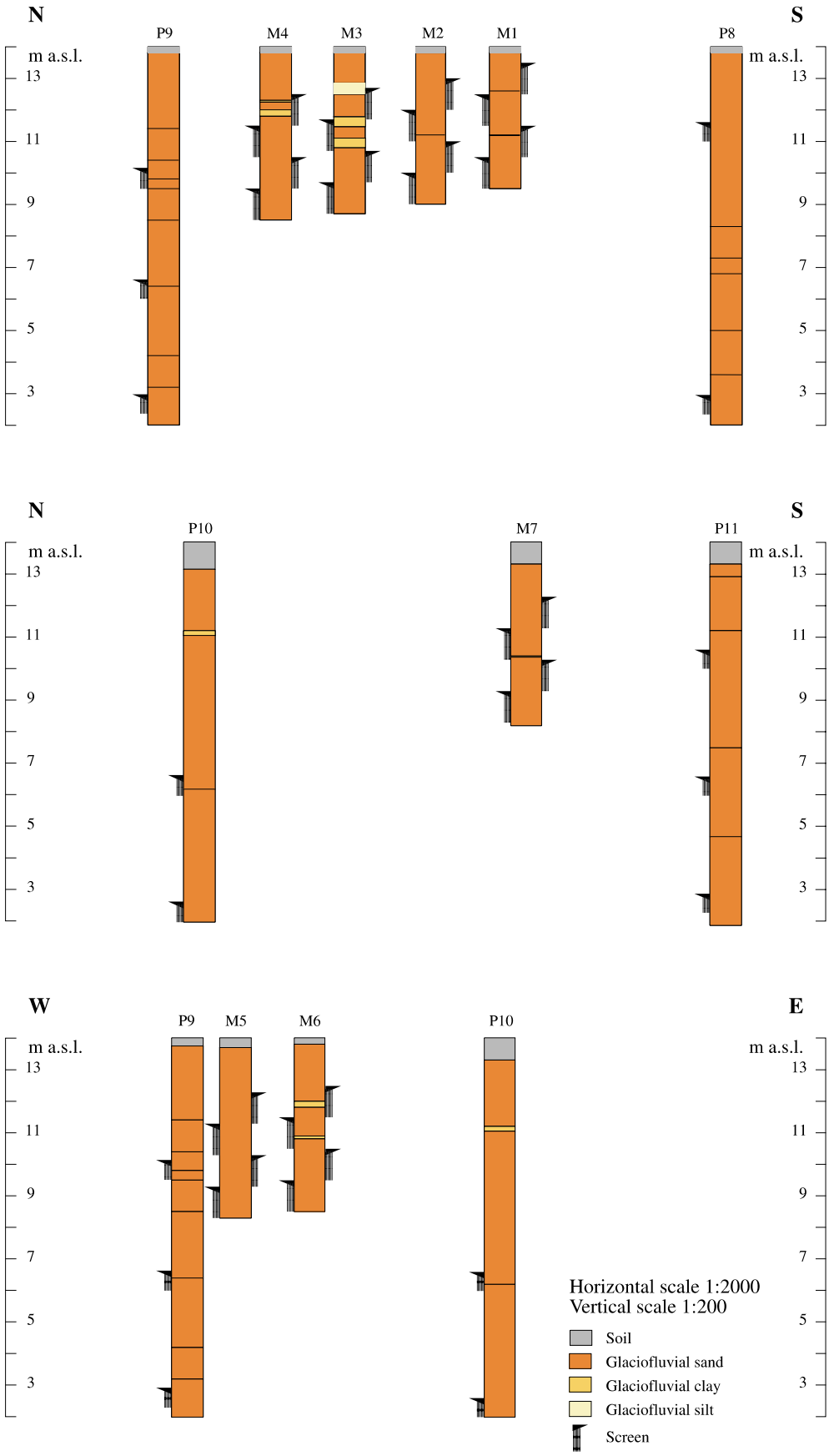


Figure A2.7. Cross sections based on wells at the site. The location of the wells is shown in Figure A2.4.

Interpretation of the depositional environment

Based on knowledge of the regional geology, the sediments within the test field are interpreted as having been deposited in a fluvial environment in front of a glacier. The sand, which occasionally contains gravel, was deposited during high-energy conditions and represents channel fill and bar deposits. In contrast, the clay and silt layers reflect deposition during low-energy conditions, probably attributable to channel switching or periods with low fluvial discharge.

Laboratory analyses

Grain size analysis

Grain size analysis has been carried out on six samples from the deeper levels of the site (see Table A2.4). The grain size analysis shows that the sand consists of fine and medium-grained sand or medium and coarse-grained sand. Two samples taken from clay layers show a clay content of approx. 32% and 39%, respectively.

Table A2.4. Texture analysis of selected well sediment samples expressed as percentage by weight.

	Grain size in mm								
Depth and location m b.g.s.	<0.002	0.002–0.020	0.02–0.63	<0.063	0.63–0.125	0.125–0.200	0.20–0.5	0.5–2.0	Sediment
P9(3.0)						6.8	44.3	44.8	Medium and coarse -grained sand
P9(5.5)				2.7	11.8	36.8	42.9	5.6	Fine and medium-grained sand
P9(8.7)				3.2	10.5	42.5	39.7	3.8	Fine and medium grained sand
P9(12.0)				0.3	1.4	4.4	46.8	47.2	Medium and coarse-grained sand
P10(2.9)	38.5	37.9	6.5	82.9	6.9	5.0	4.9	0.3	Clay
M4(8.7)	32.2	25.4	16.1	73.7	24.4	0.5	2.1	0.2	Clay

Data from GEUS Sediment Laboratory. Some of the fractions were determined by linear interpolation.

Table A2.5. **$CaCO_3$ and total organic carbon (TOC) content in selected well sediment samples.**

Locality	Depth m b.g.s.	TOC %	$CaCO_3$ %	Sediment
P8	4.7	0.17		Fine and medium-grained sand
P8	5.2	0.17		Coarse-grained sand
P8	5.7	0.08		Coarse-grained sand
P9	0.7		0	Medium-grained sand
P9	2.2	0.20	0.3	Sandy clay
P9	3.0	0.15		Medium-grained sand
P9	4.5	0.05	0	Medium-grained sand
P9	5.5	0.04	0.1	Fine and medium-grained sand
P9	5.7	0.19	2.4	Medium-grained sand
P9	6.1	0.05	1.6	Fine-medium grained sand
P9	6.5		0	Fine-medium grained sand
P9	7.2		1.6	Medium-grained sand
P9	8.0		0.2	Fine-medium grained sand
P9	8.7	0.04	0.7	Fine-medium grained sand
P9	9.8		0	Fine-medium grained sand
P9	10.3		3.3	Medium-grained sand
P9	12.0	0.06	4.2	Medium-grained sand
P10	2.9	0.14	1.2	Clay
M4	2.1	0.14	0	Clay

Data from GEUS Sediment Laboratory.

Total organic carbon (TOC) and $CaCO_3$ content

The TOC and $CaCO_3$ data are shown in Figure A2.8 and Table A2.5. In sediments containing carbonate, the carbonate content fluctuates with depth with maximum values of 4.2%. The total organic carbon content is about 1.4% in the topsoil layer at the test pits. Below the topsoil layer it decreases with increasing depth from about 0.18% to 0.04% in the deepest parts.

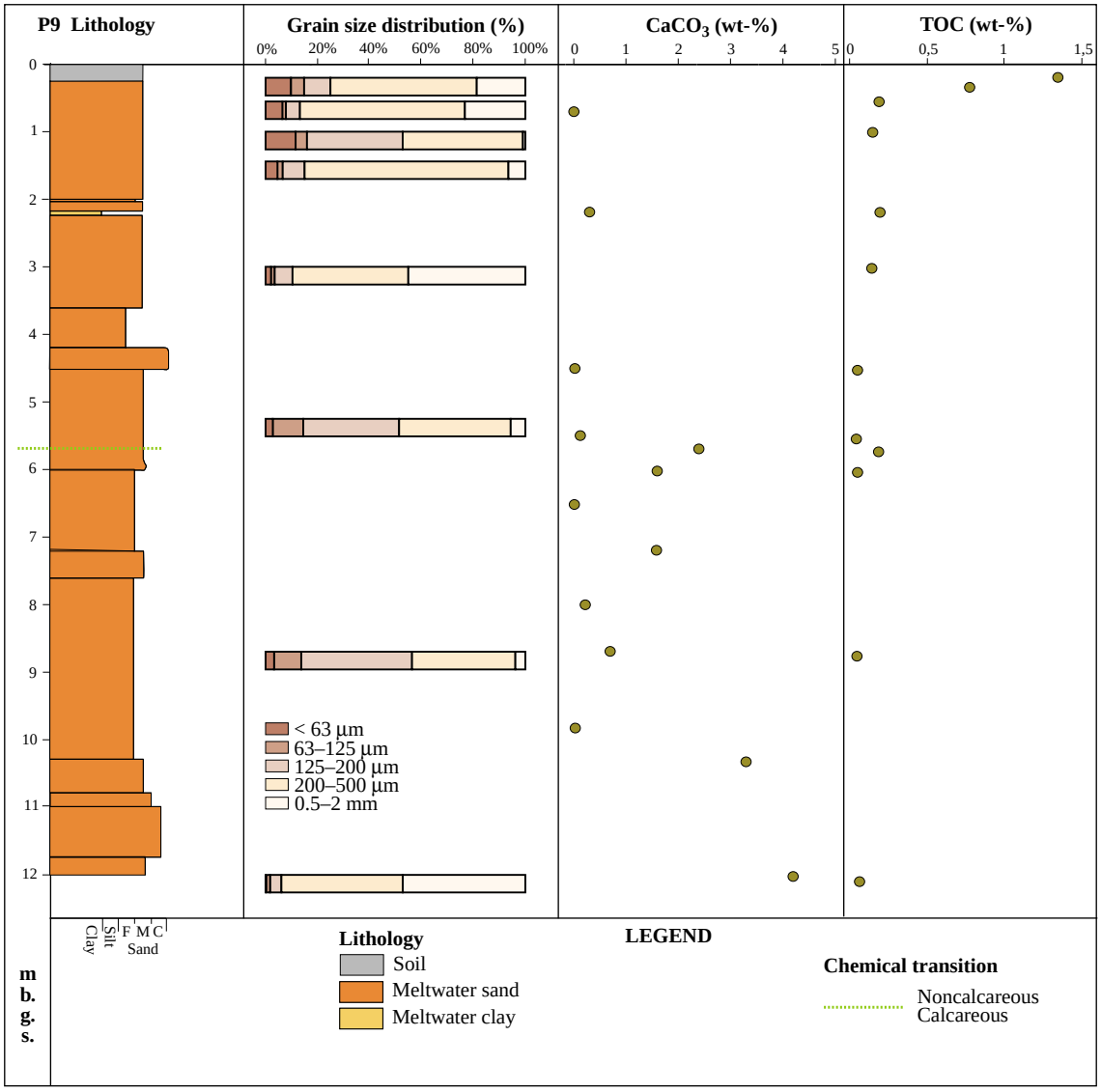


Figure A2.8. Lithology of well P9, grain size distribution and $CaCO_3$ and total organic carbon (TOC) content in the test pit. Grain size fractions larger than 2.0 mm are not included in the grain size analysis.

A2.4 Pedology

The pedological fieldwork at Jyndevad was carried out from May 25 to May 27 1999. Three soil profiles were excavated and described (Figure A2.5). One of these is located beside one of the groups of suction cups and only described in the field. In the buffer zone, 22 soil cores were collected to a depth of 120 cm (Figure A2.5). Inside the field, 48 soil samples were collected from the topsoil (0–25 cm).

Profile description

The pedological descriptions of the three profiles are summarized in Tables A2.6 to A2.8. The profile horizons are shown in Figure A2.9. Laboratory data (grain size, texture, organic matter, nutrients, and major cations) on the profiles are given in Table A2.9 and Table A2.10.

In Table A2.11 the profiles are classified according to both "A Pedological Soil Classification System Based on Danish Soils" (Madsen and Jensen, 1985) and USDA Soil Taxonomy (Soil Survey Staff, 1999).

Table A2.11. Classification of the profiles.

Profile no.	Danish Soil Classification	USDA Soil Taxonomy
1 (3092 West)	The profile had a diagnostic B horizon and will be classified as a Podsol. With no further characteristics it is a **Typipodsol**.	In view of the fact that the base saturation is >50%, the epipedon is mollic. Despite the spodical characteristics, the Bhs horizon does not meet the colour, Fe and Al requirements of spodical material and the horizon is therefore Cambic. In view of the mollic epipedon, the order is Inceptisol. In view of the udic soil moisture regime, it is an Udept. In view of the high base saturation of up to 75 cm, the soil is an Eutrudept. Because of the distribution of sandy particles the soil is therefore an **Arenic Eutrudept**.
2 (3091 South)	do.	In view of the mollic epipedon, the order is Inceptisol. In view of the udic soil moisture regime, it is a Udept. With a base saturation <60% from 25 to 75 cm this profile is a Dystrudept. Moreover, because it has a mollic epipedon and a sandy texture it is **a Humic Psammentic Dystrudept**.

Table A2.6. Description of profile 1 (3092 St. Jyndevad West).

Soil classification, DK	Typipodsol	**Soil classification, USDA**	Arenic Eutrudept
Parent material	Glaciofluvial sand	**Profile depth**	150 cm
UTM	32 U NF Easting 507716 Northing 6083324	**Drainage class**	Well drained
Landform	Glaciofluvial plain	**Groundwater level**	175 cm
Map sheet	1211 IV NV	**Vegetation**	Spring barley
Elevation	15 m DNN	**Maximum rooting**	50 cm
Topography	Flat	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	26.05.99

	Profile description **Ap (0–31 cm)** Black (10YR 2/1 f) clayey sand, containing humus, a few small stones of varying shape and type, frequent fine roots, 1–10 pores per dm^2, abrupt smooth boundary. **Bhs (31–42 cm)** Black (7.5YR 2.5/2 f) sand, containing humus, a few small stones of varying shape and type, a few fine roots, very little mottled thin coatings of clay minerals and humus between the grains of sand, weak thin granular structure, clear irregular boundary. **Bs (42–73 cm)** Dark yellowish brown (10YR 4/6 f) sand with intermixture of coarse sand, humus poor, a few small stones of varying shape and type, very little mottled thin coatings of clay minerals between the grains of sand, gradual wavy boundary. **BC (73–120 cm)** Yellowish brown (10YR 5/6 f) clayey sand with bands of silty sand, a few rounded medium clear primary spots with diffuse boundary (7.5 5/6 f), secondary spots (10YR 5/4 f), humus poor, no stones, gradual wavy boundary. **C (120–150 cm)** Light yellowish brown (10YR 6/4 f) sand, with spots (10YR 8/1 f), humus poor, no stones.
Remarks	The Ap horizon contains pale quartz sand corn. The BC and C horizons have cross-bedding structures of approx. 10 cm thick sand layers with silty brown stripes/layers (10YR 4/2 f).

Table A2.7. Description of profile 2 (3091 St. Jyndevad South)

Soil classification, DK	Typipodsol	**Soil classification, USDA**	Humic Psammentic Dystrudept
Parent material	Glaciofluvial sand	**Profile depth**	175 cm
UTM	32 U NF Easting 507810 Northing 6083075	**Drainage class**	Well drained
Landform	Glaciofluvial plain	**Groundwater level**	175 cm
Map sheet	1317 III SV	**Vegetation**	Spring barley
Elevation	15 DNN	**Maximum rooting**	50 cm
Topography	Flat	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	26.05.99

Profile description

Ap (0–33 cm)
Black (10YR 2/1 f) clayey sand, containing humus, a few small stones of varying shape and type, artificial liming, frequent fine roots, 1–10 wormholes and root channels per dm^2, very weak granular structure, smooth abrupt boundary.

Bhs (33–45 cm)
Black (5YR 2.5/1 f) clayey sand, containing humus, a few small stones of varying shape and type, some fine roots, weak coarse subangular structure, continuous thin coating of clay minerals and humus between grains of sand, clear irregular boundary.

Bs (45–89 cm)
Dark yellowish brown (10YR 3/6 f) clayey sand, humus poor, a few small stones of varying shape and type, very weak structure, diffuse wavy boundary.

BC (89–110 cm)
Yellowish brown (10YR 5/4 f) clayey sand with intermixture of coarse sand, humus poor, a few small stones of varying shape and type, very weak structure, diffuse wavy boundary.

C (110–150 cm)
Brownish yellow (10YR 6/6 f) sand, humus poor, a few small stones of varying shape and type, many horizontal stripes of thin conspicuous spots with diffuse boundary.

Remarks	C horizon: Red iron bands that follow the fine laminated structures.

Table A2.8. Description of profile 3 (St. Jyndevad North).

Soil classification, DK	Typipodsol	**Soil classification, USDA**	Humic Psammentic Dystrudept
Parent material	Glaciofluvial sand	**Profile depth**	160 cm
UTM	32 U NF Easting 507741 Northing 6083272	**Drainage class**	Well drained
Landform	Glaciofluvial plain	**Groundwater level**	175 cm
Map sheet	1317 III SV	**Vegetation**	Spring barley
Elevation	15 DNN	**Maximum rooting**	50 cm
Topography	Flat	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	24.05.99

Profile description

Ap (0–30 cm)
Black (10YR 2/1 f) clayey sand, containing humus, a few small stones of varying shape and type, artificial liming, frequent fine roots, 1–10 wormholes and root channels per dm^2, very weak granular structure, smooth abrupt boundary.

Bhs (30–48 cm)
Black (5YR 2.5/1 f) clayey sand, containing humus, a few small stones of varying shape and type, some fine roots, weak coarse subangular structure, continuous thin coatings of clay minerals and humus between grains of sand, clear broken boundary.

Bs (48–73 cm)
Dark yellowish brown (10YR 4/6 f) clayey sand, humus poor, a few small stones of varying shape and type, very weak structure, no roots, gradual wavy boundary.

BC (73–84 cm)
Dark yellowish brown (10YR 4/4 f) clayey sand, humus poor, a few small stones of varying shape and type, very weak structure, diffuse wavy boundary.

C (84–160 cm)
Light yellowish brown (10YR 6/4 f), humus poor, a few small stones of varying shape and type, lots of horizontal strips of medium conspicuous spots with diffuse boundary.
Textural band: Yellowish brown (10YR 5/6 f) medium silty sand, with a few horizontally striped diffuse mottles of dark yellowish brown (10YR 4/4 f).

Remarks	None.

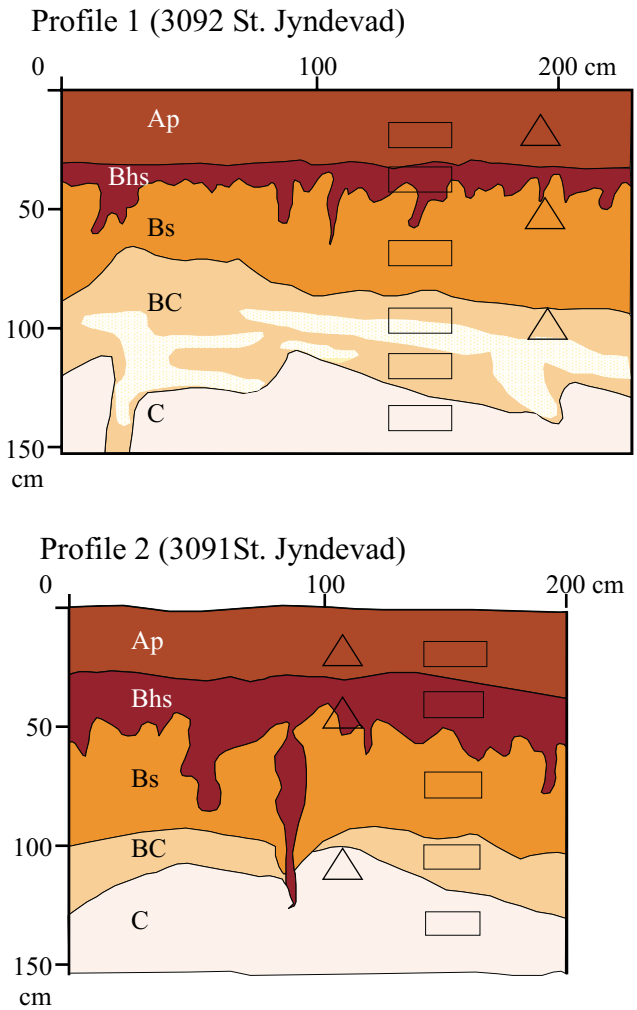


Figure A2.9. Schematic drawings of the profiles showing horizon distribution. Rectangular boxes indicate sampling points for soil texture and soil chemistry. Triangular boxes indicate sampling points for hydrological analysis.

Table A2.9. Soil texture analysis from the pedological profiles.

Pro. no.	Hor. no.	Horizon	Depth cm	Soil texture (mm) % <0.002	0.002–0.02	0.02–0.63	0.63–0.125	0.125–0.2	0.2–0.5	0.5–2	$CaCO_3$ %	OM[1] %
1	1	Ap	17–27	5.3	3.2	1.0	5.0	9.9	55.1	18.3	–	2.3
1	2	Bhs	33–42	4.6	1.8	1.0	2.8	6.8	61.2	20.6	–	1.3
1	3	Bs	51–61	4.0	1.4	1.0	1.4	5.4	63.3	23.2	–	0.3
1	4	BC	85–95	5.9	0.5	1.0	4.5	46.1	41.2	0.7	–	0.1
1	5	BC	97–105	9.6	0.9	1.0	4.4	36.8	46.2	0.9	–	0.3
1	6	C	137–147	3.0	0.5	1.0	2.1	8.4	78.4	6.5	–	0.1
2	1	Ap	13–23	5.2	2.8	1.6	9.7	19.2	46.4	11.7	–	3.4
2	2	Bhs	34–44	5.6	1.9	1.3	6.6	14.9	50.3	17.5	–	1.9
2	3	Bs	67–77	4.0	0.5	1.0	3.4	11.7	54.5	24.4	–	0.5
2	4	BC	97–107	3.5	0.9	1.0	2.6	5.8	46.2	39.7	–	0.3
2	5	C	124–134	3.4	0.5	1.0	1.1	7.1	78.6	8.2	–	0.1

1) OM: Organic matter. Om = 1.72 x TOC. Analysed by DIAS.

Table A2.10. Soil chemistry of samples from the pedological profiles.

Pro. no.	Hor. no.	N_{total} %	C/N	P_{total} mg/kg	pH[1]	K	Na	Ca	Mg	Total bases	H^+	CEC	Base Sat. %	Fe (Ox) mg/kg	Al (Ox) mg/kg
						cmol/kg									
1	1	0.11	12	545	6.17	0.28	0.06	5.27	0.42	6.03	0.57	6.6	91	1612	944
1	2	0.06	13	268	5.82	0.05	0.04	2.71	0.27	3.07	0.43	3.5	88	1252	1952
1	3	0.03	6	142	5.77	0.04	0.02	0.76	0.14	0.96	0.74	1.7	57	828	1414
1	4	0.02	3	106	5.68	0.13	0.02	1.77	0.4	2.32	0.78	3.1	75	992	1010
1	5	0.03	6	87	4.45	0.17	0.03	2.47	0.3	2.97	2.53	5.5	54	1220	1264
1	6	0.02	3	79	4.41	0.03	0.01	0.15	0.02	0.21	0.99	1.2	18	796	636
2	1	0.13	15	440	5.64	0.19	0.07	6.12	0.5	6.88	1.72	8.6	80	1428	874
2	2	0.06	18	209	5.55	0.04	0.03	3.32	0.18	3.57	2.63	6.2	58	2016	2200
2	3	0.03	10	144	4.99	0.03	0.01	0.39	0.02	0.45	1.45	1.9	24	936	1848
2	4	0.03	6	100	5.92	0.03	0.02	0.57	0.03	0.65	0.95	1.6	41	1088	1680
2	5	0.02	3	84	5.39	0.02	0.01	0.27	0.02	0.32	0.88	1.2	27	1252	1032

1) pH determined in $CaCl_2$ solution. Analysed by DIAS.

Total carbon mapping

The samples from the topsoil inside the field were analysed for total organic carbon (TOC), which varied between 1.4 and 2.2% (dry weight), with a mean of 1.8±0.2%. The concentration is highest in the southwestern part of the field and lowest in the northeastern part of the field (see Figure A2.10).

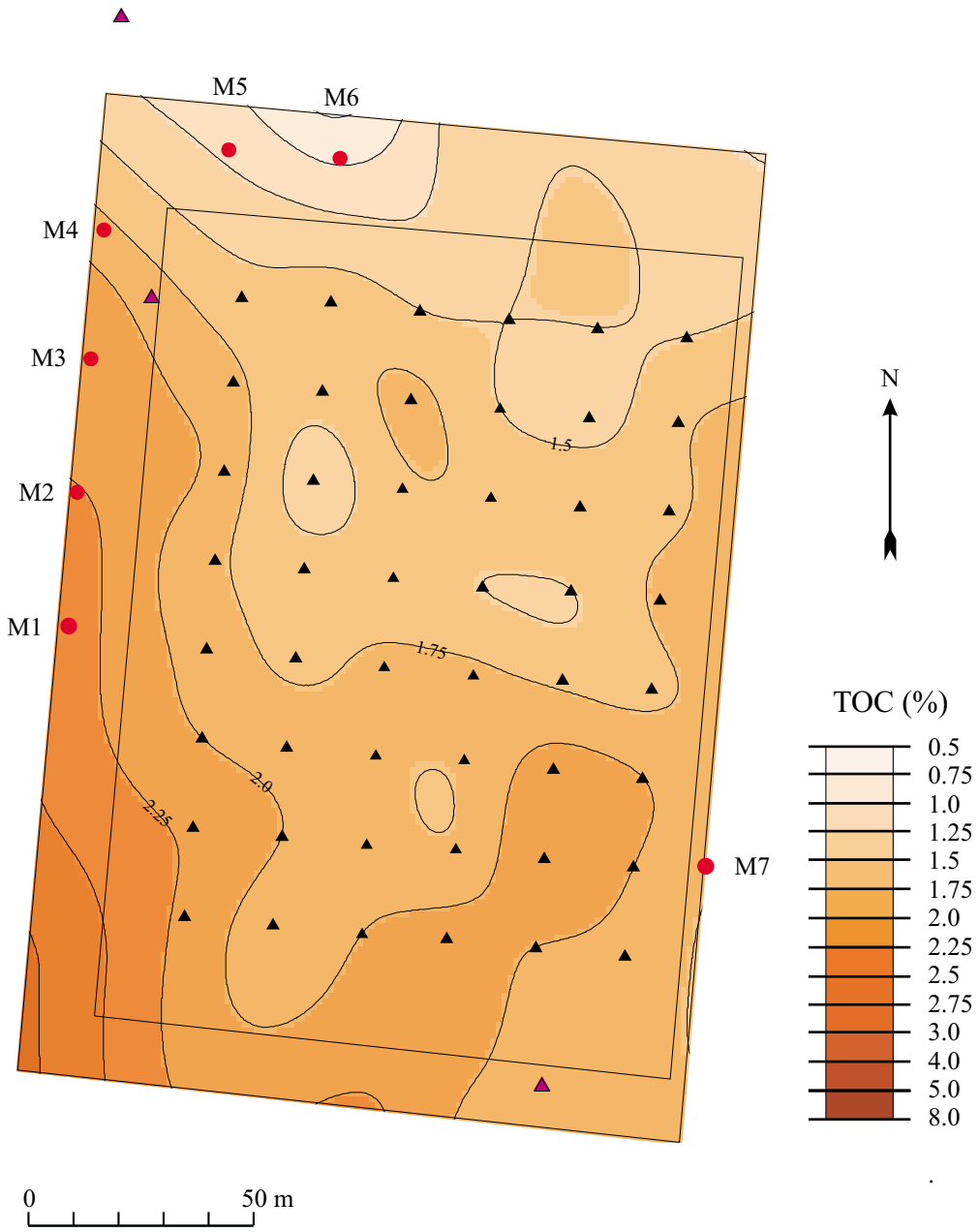


Figure A2.10. Map showing total organic carbon (TOC) content within the test field. Sampling points are indicated by ▲.

Soil cores from the buffer zone

The soil cores show that with few exceptions, the succession of horizons is the same in the entire area. The thickness of the Ap horizon varies from 23 to 33 cm. The thickness of the Bhs horizon varies from 7 to 25 cm in the entire area. Below this lies the Bs horizon with a diffuse lower border.

Pedological development

Hansen (1976), Heidmann (1989) and Greve *et al.*(1998) have previously carried out pedological and soil type investigations at the experimental station. These profiles all lie northeast of the test field at a distance of 0.4–1.4 km. Data are also available for a Square Grid Profile (Statens Planteavlsforsøg, 1996) approx. 2.5 km to the southwest.

The grain size distribution of the plough layer in profile 1 (West) is 55% coarse medium sand, approx. 20% coarse sand, and 5.3% clay. A texture band at a depth of 100 to 130 cm contains 9.6% clay. In the C horizon the texture is better sorted containing 78% coarse medium sand. To some extent the distribution is the same in profile 2 (South), although the texture band is missing. The six reference profiles (mentioned above) all show very similar grain size distribution, i.e. approx. 60–70% coarse medium sand and coarse sand. Due to the coarse grain size distribution the soil is almost structureless except in the Bhs horizon, which has a slightly coarse subangular structure due to humus, Fe, and Al deposition.

Only the Bhs and the Bs horizons remain from what was most likely the original succession of horizons (OA, E, Bh, Bhs and Bs) (Figure A2.9). Eluvial material (washed-out E horizon) was only found at a single drilling site. Bleached quartz sand grains were found in the plough layer – a trace of a previous E horizon. The raw humus layer (OA) and the washed-out horizon (E) have been mixed by ploughing, and the carbon content has subsequently been enhanced by fertilization.

It can also be seen that the fertilization has resulted in increased phosphorous levels in the Ap horizon (Table A2.10). The high content of Fe and Al in the Bhs horizon together with the high C/N ratio clearly shows that the soil has been podsolized. In profile 1 (West) the Al and Fe levels are not coincidental as the Fe content is higher in the plough layer whereas the Al content is highest in the Bhs horizon. This must be attributable to the greater mobility of aluminium (Duchafour, 1979) and the fact that the Bh horizon may have been incorporated into the plough layer. A podsol would normally have a low pH (approx. 4) that increased with increasing depth. Because of agricultural use of lime, however, the pH profile is now the reverse, pH being highest near the surface. The soil should be characterized as a partially developed podsol since the Bhs horizon is only faintly cemented (Duchafour, 1979). The expected, strongly cemented Bh horizon (hard pan layer) is absent, probably having been removed by cultivation.

The rooting depth is only about 40 cm and has been demonstrated in both the present investigation and by Nielsen and Møberg (1985).

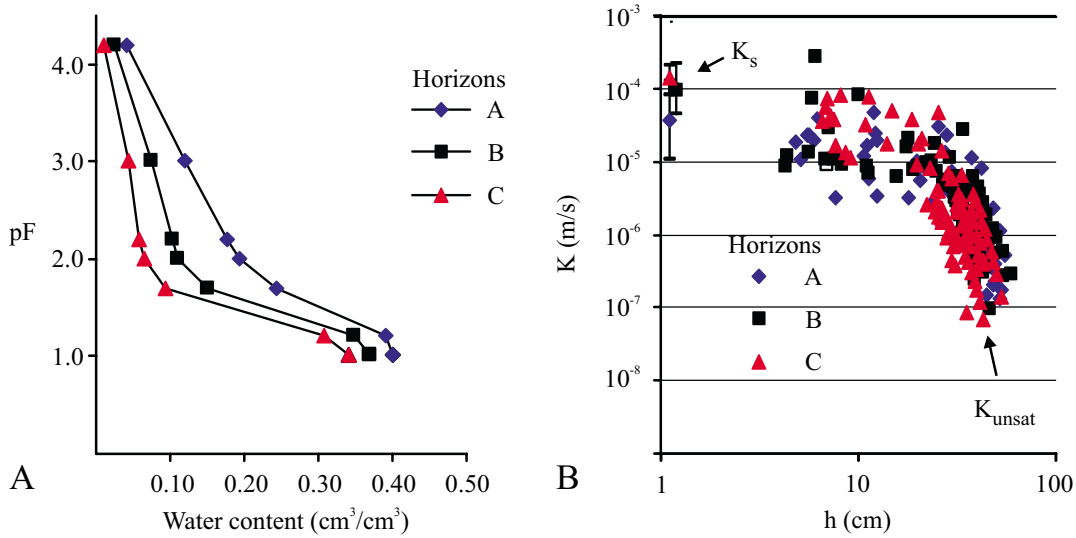


Figure A2.11. A) Retention curve based on values for the soil-water potential determined on the small soil cores samples (100 cm^3). The data are the mean values from the three profiles. B) The unsaturated hydraulic conductivity (K_{unsat}) as a function of soil water potential in cm H_2O and the saturated hydraulic conductivity (K_s) determined on the large soil cores (6,280 cm^3).

The soil is generally well drained as far as the profiles go, although red bands of iron deposits in profile 2 (South) bear witness of faintly hydromorph features due to temporary water storage above the underlying texture band (Table A2.7). The soil cores exhibit the same, but in the more low-lying southwestern part of the area, where the groundwater table is approx. 1 m b.g.s. Above this there is a 40 cm thick BC horizon with reddish iron deposits and faintly striped pseudogley.

Soil hydrology

Soil cores (100 cm^3 and 6,280 cm^3) for the measurement of hydrological properties (soil water characteristics and hydraulic conductivity) were sampled at three levels corresponding to the A, B and C horizons.

The soil water characteristics for the nine small cores (100 cm^3) from each horizon are shown together with bulk density and porosity in Table A2.12 and Figure A2.11.

Table A2.12. Soil water characteristics determined on the small soil cores, pF = $\log_{10}(-h)$

Profile no.	Horizon	Depth cm [2]	Water content at pF values cm^3/cm^3							Bulk density g/cm^3	Porosity[1] cm^3/cm^3
			1.0	1.2	1.7	2.0	2.2	3.0	4.2		
1 (3092)	Ap	15	0.41	0.40	0.23	0.19	0.17	0.12	0.04	1.37	0.48
	Bhs/Bs	40	0.35	0.33	0.15	0.11	0.10	0.07	0.01	1.49	0.44
	BC	115	0.34	0.32	0.10	0.06	0.06	0.04	0.01	1.52	0.43
2 (3091)	Ap	15	0.40	0.39	0.28	0.22	0.20	0.13	0.05	1.42	0.47
	Bhs/Bs	40	0.39	0.36	0.20	0.15	0.14	0.10	0.03	1.38	0.48
	C	130	0.34	0.28	0.09	0.07	0.06	0.05	0.01	1.48	0.44
3(North)	Ap	15	0.39	0.38	0.22	0.17	0.16	0.11	0.03	1.43	0.46
	Bhs	40	0.37	0.35	0.10	0.07	0.07	0.05	0.03	1.47	0.44
	C	110	0.34	0.32	0.09	0.06	0.05	0.04	0.01	1.50	0.43

1) Assuming a particle density of 2.65 g/cm^3.
2) Mid-point of soil core

The soil water characteristics show that due to a low water-holding capacity most of the water drains out of the soil at a pF value of 2. The majority of the soil pores are about 100 μm (tube-equivalent diameter), see Figure A2.12.

The saturated and unsaturated hydraulic conductivity determined on the large cores (6,280 cm^3) are shown in Figure A2.11. Hydraulic conductivity was high ranging from saturation until a soilwater potential of about –30 cm H_2O, whereafter the conductivity decreased rapidly. The lowest values are found in the Ap horizon because of the higher organic matter content than in the B and C horizons. Compared to the more loamy soils, inter-measurement variability is low.

Measurements of saturated hydraulic conductivity and air permeability using small (100 cm^3) or large (6,280 cm^3) soil samples did not reveal any significant differences due to the weakly structured nature of the soil. The soil sample is thus representative irrespective of whether a small or a large soil sample is used for the analysis.

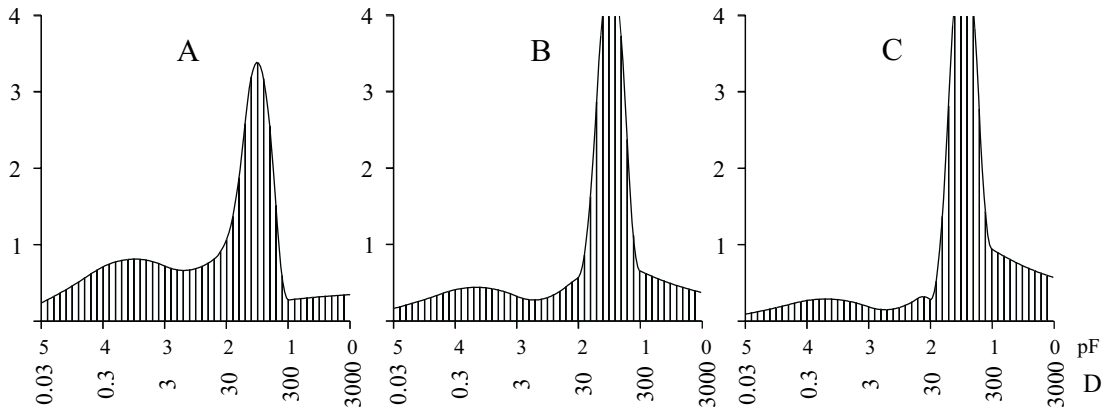


Figure A2.12. Pore size distribution measured (A, B, and C horizon) calculated from water retention data assuming the unity D=3000/10pF (D = pore diameter equivalent diameter, µm). A cubic spline interpolation procedure is used to yield discrete interpolate values on the sum curve obtained from the water retention curves. Abscissa: pF=log10(-h) in which h is the soil water potential in cm H_20. D = pore diameter, µm. Ordinate: percentage of pore volume per 1/10 pF-values, % v/v.

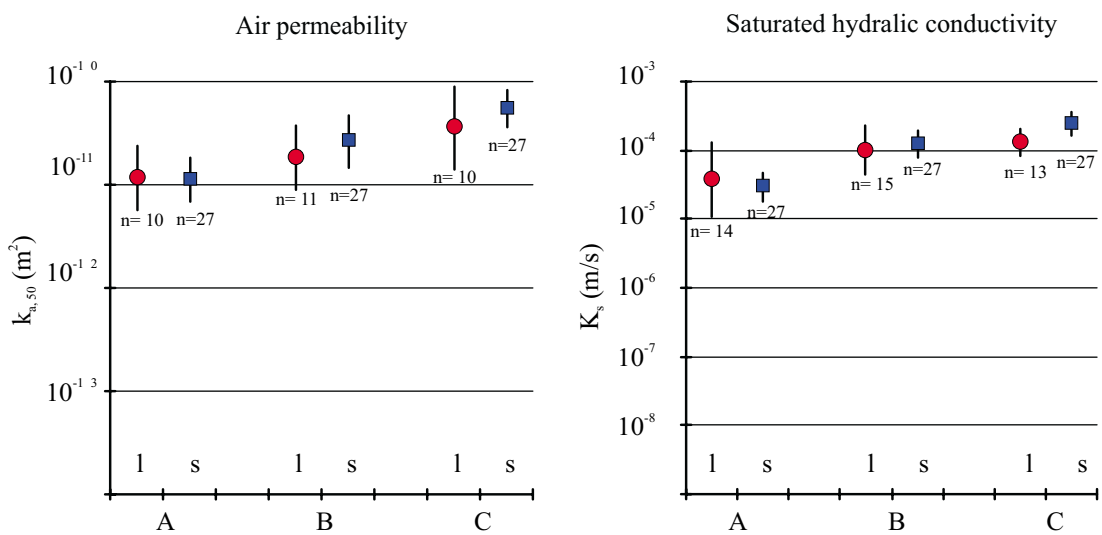


Figure A2.13. Air permeability at a water content of –50 cm H_20 ($k_{a,50}$) and saturated hydraulic conductivity (K_s) measured on large (6,280 cm^3) samples (●) and small (100 cm^3) samples (■).

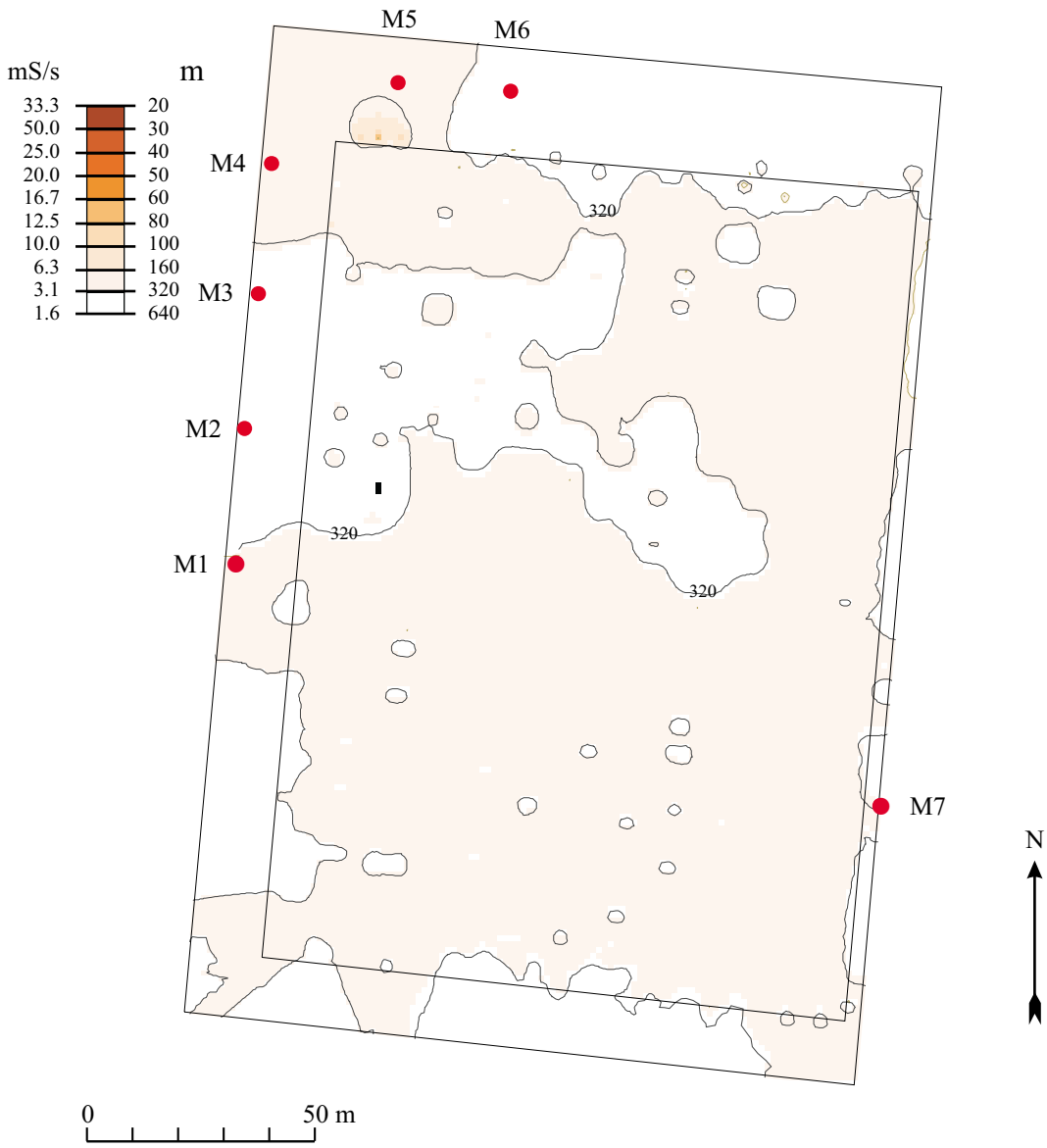


Figure A2.14. Resistivity maps of the area.

A2.5 Geophysical mapping

Since destructive mapping methods are not accepted in the test field, it was decided to use EM-38 and ground-penetrating radar.

EM-38

The EM-38 recordings revealed only minor variation (Figure A2.14). A 20 m wide band of higher values crosses the area from the west to east. The same pattern is seen in small areas scattered throughout the test field. The band and the small areas can also be seen as dark shadows on the orthophotograph. This is attributable to minor depressions in the topography with a higher content of humus-rich horizons or thicker humus-rich

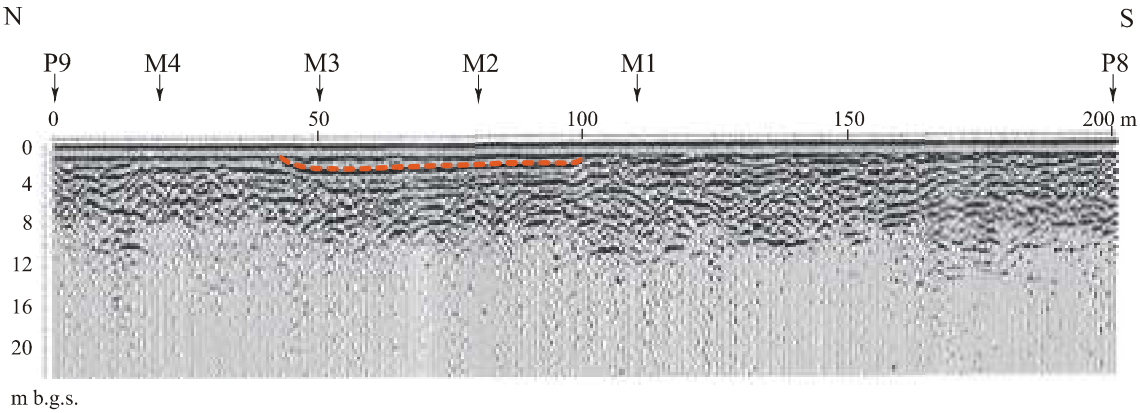


Figure A2.15. Ground penetrating radar profile.

horizons. Compared with the TOC (A2.10), there is no obvious connection to the carbon content of the plough layer, however.

Ground-penetrating radar (GPR)

The ground-penetrating radar mapping was conducted using 100 MHz aerials and a presumed wave velocity of 0.130 m/ns along a grid lines at 20 m x 20 m. The reflectors on the GPR cross sections generally form complex structures indicating cross-bedding and horizontal beds of varying grain size. The penetration depth varies from 7–16 m. Areas where the penetration depth is greater than 12 m seem to be randomly distributed. In areas where the penetration depth is low this may be due to the occurrence of one or more silt/clay layers near the ground surface or because the mean grain size of the sediments is lower than in the remaining areas. Several of the clay horizons occurring in the wells are seen as continuous reflectors, up to 100 m long, in the georadar cross sections. The clay layer occurring 2.9–3.2 m b.g.s. at monitoring well M3 probably corresponds to the thin clay layer occurring 2.8 m b.g.s. at monitoring well M1, as indicated on the N-S georadar cross section 1 (Figure A2.15). The clay layer has not been observed in monitoring well M2, however, as would have been expected on the basis of the GPR cross section. The thin clay layer occurring 3.6 m b.g.s. at monitoring well M7 can be followed on the S-N georadar cross section 3 over a distance of approx. 100 m starting immediately north of piezometer P11. The same clay layer is seen as an approx. 60 m long reflector on the E-W georadar cross section 12. This indicates that some of the clay layers observed in the wells cover relatively large areas within the test field.

Appendix A2.1. Cultivation and pesticide application history at Jyndevad.

Year	Crop	Date	Pesticide brand	Dose per ha
Western part				
1995	Spring barley		Express	§
			Dantril	§
1996	Spring barley		Express	§
			Dantril	§
			Roundup	§
1997	Potatoes		Sencor WG	0.35 kg
			Unknown fungicides	§
1998	Potatoes		Sencor WG	0.35 kg
			Unknown fungicides	§
1999	Spring barley	10.05.1999	Logran 20 WG	0.015 kg
		10.05.1999	Mantrac (manganese fertilizer)	
Eastern part				
1995	Spring barley		Express	§
			Dantril	§
1996	Peas		Unknown	§
1997	Winter wheat		Biotril	0.5 l
1998	Maize		Roundup	2.0 l
			Gardoprim	1.5 l
			Lentagran	2.0 l
1999	Spring barley	10.05.1999	Logran 20 WG	0.015 kg
		10.05.1999	Mantrac (manganese)	

§) Information of the dose does not exist.

Site Characterization and Monitoring Design

Annexe 3.

Site 3: Silstrup

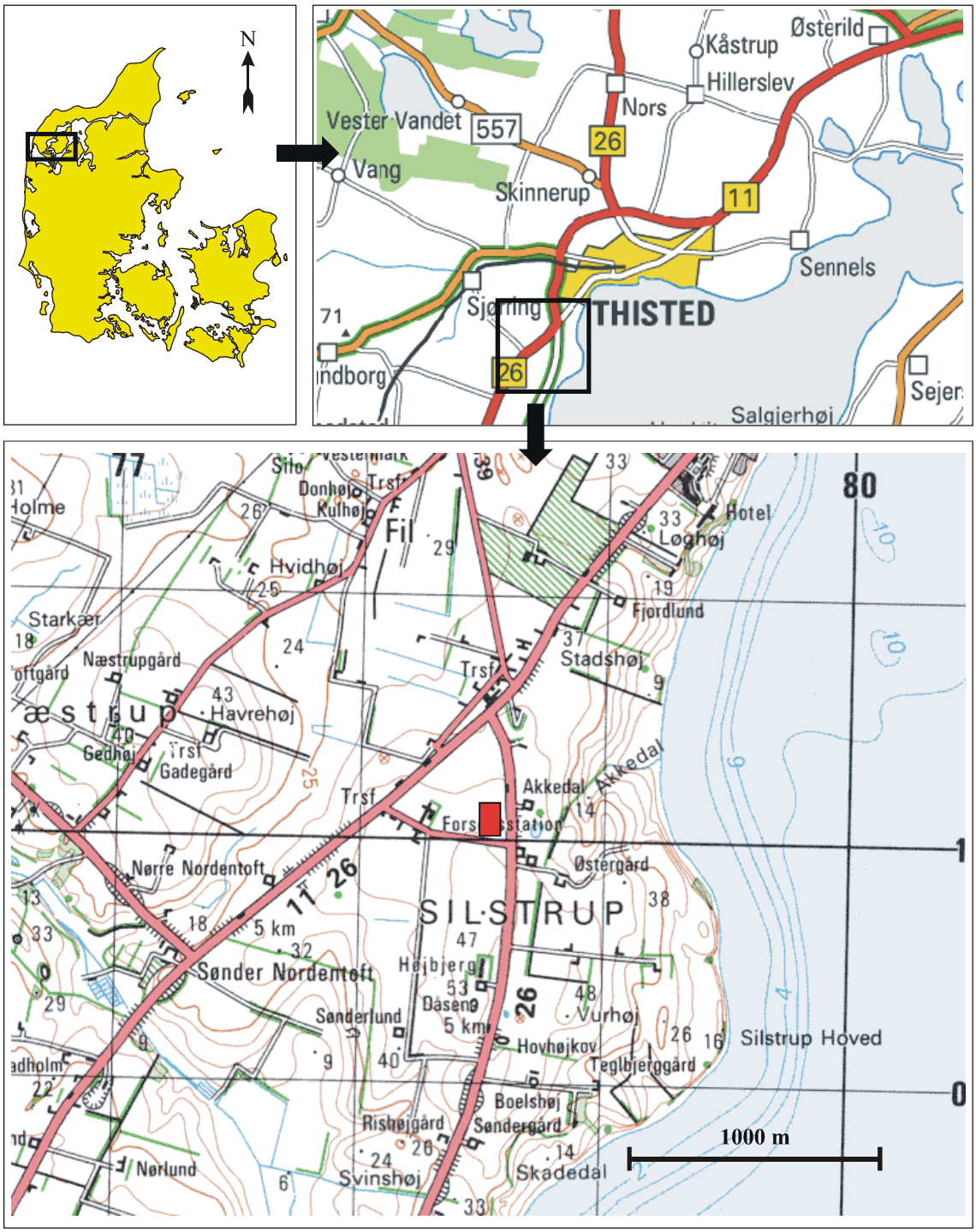


Figure A3.1. Location of the test field.

A3.1 Location, ownership and earlier cultivation and use

The test field is situated at Silstrup south of Thisted in northwestern Jutland (Figure A3.1), and is owned by the Danish Institute of Agricultural Sciences (DIAS). The site characteristics are summarized in Table A3.1.

Table A3.1. Site characteristics.

Length and width of the test field	185 m x 91 m
Total area of the site, incl. buffer zone	3.3 ha
Area of the test field	1.69 ha
Municipality	Thisted
County	Viborg
Land registry no.	2a, Silstrup, Tilsted
Ownership	DIAS, Silstrup Experimental Station Højmarken 12 7700 Thisted

Earlier use

As is apparent from Figure A3.2, the field has been farmland at least since 1942. In 1966 the area was systematically drained, as seen in Figure A3.4. The area had been farmed as a normal field for the preceding 17 years, and had not been used for plot experiments. Cultivation and pesticide application history of the field during the 17 years prior to the present investigations are summarized in Appendix A.3.1.

After work on the site installations had been initiated it was discovered that the road just east of the site had previously traversed part of the test field (Figure A3.2). The road was apparently straightened in the 1940s. As the presence of an old roadbed or associated earthworks might influence the hydraulic properties of the area, the test field was moved 45 m further to the west.

A3.2 Technical installations

All installations at Silstrup are numbered according to the code described in Section 3. In the present description, however, the site-specific code for Silstrup, i.e. “3”, has been omitted for the sake of simplicity. The locations of all installations were selected on the basis of the drainage system and the groundwater flow pattern (Figure A3.3) and are shown in Figure A3.4.

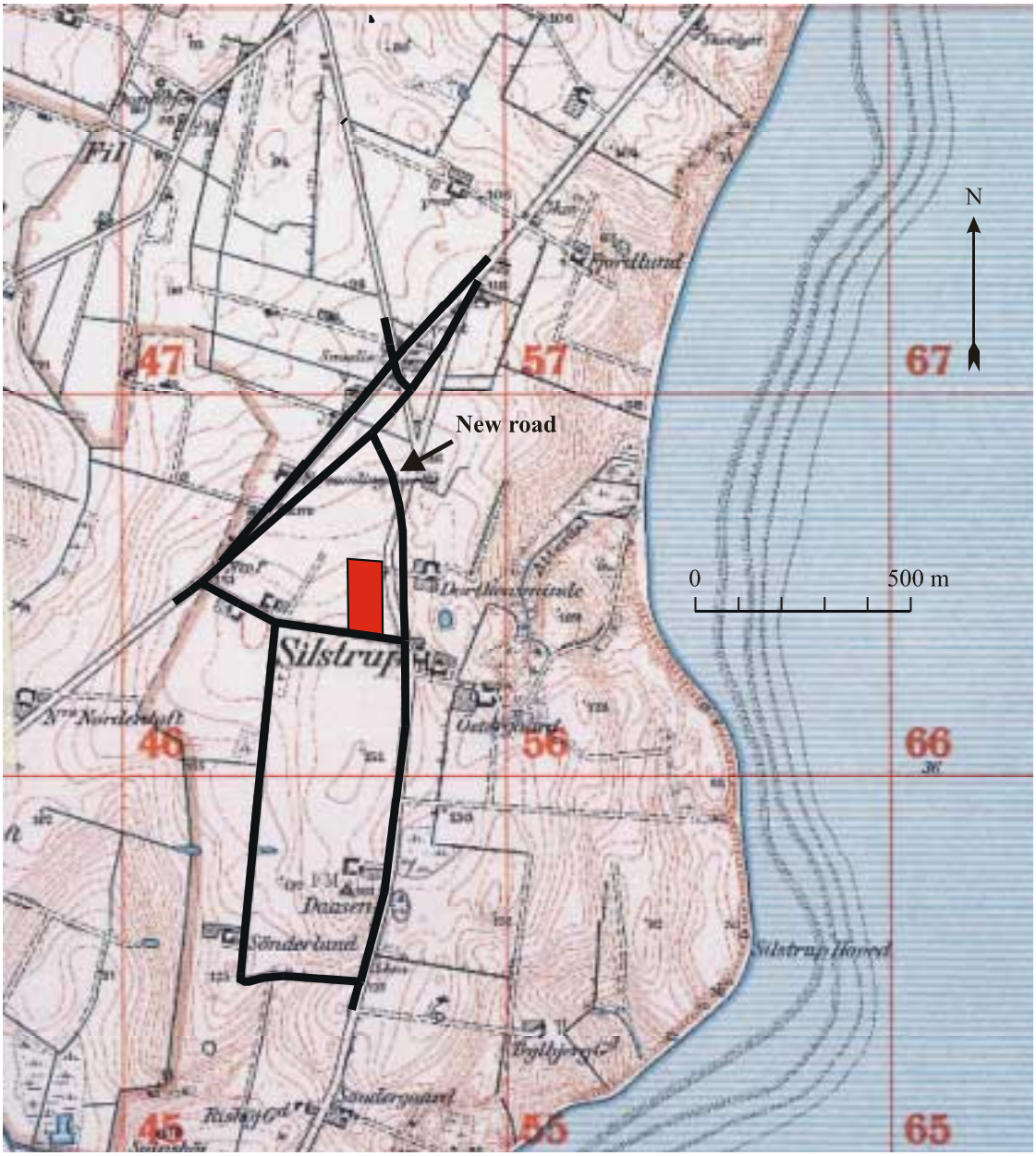


Figure A3.2. Topographic map 1:20.000 from 1942. The test field is marked as a red square. New road system is shown in black.

Buffer zone

The width of the buffer zone is 18 m along the western and eastern borders, and 5 m along the southern border, where a small road acts as an additional buffer zone. North of the field the buffer zone is more than 10 m wide.

Suction cups, TDR and Pt-100 sensors.

The suction cups, TDR and Pt-100 sensors at Silstrup were installed in two excavations S1 and S2 (Figure A3.4) in accordance with Section 3.3.

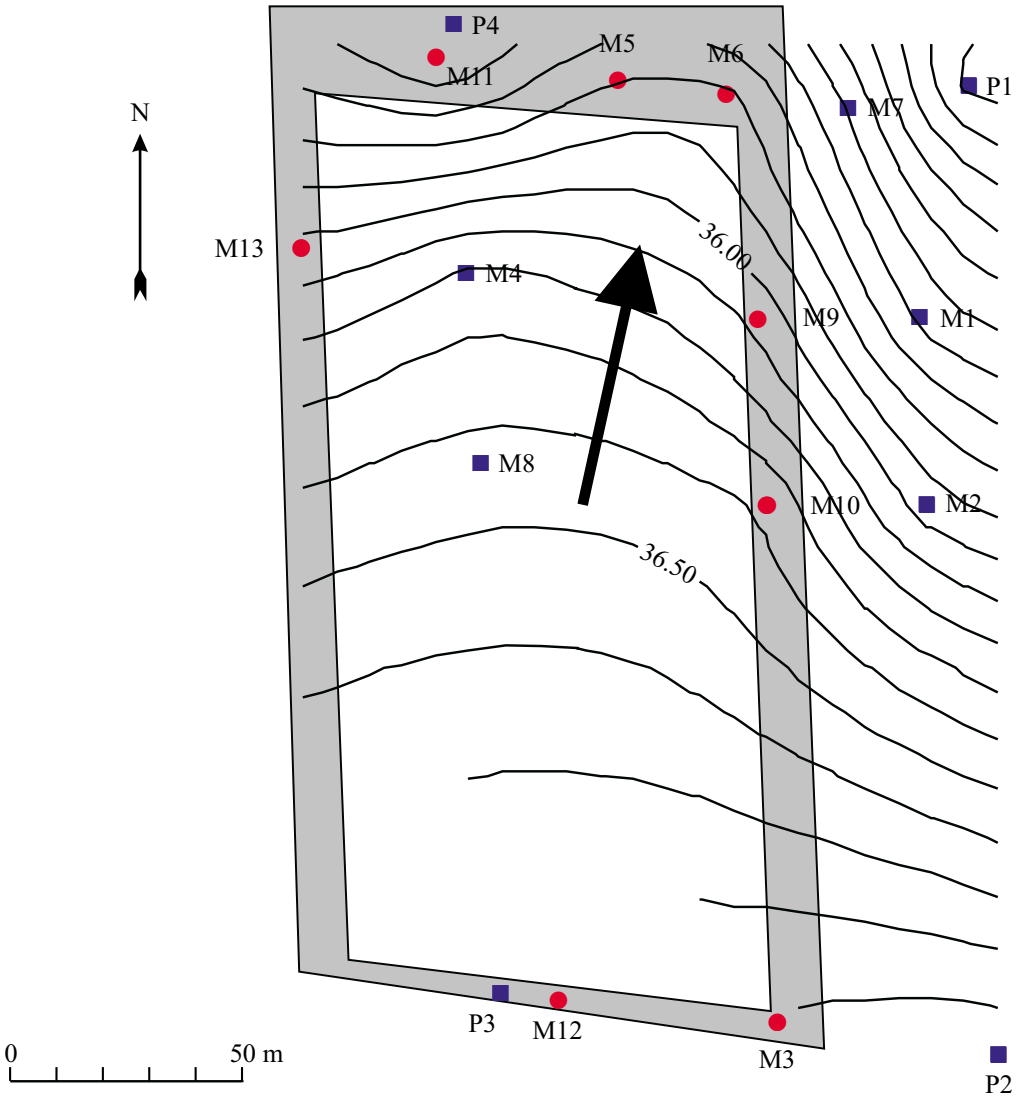


Figure A3.3. Potential head (m a.s.l.) at the site measured in February 2000 and the direction of the ground water flow.

Wells

Horizontal sampling wells

Two 58 m, long horizontal sampling wells H1 and H2 were installed (Figure A3.4), each of which consists of three 18 m screen sections separated by 1 m bentonite seals. The first screens in both wells (H1.1 and H2.1) are located within a lateral distance of 17 m from the western edge of the test field.

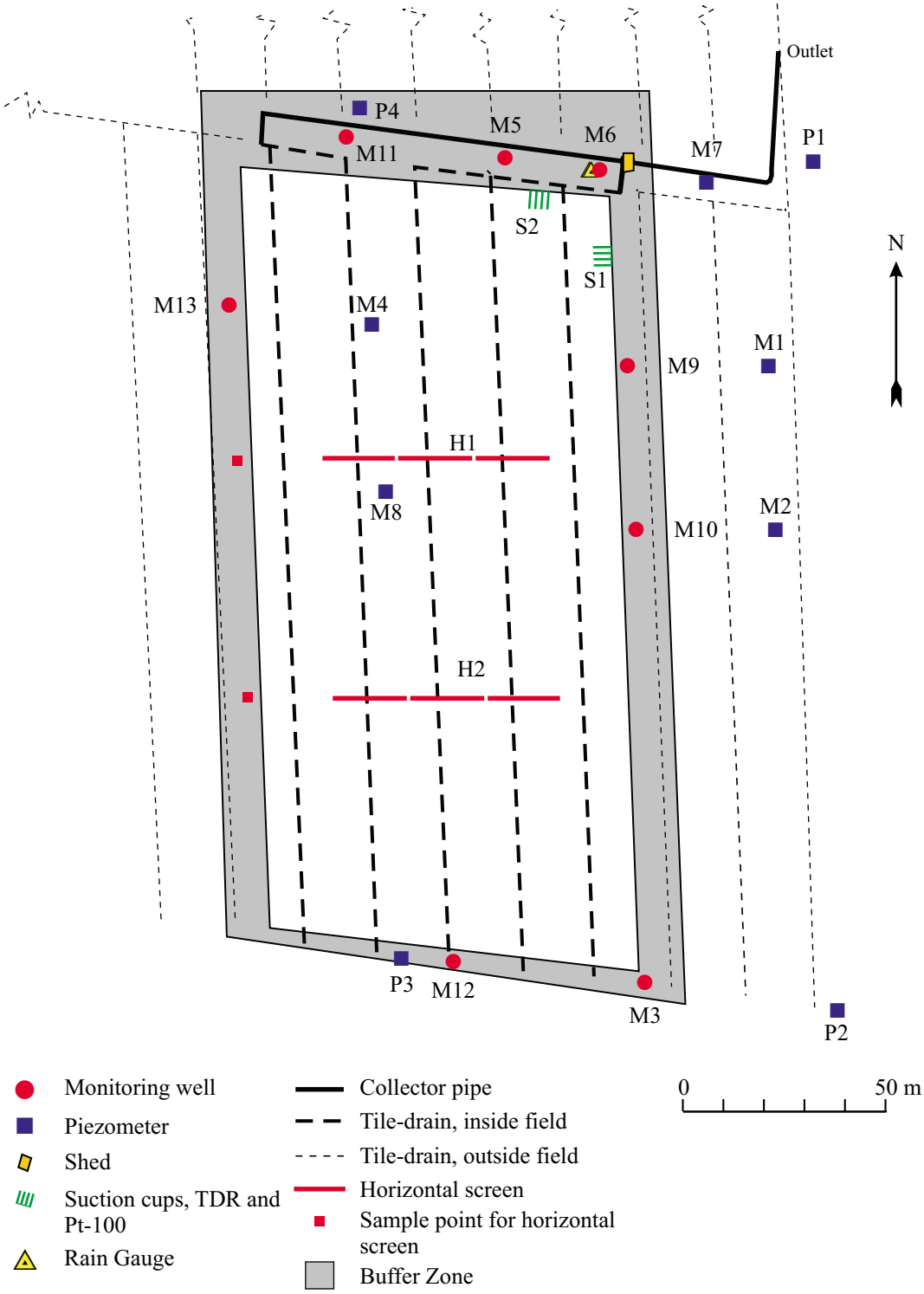


Figure A3.4. Sketch of the field showing the test and buffer zones and location of installations.

The wells were drilled perpendicular to the edge of the field. The screens are 3.5 m b.g.s. The depth of well H1 deviates up to 0.09 m from the intended position of 3.5 m b.g.s., whereas well H2 deviated 0.34 m. According to the drilling company, part of H2 follows a "pavement", probably a clay till rich in stones and boulders.

Installation of piezometers

All wells at Silstrup were drilled as cased wells with a 6" (152 mm) solid stem auger. In some sandy intervals below the groundwater head, however, a bailer was used to clean the borehole before installation of the screen.

As a preliminary survey, one borehole was drilled in February 1999 (DGU no. 30.1120) near to well P3 in the southeastern corner of the field. Rafts of glacially dislocated Tertiary clay were found in this borehole and it was therefore decided to abandon it and look for a better location.

In May 1999, however, it was decided to go ahead with the site, and three wells P1, P2 and P4 each containing three piezometers were drilled in order to start monitoring the groundwater head. In august 1999 a third well, P3, containing three piezometers was drilled. The depth of the piezometers at Silstrup is summarized in Table A3.2.

Table A3.2. Depth of the piezometer screens.

Well no.	DGU no.	Upper screen m b.g.s.	Middle screen m b.g.s.	Lower screen m b.g.s.
P1	30. 1123	2.0-2.5	3.5-4.0	11.5-12.0
P2	30. 1122	3.0-3.5	5.5-6.0	11.5-12.0
P3	30. 1191	3.0-3.5	6.1-6.6	11.2-12.2
P4	30. 1124	2.75-3.25	4.5-5.0	11.5-12.0

Monitoring wells

A total of 13 monitoring well clusters (M1–M13) each consisting of four individual wells were installed at Silstrup from August 8 1999 to September 9 1999. The technical specifications are described in Section 3.1.2.

The monitoring well screens of all 13 clusters are located at the following depths:

Mx.1: 1.5–2.5 m b.g.s.
Mx.2: 2.5–3.5 m b.g.s.
Mx.3: 3.5–4.5 m b.g.s.
Mx.4: 4.5–5.5 m b.g.s.

Monitoring well clusters M1 to M8 were installed first. Thereafter it was decided to relocate the area 45 meters to the west, as described above. Monitoring well clusters M9 to M13 were thereafter installed to cover the new area. The new area also encompasses well clusters M4 and M8. This was considered acceptable provided that the two well clusters were not used for monitoring.

Drainage system

The experimental station was systematically drained by DIAS in the 1960s. To facilitate experimental work, the drainage system for each field is separate. The drains were laid manually in open machine-excavated trenches. The design of the drainage system is illustrated in Figure A3.4.

The design of the drainage system in the test field is simple, consisting of five parallel field drains running from south to the north end, where they connect to a transverse collector drain. In the northeast corner of the field the collector drain is connected to a main drain, which runs northwards alongside the major public road.

The drainpipes are clayware, with an inner diameter of 6.5 cm for laterals and 8 cm and 10 cm for the mains. The lateral drains are enveloped by seashells (mussel shells) to improve permeability.

The initial plan was to place the measuring chamber at the northeastern corner and to establish relatively simple and short pipe connections to the existing drainage system. Due to relocation of the site, however, this had to be changed.

New collector pipes and measuring chamber

The two easternmost pipes were severed and replaced by two similar drains from the neighbouring field to the west. The measuring chamber was placed in the northeastern corner of the revised field boundary. As the two new drains had their outflow towards the west, a new pipe had to be installed to lead the water from the northwestern corner to the measuring chamber in the northeastern corner. This was done with 90 metres of Ø 90 mm PE pipe along the northern boundary of the experimental field. The slope of the

pipe is only 2‰. The collector pipe carrying the water from the three other drainpipes was connected close to the chamber by a few meters of Ø 110 mm PE pipe (outer diameter) with plenty of slope. These pipes are watertight, welded in situ.

The measuring chamber is made from Ø 125 cm concrete rings and has a 30° v-notch weir. To collect the water from the two new drains to the west, the chamber had to be placed 75 cm deeper than the original drainpipe and with limited slope in the outlet.

Dimension of the outlet

The main 10 cm drainpipe along the public road has a rather steep slope of 13–16‰. To obtain slope from the chamber, the outlet was established 60 m downstream. The pipe used is a Ø 160 mm smooth PVC pipe with rubber fittings. The PVC pipe was connected to the existing 10 cm clay pipe by a PVC T-junction. The slope of the new pipe is only 2‰, but giving an elevation of 5–10 cm near the chamber.

The drained area of the experimental field is 1.69 ha. The capacity of the new 160 mm pipe is approx. 10 l sec^{-1} ha^{-1}, which should be ample. If there are limitations, these should be found further downstream in the 10 cm tile drain, which has a water-carrying capacity of approx. 6 l sec^{-1} ha^{-1} and a catchment area of 3 ha.

On several occasions during the season 1999/2000, however, the water level in the measuring chamber rose above the notch by more than a 1 m.

New information on the upstream catchment area revealed that two fields south of the experimental field were connected to the main pipe such that the catchment area is actually almost three times the expected area. This connection was not shown on the original map of the drainage system, and probably explains the inadequate capacity of the old main. Additional information was compiled on the conditions downstream. It revealed that new pipes had been installed on the neighbouring field and under the road, probably in 1994 in connection with regulation of the main road. Approx. 200 m north of the measuring chamber there is a new main drain with a much higher capacity.

In September 2000 the outlet from the measuring chamber was disconnected from the old 10 cm main and extended 160 m to the north. The new pipe is a Ø 160/140 mm corrugated pipe without perforations. The lower end was connected to an inspection chamber from where the drain continues as a 160/145 mm corrugated drainpipe installed around 1994. The new stretch has an average slope of 16‰. The outlet from the measuring chamber runs eastwards perpendicular to the road for the first 36 m and thereafter 182 m northward parallel to the road a few meters west of the old main drain. The first

60 m consist of watertight smooth PVC pipes tightened with rubber rings, while the rest is watertight corrugated PE pipe in 25 m lengths, assembled with non-tight connections.

The initial work was carried out in August 1999 and the main work in September 1999, while the outlet was extended in September 2000.

A3.3 Geology

Regional geology

The area around Silstrup displays a number of spectacular geological features. The most prominent – a salt dome called the Thisted Structure – considerably influences the local geology. Vertical movement of 3 to 4 km within the dome has brought Tertiary and Cretaceous chalk to the surface just north of Silstrup. The salt in the dome is still rising, the uplift in the area being estimated at 2.5 mm/yr (Hansen and Håkansson, 1980). A number of terminal moraines formed by the Great Belt–North Jutland re-advance during the Late Weichselian (Houmark-Nielsen, 1987), and which can be traced from the city of Randers to Thy, comprise another important regional geological element. Around Silstrup these terminal moraines often consist of glaciotectonic thrust fault complexes where Tertiary sediments such as the Paleocene-Eocene diatomite and Oligocene mica clay and glacial sediments such as clay till and glaciofluvial clastics are important elements in the thrust sheets (Gry, 1940; Klint and Pedersen, 1995). Just east of the test field in the coastal cliff Silstrup Hoved there is a thrust sheet complex in a coastal cliff section consisting of Paleocene diatomite and Oligocene mica clay. The test field is located on a ridge complex overlain by a till cover.

According to Gry (1940), the fold axis orientation at Silstrup Hoved is 166° caused by deformation from the east. The same direction can be observed in the long axis of the elongated hills in the area around Silstrup, probably reflecting the same deformation phase. The presence of other fold axis orientations (personal communication: Stig Schack Pedersen, GEUS) proves that there have been several deformation phases in the area. On the basis of the varied fold axis orientation patterns in the coastal cliffs around Thisted Bredning, Gry (1940) interpreted the present day depression (Thisted Bredning) as the product of a glacial lobe formed during the Late Weichselian. The variety of fold axis orientations in the area could also be attributable to a number of ice advances of different ages leaving different orientations as a consequence of a series of glaciotectonic events.

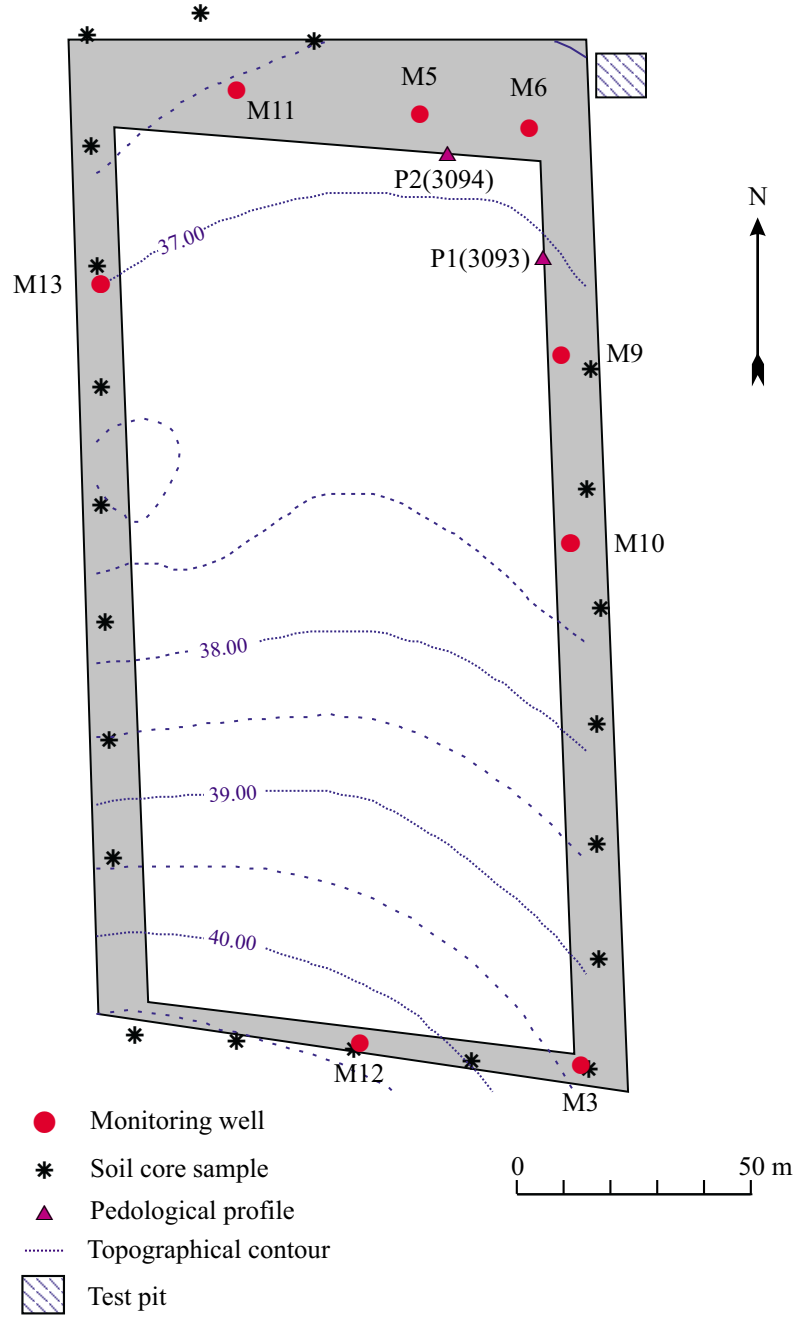


Figure A3.5. Topography at the site and location of soil cores, test pit and monitoring wells.

Geomorphology

The test site is situated between 36 and 45 m a.s.l. close to the top of an elongated hill. The surface slopes approx. 2.2% towards NNE (see Figure A3.5). 200 m east of the site the surface drops abruptly from 30 m a.s.l. to sea level.

Figure A3.6 shows the field superimposed on the map of Quaternary sediments in Denmark (Hermansen and Jacobsen, 1998), the Soil Classification map and a 1999 aerial orthophotograph of the field. As is apparent, the field is located on a loamy soil (JB7). This is in good agreement with the fact that the map of the Quaternary sediments of Denmark places the field in an area of ML, which is a clay till. Based on the orthophotograph, the field appears to be homogenous.

Geology of the monitoring wells and piezometer wells.

The wells drilled at Silstrup revealed a homogenous cover of clay till rich in chalk and chert of Cretaceous and Early Tertiary origin. Cross sections containing the wells drilled at the site are found in Figure A3.7 and A3.8. According to grain size analysis (Table A3.4 and Figure A3.11) the clay till consists of clay (20–35%), silt (20–40%) and sand (20–40%). Gravel constitutes approx. 5%, but occasionally up to 20%. The $CaCO_3$ content ranges from 20 to 45% by weight in the clay till. At some intervals the till has been described as a sandy till (MS), i.e. contains less than 12–14% clay.

Thin layers and lenses of glaciofluvial sand (DS) are found in some wells, often described as alternating thin beds of sand occasionally with silt and clay stringers (VS). None of these layers can be correlated.

In M3, M12 and P3, Oligocene clay and silt were encountered, presumably “Cilleborg Clay” (Gry, 1940; personal communication: Peter Roll Jakobsen, GEUS). In M12, Oligocene clay was encountered at 2.5 m b.g.s. – the most shallow occurrence at the site. In all wells where Oligocene sediments were penetrated, clay till was found underneath. As a consequence, all Oligocene sediments in the test field are glacially dislocated. In several wells in the region, glaciotectonites with Oligocene clays and silt were found (Pedersen, 1989).

Three levels of oxidation can be observed in the upper 12 m of the till. In most wells an upper zone with yellowish brown and brownish yellow coloration is found from below the topsoil to a depth varying from 2.5 to 5 m b.g.s. Below this a suboxic zone with greyish brown till is found to a depth of 4 to 6 m b.g.s. This zone is typically 0.2 to 0.5 m thick. Below this zone there is a reduced zone of olive grey and grey-coloured till.

A B

C

Figure A3.6. Location of the test field (red square) superimposed on: A) The soil type map. JB 5/6: Sandy loam soil, JB 7: Loamy soil. B) Map of Quaternary sediments in Denmark, ML: Clay till. C) An aerial orthophotograph (Kampsax Geoplan, DDO1999).

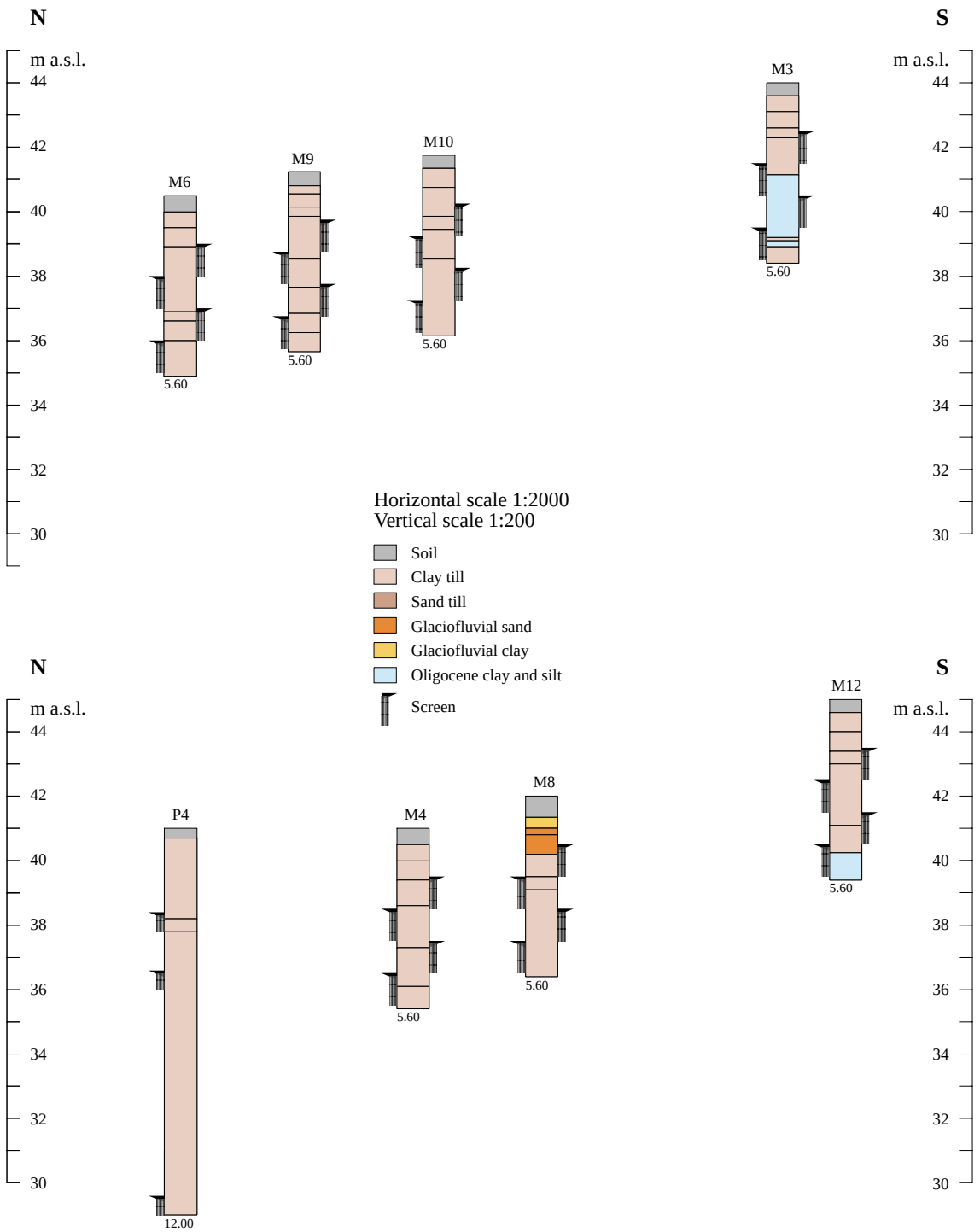


Figure A3.7. N-S cross sections based on wells at the site. The location of the wells is shown in Figure A3.4.

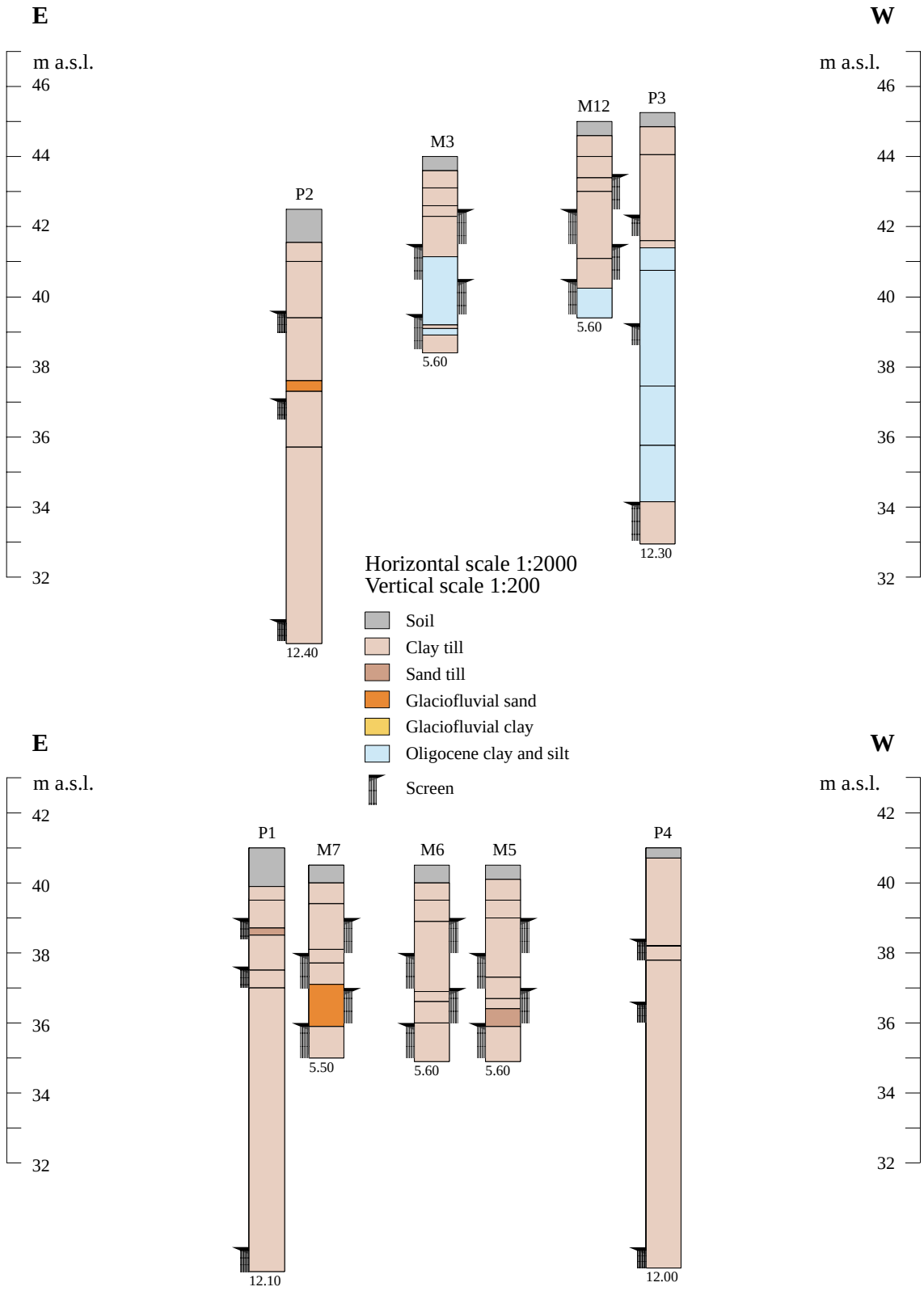


Figure A3.8. E-W cross sections based on wells along the southern and northern ends of the test field. The location of the wells is shown in Figure A3.4.

Geology of the test pit and drainage ditch excavations

A test pit was excavated to 5.0 m b.g.s. using a backhoe in the buffer zone of the north-eastern corner of the test field (Figure A3.5) for field vane tests, fracture descriptions and characterization, fabric analysis, and lithological description. Samples were taken for grain size analysis, $CaCO_3$ content, clay mineral analysis, and exotic stone counts.

Lithological description

The depths in the following descriptions (Table A3.3) are average depths from the test pit, and correspond to the log in Figures A3.9–A3.11. The description follows Larsen *et al,*(1995).

Table A3.3. Lithological descriptions from the test pit at Silstrup.

Depth m b.g.s.	Description	Sample number
0.0–0.5	Topsoil, dark brown to black, numerous biopores and desiccation fractures.	DIAS
0.5–1.0	Clay till, strong mix of sand and gravel, yellowish brown, noncalcareous.	DIAS
1.0–1.3	Clay till, mix of silt, sand strong mix of gravel, some pebbles and boulders, yellowish brown with pale olive spots. Calcareous in some parts of the profile from 1.0 m b.g.s. Heavily fractured.	DIAS
1.3–1.5	Clay till, weak mix of silt and sand, mix of gravel clay veins, strong brown. Thickness varies from 40 to 25 cm. At 1.3 m b.g.s. a small fold axis in a folded sand vein was measured to 42/8 indicating a deformation from southeast.	8803
1.5–3.5	Clay till, mix of silt, weak mix of sand, strong mix of gravel, lots of chert and chalk fragments in the gravel fraction, fractures with Fe and Mn oxides. Light yellowish brown. Calcareous. A number of fractures were encountered in the suboxic zone, which were olive coloured (5Y 4/3).	8804 + 8805 + 8806
3.5–5.0	Clay till, mix of silt, weak mix of sand, strong mix of gravel and pebbles, olive grey, rich in chert and chalk. Very few fractures with Fe oxides reach 4.0 m b.g.s. Calcareous. At 4.25 m b.g.s. striation was measured on a rock to 02/18 indicating a deformation from the north.	8807 + 8808 + 8840 + 8841

Fracture description

In order to develop a conceptual model of the fracture systems and macropores at the test field, fracture system parameters were measured in the test pit excavation: orientation at various depths, positions and frequencies. On the basis of these measurements, a number of fracture parameters were calculated. In Figure A3.9 and A3.10, the data are plotted and the fracture systems described according to Klint and Gravesen (1999). Be-

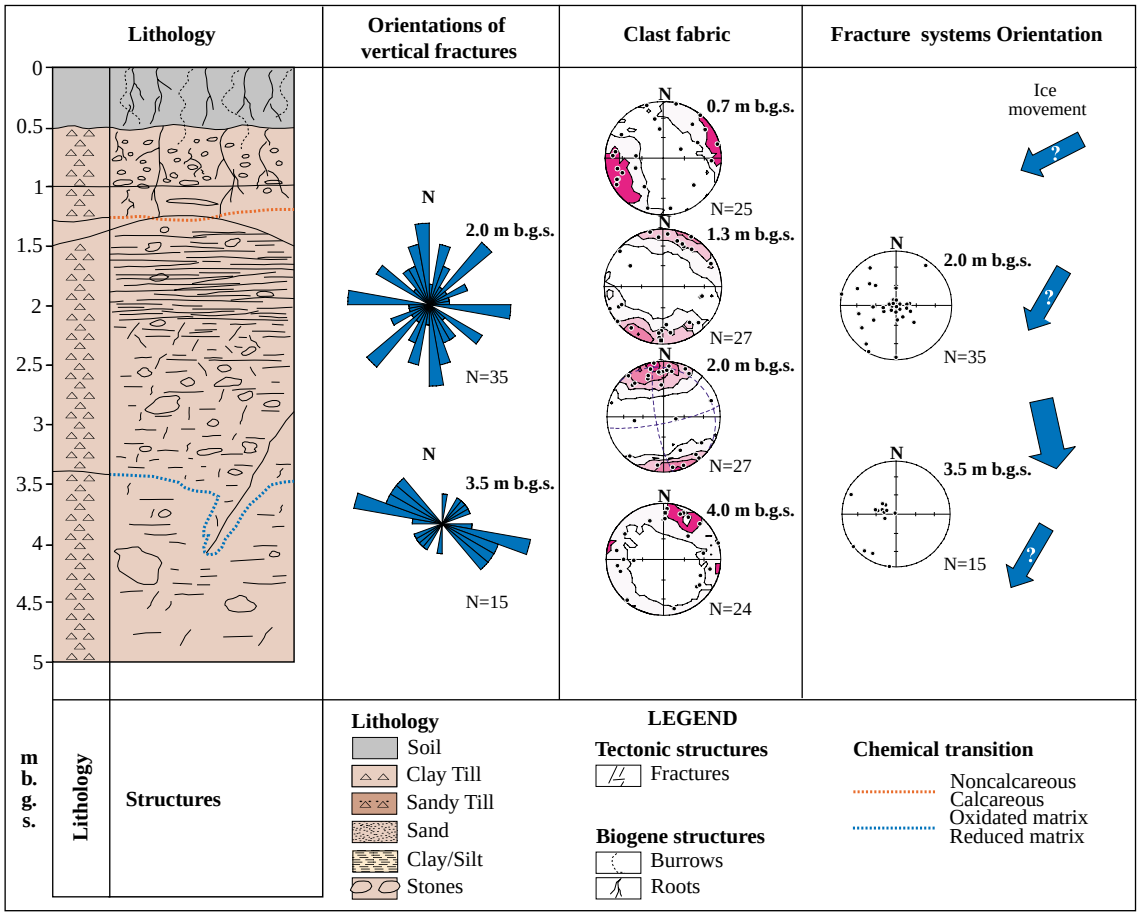


Figure A3.9. Lithology, fracture orientation, clast fabric data and interpreted ice movement direction.

sides the fracture analysis, fabric in the till and fold axis in folded sand veins were measured in order to describe the stratigraphic relations in the test pit excavation.

Fracture trace frequency was measured in two profiles in the test pit excavation, a north-facing wall and an east-facing wall. In general the fracture systems at Silstrup are dominated by postdepositional fractures attributable to desiccation and cryogenic processes.

From the surface and to 0.7–0.8 m b.g.s. in the test pit excavation, desiccation fractures and biopores dominate to such a degree as to preclude proper estimation of the fracture trace frequency. This unit can be described as heavily fractured and bioturbated. At 0.6 m b.g.s. there were an estimated 400 biopores/m^2.

From 0.7 to 1.8 m b.g.s. the till is intensely fractured by a horizontal/subhorizontal fracture system, possibly connected to freeze-thaw processes in a periglacial environment, or to horizontal shear from a glacier.

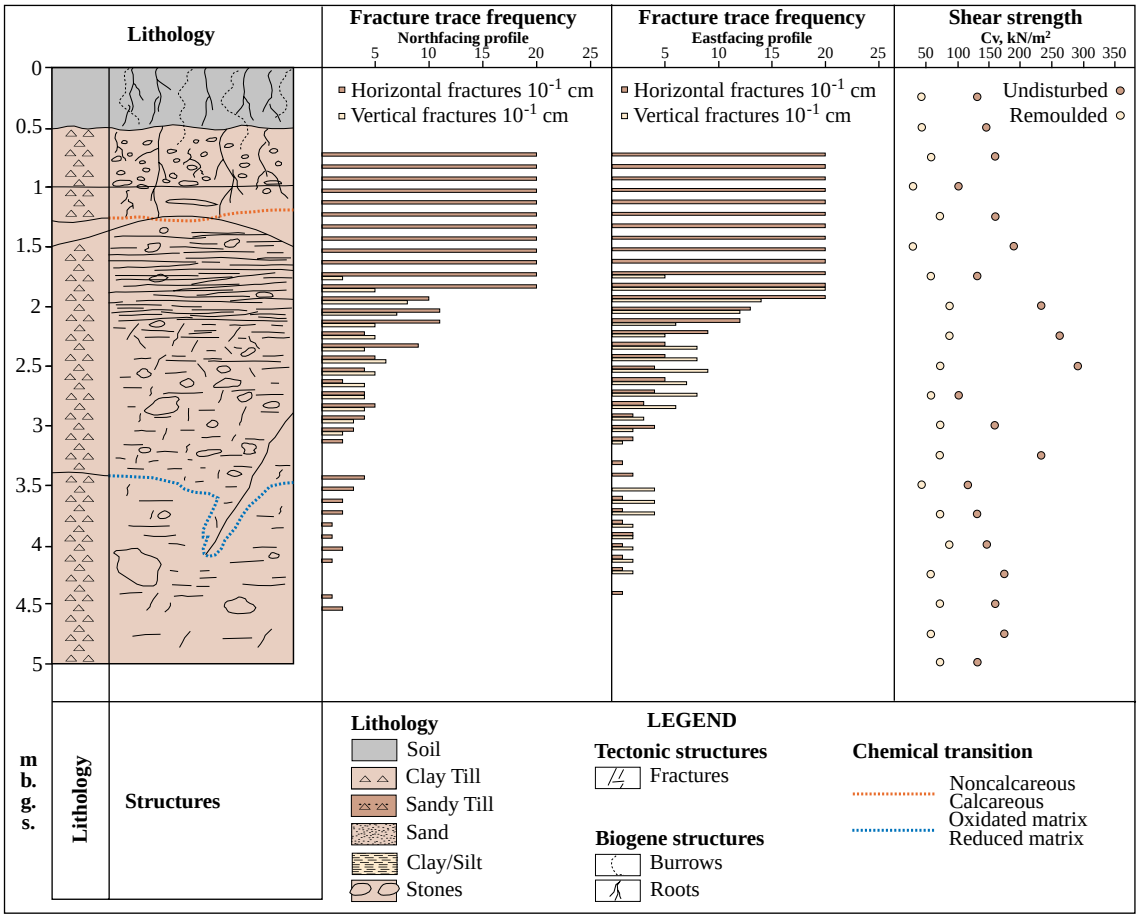


Figure A3.10. Lithology, fracture trace frequency and shear strength in the test pit.

From 1.8 to 3.1 m b.g.s. the fracture trace frequency diagram reveals a system of small vertical or near vertical fractures that peaked at 8–20 fractures/m approx. 2 m b.g.s., thereafter decreasing in number with increasing depth. They disappear at 3.2 m b.g.s. in the north-facing profile and at 4.4 m b.g.s. in the east-facing profile.

From 3.1 to 4.5 m b.g.s. few vertical fractures exist and the horizontal/subhorizontal fractures dominate. Only one major fracture crossed the suboxic zone at 3.5 m b.g.s. in the test pit.

In the upper 1 m, traces of agricultural processes, bioturbation and desiccation cracks dominate to such a degree as to obscure all fracture systems. It is noteworthy that the number of macropores is high, however.

As is apparent from Figure A3.9, one fracture system can definitely be recognized at Silstrup, i.e. the horizontal and subhorizontal fractures. The remainder of the fractures

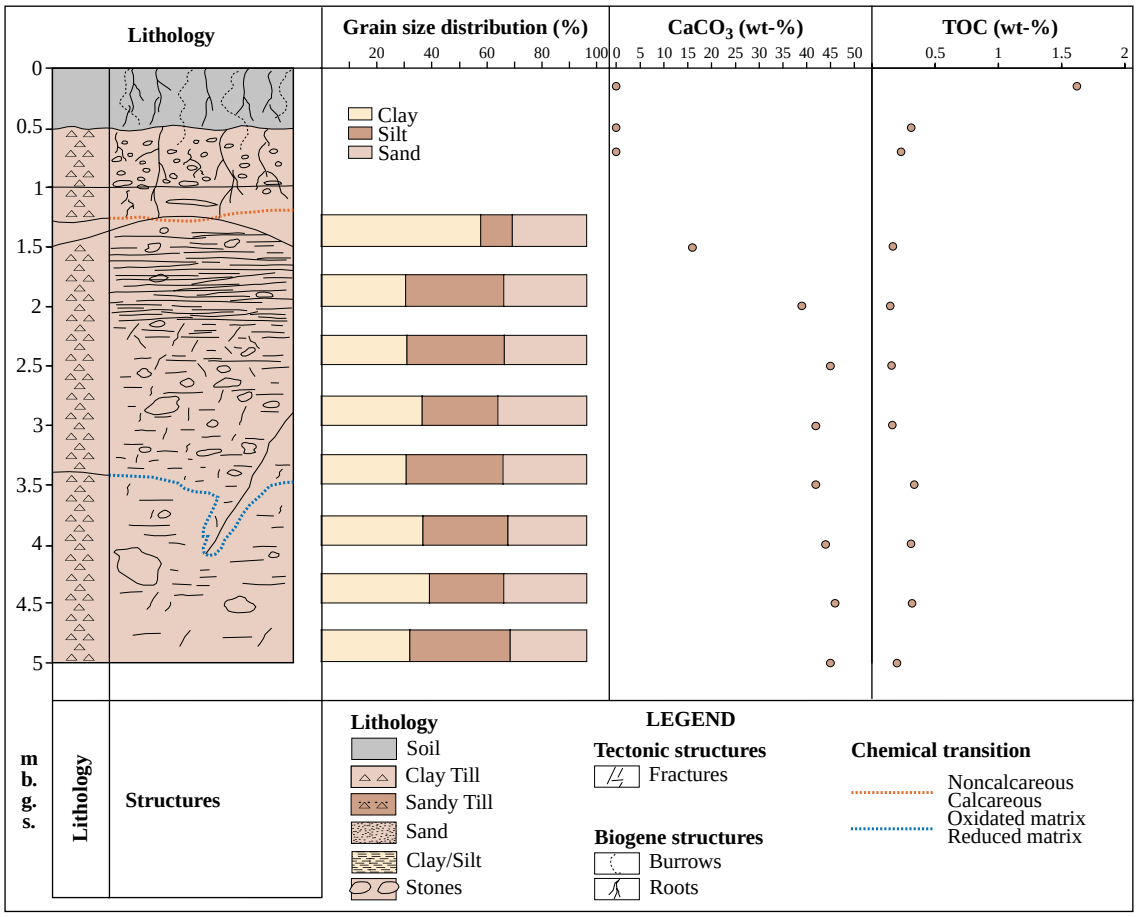


Figure A 3.11. Lithology, grain size distribution and $CaCO_3$ and total organic carbon (TOC) content in the test pit. Grain size fractions larger than 2.0 mm are not included in the grain size analysis.

found in the test pit represent a variety of orientations and the data set is too small to determine whether a second or third fracture system is present.

Fracture geochemistry

Five depth-dependent types of coating could be observed on the fracture surfaces in the test pit.

I. 0.3–1.0 m b.g.s. In the upper part of the clay till the fractures and biopores are either coated with clay skin or topsoil. Root traces are found in many fractures. The matrix is oxidized.

II. 1.0–2.0 m b.g.s. The fractures and biopores are surrounded by a grey halo, reflecting oxygen depletion and reduced conditions in the close vicinity of the fractures caused by decomposition of organic matter. The matrix is oxidized.

III. 2.0–3.3 m b.g.s. The fractures are coated with Fe oxides and some manganese oxides. The matrix is oxidized.

IV. 3.3–3.5 m b.g.s. In this narrow interval an olive-coloured coating was observed that is considered as being indicative of a fluctuating groundwater head (personal communication: Vibeke Ernstsen, GEUS). The matrix is suboxic.

V. 3.5–5.0 m b.g.s. In the reduced clay till no coating was observed except for one fracture that was FeO- and MnO-coated to a depth of almost 4.5 m b.g.s. The matrix is reduced.

Clast fabric analysis

Clast fabric analyses were performed at four depths 0.7, 1.3, 2.0 and 4.0 m b.g.s. (Figure A3.9). The analysis at 0.7 m b.g.s. revealed a weak fabric from the northeast. At 1.3 m b.g.s. this fabric indicates a north-northeasterly direction, whereas the analysis at 2.0 m b.g.s. revealed a strong fabric indicating iceflow from the north, an observation that is in good agreement with a striation measured on a boulder at the same level. The lowermost analysis revealed a weak fabric, and is nonconclusive.

Field vane tests

Field vane tests were performed in the test pit excavation at 25 cm intervals from top to bottom (Figure A3.10). Down to a depth of 2.5 m b.g.s. the undisturbed shear strength (Cv) increases from approx. 50 to approx. 290 kN/m^2. From 2.5 to 3.0 m b.g.s. the shear strength varies. From 3.5 to 5.5 m b.g.s. the shear strength ranges from 120 to 175 kN/m^2.

Laboratory analyses

Grain size analysis

Grain size analysis has been carried out on 15 samples from the site (Table A3.4). This describes the clay till as rich in clay, ranging from 28% to 36% clay. One sample from 1.5 m b.g.s. contained 58% clay. The Oligocene sediments are dominated by silt (40–80%) and clay (20–30%). As they are laminated or bedded, however, individual horizons will have higher or lower clay:silt ratio than indicated by the grain size analysis, which will influence the hydraulic properties.

Table A3.4. Texture analysis of sediment from the test pit and from selected wells.

	Grain size in mm							
Depth and location m b.g.s.	<0.002	0.002-0.020	0.02-0.63	0.63-0.125	0.125-0.200	0.20-0.5	0.5-2.0	Sediment
Test pit								
1.5	57.8	7.6	3.8	8.8	6.4	10.6	5.1	Clay till, oxidized
2.0	30.4	26.1	9.4	9.1	7.0	12.4	5.5	Clay till, oxidized
2.5	31.2	26.1	9.1	7.8	6.6	13.3	5.9	Clay till, oxidized
3.0	36.5	21.3	6.2	8.1	7.1	14.4	6.4	Clay till, oxidized
3.5	30.8	27.9	7.3	7.6	6.9	13.6	6.0	Clay till, reduced
4.0	36.8	24.3	6.4	7.5	6.8	12.6	5.6	Clay till, reduced
4.5	39.2	22.0	4.8	7.7	7.1	13.1	6.0	Clay till, reduced
5.0	32.0	30.8	5.7	7,2	6.3	11.8	6.0	Clay till, reduced
Wells								
P3(2.5)	40.2	16.1	6.0	9.6	8.0	14.0	6.2	Clay till
P3(5.5)	18.1	53.0	26.9	1.6	0.1	0.2	0.1	Oligocene silt
P3(8.5)	30.7	51.0	10.5	6.5	0.5	0.6	0.2	Oligocene silt
P3(10.0)	30.5	36.2	6.3	7.1	5,4	9.6	5.0	Oligocene clay
M7(4.0)	27.2	24.7	6.7	8.2	7.2	18.2	7.8	Sand, medium to coarse, mix of silt, clay
M13(4.0)	27.8	34.1	6.2	6.8	6.2	12.6	6.2	Clay till
M8(1.5)	21.1	13.6	4.7	12.3	12.3	25.7	10.2	Sand, mix of clay, laminated

Data from GEUS Sediment Laboratory. Some of the fractions were determined by linear interpolation.

Clay mineral analysis

Clay mineral analysis was carried out in three samples from the test pit. All three samples showed that the clay fraction (<2 µm) in the till at Silstrup is dominated by smectite. Other minerals present are vermiculite, illite, kaolinite and quartz.

Fine gravel analysis

Fine gravel analysis has been carried out on two samples from the test pit excavation (Figure A3.12). The sample taken from 5.0 m b.g.s. reveals a local dominance of Mesozoic and Cenozoic limestone and flint, originating from the Thisted Structure. The sample from 1.5 m b.g.s. has a similar composition regarding the noncalcareous clasts, but a lower content of Mesozoic and Cenozoic limestone. This might reflect both the more shallow depth and subsequent dissolution of carbonates and a change in iceflow direction. The lower sample reflects an iceflow in close contact with the Thisted Structure while the upper sample indicates iceflow, possibly in a southwesterly direction.

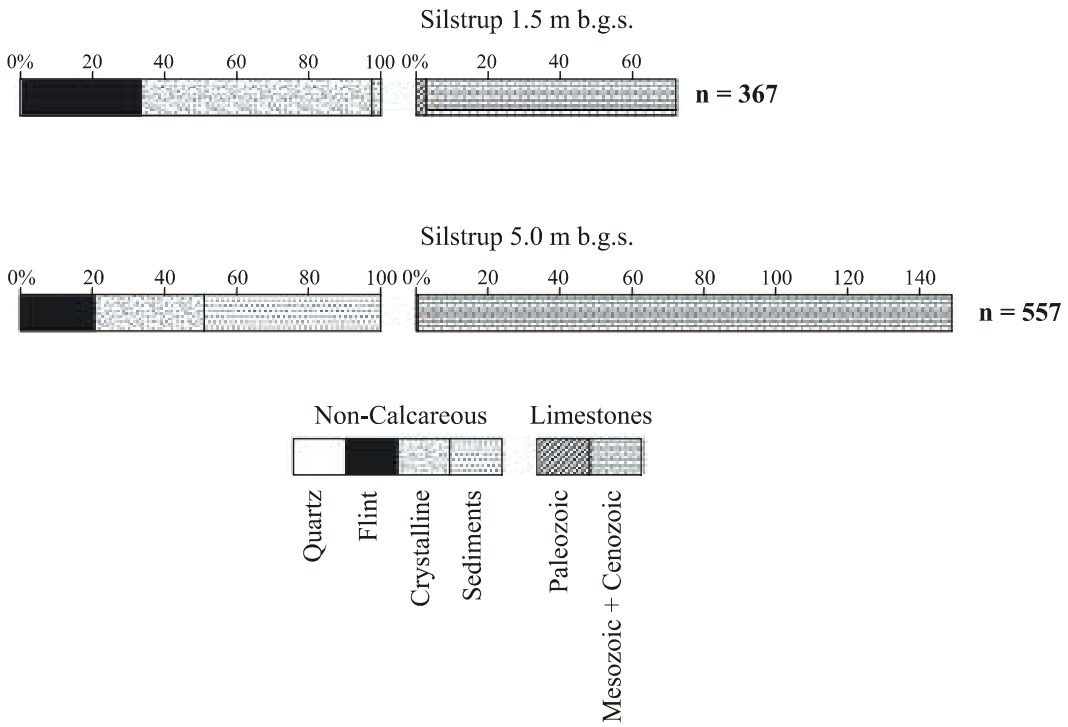


Figure A3.12. Fine gravel analysis from two levels in the test pit. n is the number of grains counted.

The difference in the composition of noncalcareous clasts points towards two till units in the test pit excavation, or at least a change in iceflow direction.

Total organic carbon (TOC) and $CaCO_3$ content

The TOC and $CaCO_3$ data are shown in Figure A3.11 and Table A3.5. The $CaCO_3$ content of the clay till at Silstrup is high, ranging from 21% weight to 45% weight (mean value of 38%), reflecting the fact that the site is located in the "shadow" of the Thisted Structure. In the test pit the mean $CaCO_3$ content is 42% while that of the Oligocene sediments found in the northern part of the field ranges from 21% to 55%.

The total organic carbon data from the test pit reveal a significant change in TOC content at 3.5 m b.g.s., where TOC doubled from 0.16 to 0.33% reflecting the transition zone from oxic conditions to reduced conditions. In the Oligocene silt at piezometer P3 located 5.5 m b.g.s. TOC was 2.12%. In the other two Oligocene samples, however, TOC was less than 1%.

Table A3.5. Sediment $CaCO_3$ and total organic carbon (TOC) content in the test pit and selected wells.

Locality	Depth m b.g.s.	TOC %	$CaCO_3$ %	Sediment
Test pit	1.5	0.17	16	Clay till, oxidized
Test pit	2.0	0.14	39	Clay till, oxidized
Test pit	2.5	0.15	45	Clay till, oxidized
Test pit	3.0	0.16	42	Clay till, oxidized
Test pit	3.5	0.33	42	Clay till, reduced
Test pit	4.0	0.31	44	Clay till, reduced
Test pit	4.5	0.32	46	Clay till, reduced
Test pit	5.0	0.20	45	Clay till, reduced
P3	2.5	0.19	37	Clay till
P3	5.5	2.1	21	Oligocene silt
P3	8.5	0.73	42	Oligocene clay
P3	10.0	0.29	55	Oligocene clay
M7	4.0	0.24	27	Sand, medium to coarse, mix of silt, clay
M13	4.0	0.17	21	Clay till
M8	1.5	0.15	20	Sand, mix of clay, laminated

Data from GEUS Sediment Laboratory.

Porosity and permeability

No data are available from Silstrup.

A3.4 Pedology

Pedological field work

The pedological field work at Silstrup was carried out from August 30 to September 2 1999. Two soil profiles were excavated and described (Figure A3.5). These were located beside each of the two groups of suction cups. In the buffer zone, 21 soil cores were collected to a depth of 120 cm (Figure A3.5). Inside the field, 36 soil samples were collected from the topsoil (0–25 cm).

Table A3.6. Description of profile 1 (3093 Silstrup East).

Soil classification, DK	Pseudogleytypilessive	**Soil classification, USDA**	Alfic Argiudoll
Parent material	Clay till	**Profile depth**	200 cm
UTM	32V MJ Easting 478551 Northing 6310172	**Drainage class**	Moderately well drained
Landform	Glacial ridge complex	**Groundwater level**	220 cm
Map sheet	1116 I NV	**Vegetation**	Stubble
Elevation	37 m DNN	**Maximum rooting**	160 cm
Topography	Gentle slope	**Authors**	Søren Torp
Slope	1-2°	**Date of description**	30.08.99

Profile description

Ap (0-32 cm)

Greyish brown (10YR 3/2 f) clay, containing humus, a few small and medium size stones of mixed type, some fine roots, 1-10 wormholes and root channels per dm^2, very weak thin granular structure, slight sticky when wet, clear smooth boundary.

Bv (32-80 cm)

Yellowish brown (10YR 5/4 f) sandy heavy clay, humus poor, lots of small and medium size stones of mixed form and type, a few small soft Fe and Mn oxide and hydroxide nodules of mixed form, some fine roots, 1-10 wormholes and root channels per dm^2, moderately coarse columnar structure, sticky consistency when wet, mottled thick coatings of clay minerals and humus in root channels and on aggregate peds, gradual wavy boundary.

Bt(g) (80-135 cm)

Yellowish brown (10YR 5/4 f) heavy clay with some vertical stripes of clear light olive brown (2.5Y 5/4 f) spots with diffuse boundary, secondary spots of pinkish grey (7.5YR 6/2 f), humus poor, some small and medium size stones of mixed form and type, a few small soft Fe and Mn oxide and hydroxide nodules of mixed form, a few fine roots, 1-10 pores per dm^2, strong coarse columnar structure, very sticky consistency when moist, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.

BC(g) (135-160 cm)

Brown (10YR 5/3 f) clay with some vertical stripes, large conspicuous yellowish brown (10YR 5/8 f) spots with clear boundary, humus poor, some small and medium size stones of mixed form and type + lumps of chalk, a few small soft Fe oxide and hydroxide nodules of mixed form, a few fine roots, 1-10 pores per dm^2, moderately coarse columnar structure, sticky consistency when wet, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.

Cc(g) (160-200 cm)

Very pale brown (10YR 7/3 f) clayey silty sand with lots of vertical stripes of big clear brownish yellow (10YR 6/6 f) spots with clear boundary, humus poor, lots of small and medium size stones of mixed form and type + lumps of lime, a few small soft Fe oxide and hydroxide nodules of mixed form, very calcareous mainly as lumps, moderately medium strong angular structure, sticky consistency when moist, mottled, moderately thick coatings of clay minerals on aggregate peds.

Remarks	Chimney continues to a depth of 230 cm.

Table A3.7. Description of profile 2 (3094 Silstrup North).

Soil classification, DK	Pseudogleytypibrunjord	**Soil classification, USDA**	Typic Hapludoll
Parent material	Clay till	**Profile depth**	190 cm
UTM	32 V MJ Easting 478533 Northing 6310193	**Drainage class**	Moderately well drained
Landform	Glacial ridge complex	**Groundwater level**	220 cm
Map sheet	1116 I NV	**Vegetation**	Stubble
Elevation	37 m DNN	**Maximum rooting**	95 cm
Topography	Gentle slope	**Authors**	Søren Torp
Slope	1-2 °	**Date of description**	31.08.99

Profile description

Ap (0-30 cm)

Very dark greyish brown (10YR 3/2 f) clay, containing humus, a few small stones of varying shape and type, some fine roots, 1-10 pores per dm^2, moderately coarse granular structure, weak sticky consistency, clear smooth boundary.

Bv (30-60 cm)

Yellowish brown (10YR 5/4 f) clay with lots of vertical medium clear dark greyish brown (10YR4/2 f) spots with clear boundary, humus poor, a few small stones of varying shape and type, frequent fine roots, 1-10 pores per dm^2, strong coarse angular structure, weak sticky consistency, moderately thick mottled coatings of clay minerals and humus in root channels and wormholes, diffuse wavy boundary.

Bv(g) (60-95 cm)

Yellowish brown (10YR 5/3 f) clay with many vertical stripes of large clear yellowish brown (10YR 5/6 f) spots with clear boundary, humus poor, a few small and medium size stones of mixed form and type, a few small soft rounded Fe and Mn oxide and hydroxide nodules, frequent fine roots, 1-10 pores per dm^2, strong coarse angular structure, weak sticky consistency, moderately thick spotted coatings of clay minerals and humus in root channels and wormholes, clear wavy boundary.

Cc (95-132 cm)

Very pale brown (10YR 7/3 f) clay, humus poor, a few small and medium size stones of mixed form and type + lumps of lime, a few small soft rounded Fe and Mn oxide and hydroxide nodules, strongly calcareous, mainly as lumps, a few fine roots, strong coarse angular structure, weak sticky consistency, thin spotted coatings of clay minerals and humus on aggregate peds, clear wavy boundary.

2Cc texture bands (132-155 cm)

Yellowish brown (10YR 5/4 f) clayey silt with lots of horizontal stripes, medium yellowish brown (10YR 5/8 f) spots with clear boundary, humus poor, a few small stones of varying shape and type, strongly calcareous mainly as lumps, moderately coarse angular structure, sticky consistency, gradual wavy boundary.

Cc(g) (155-190 cm)

Very pale brown (10YR 7/3 f) sandy heavy clay, with lots of rounded within clear yellowish brown (10YR 5/8 f) spots with diffuse boundary, humus poor, a few small and medium size stones of mixed form and type + lumps of lime, a few small soft rounded Fe oxide and hydroxide nodules, calcareous mainly as powder, strong coarse angular structure, sticky consistency in wet condition.

Remarks	The Bv horizon: Vertical wormholes 4-6 mm in cross section containing humus along the edge and some with fine roots. The Bv(g) horizon: Thick coherent clay skins around stones.

Table A3.8. Soil texture analysis from the pedological profiles.

Pro. no.	Hor. no.	Horizon	Depth	Soil texture (mm) %							$CaCO_3$ %	OM[1] %
			cm	<0.002	0.002–0.02	0.02–0.63	0.63–0.125	0.125–0.2	0.2–0.5	0.5–2		
1	1	Ap	10–20	18.3	16.4	13.4	16.3	8.8	16.4	7.1	–	3.4
1	2	Bv	45–55	30.1	13.9	10.9	14.9	8.5	14.1	6.9	–	0.5
1	3	Bt(g)	115–125	43.4	18.6	2.5	10.0	8.4	12.0	4.8	–	0.3
1	4	BC(g)	150–160	24.6	13.4	11.8	10.6	8.4	18.2	12.8	–	0.2
1	5	Cc(g)	190–200	11.4	9.1	11.3	8.0	5.6	13.4	3.8	37.3	–
2	1	Ap	10–20	26.6	15.4	10.2	14.9	10.4	15.3	6.4	–	2.8
2	2	Bv	46–56	27.9	14.1	12.7	15.2	8.4	15.2	6.0	–	0.5
2	3	Bv(g)	67–77	25.9	14.1	12.8	14.6	11.0	15.0	6.2	–	0.4
2	4	Cc	106–116	17.5	10.5	10.3	9.6	7.2	11.0	5.6	28.3	–
2	5	Cc(g)	138–148	34.5	11.5	5.3	11.2	6.8	10.8	4.4	15.4	0.1

1) OM: Organic matter, OM = 1.72 x TOC. Analysed by DIAS.

Table A3.9. Soil chemistry of samples from the pedological profiles.

Pro. no.	Hor. no.	N_{total}	C/N	P_{total}	pH[1]	K	Na	Ca	Mg	Total bases	H^+	CEC	Base sat.	Fe (Ox)	Al (Ox)
		%		mg/kg					cmol/kg				%	mg/kg	
1	1	0.2	10	506	6.66	0.23	0.19	17.1	0.97	18.5	2.2	20.7	89	2892	918
1	2	0.05	6	144	6.67	0.26	0.17	14.7	1.13	16.3	3.53	19.8	82	2364	1120
1	3	0.05	3	197	7.39	0.29	0.3	19.3	1.82	21.7	–	17.6	100	2624	1208
1	4	0.03	4	363	7.38	0.24	0.22	13.2	0.92	14.6	0.24	14.8	98	1700	670
1	5	0.02	–	353	7.75	0.12	0.13	19.6	0.43	20.3	–	7.4	100	750	304
2	1	0.17	10	396	7.01	0.26	0.17	17	0.87	18.3	2.07	20.4	90	2708	954
2	2	0.05	6	136	7.24	0.26	0.17	16.6	1.02	18	1.29	19.3	93	2052	1172
2	3	0.05	5	164	7.44	0.2	0.16	16.8	0.76	17.9	–	12.1	100	1200	908
2	4	0.03	–	337	7.67	0.15	0.14	20.1	0.38	20.8	–	8.3	100	740	434
2	5	0.04	1	419	7.72	0.27	0.16	26	0.68	27.1	–	21.2	100	1326	640

1) pH determined in $CaCl_2$ solution. Analysed by DIAS.

Profile description

The pedological descriptions of the two profiles are summarized in Tables A3.6 and A3.7. The profile horizons are shown in Figure A3.13 while the laboratory data (grain size, texture, organic matter, nutrients, and major cations) are summarized in Table A3.8 and A3.9.

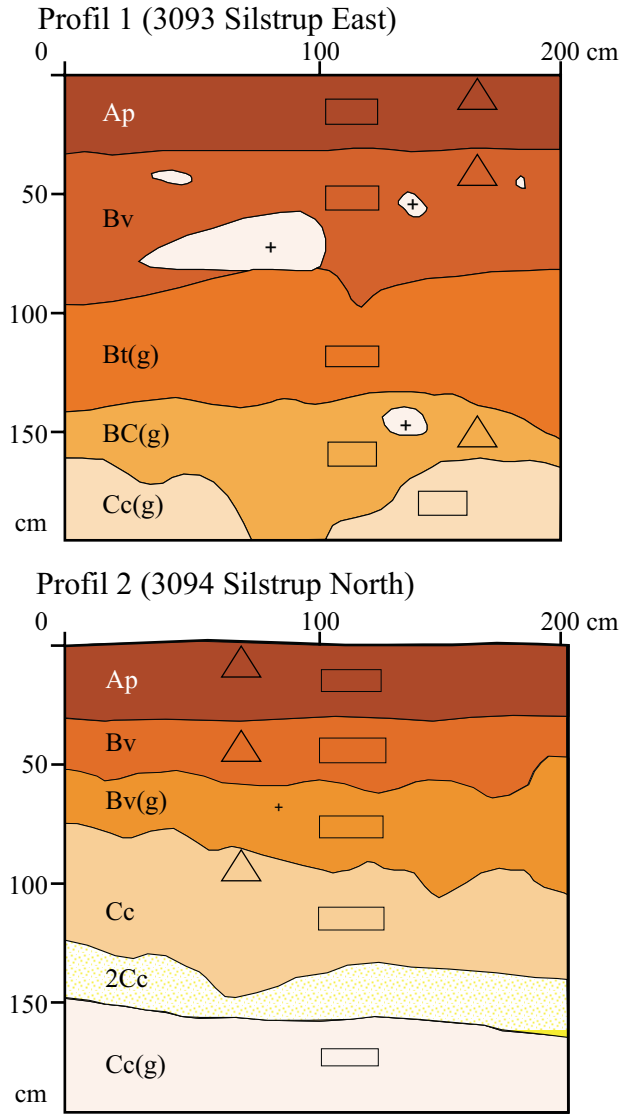


Figure A3.13. Schematic drawings of profiles showing horizon distribution. Rectangular boxes indicate sampling points for soil texture and soil chemistry. Triangular boxes indicate sampling points for hydrological analysis. White areas with + symbolise stones.

In Table A3.10 the profiles are classified according to "A Pedological Soil Classification System Based on Danish Soils" (Madsen and Jensen, 1985) and USDA Soil Taxonomy (Soil Survey Staff, 1999).

Table A3.10. Classification of the profiles.

Profile no.	Danish Soil Classification	USDA Soil Taxonomy
1 (3093 East)	The soil has a Bt horizon and is therefore a Lessive soil. As it has no further characteristics it is a Typilessive. Because there is Pseudogley, it is a **Pseudogleytypilessive**.	The soil has a high base saturation and a high organic matter content. It is therefore a Mollisol, and at the sub-order level is a Udoll. Because there is an argillic horizon, the soil is an Argiudoll. The colour requires it to be classified at the sub-group level as an **Alfic Argiudoll**.
2 (3094 North)	Because the soil has more than 8% clay, 30% silt and no Bt horizon, it is a Brunjord. At the group level a Typibrunjord. Because of the Pseudogley, it is a **Pseudogleytypibrunjord**.	Because there is a mollic epipedon and a high base saturation throughout the profile, it is a Mollisol. Having no special diagnostic horizons, the soil is a Udoll, Hapludoll and finally, a **Typical Hapludoll**.

Soil cores from the buffer zone

There is little variation in soil type in the area. The most common horizon subdivision is Ap–Bv–Bt(g) and in some places Ap2, BC, C. C horizons mainly occur in the western part of the soil cores taken from the buffer zone. The location is apparent on Figure A3.5. The presence of Pseudogley from a depth of approx. 70 cm (40-90 cm) in soil cores taken from the buffer zone indicates temporary water saturation during moist periods.

Comparison of the EM 38 map (Figure A3.18A) and the soil cores indicates a uniform topsoil but a more variable clay content in the underlying soil.

Total carbon mapping

The samples from the topsoil inside the test field were analysed for total organic carbon (TOC), which varied between 1.9% and 2.4% (dry weight) with a mean of 2.2% ± 0.1%. The concentration was lowest in the northern part of the field (Figure A3.14).

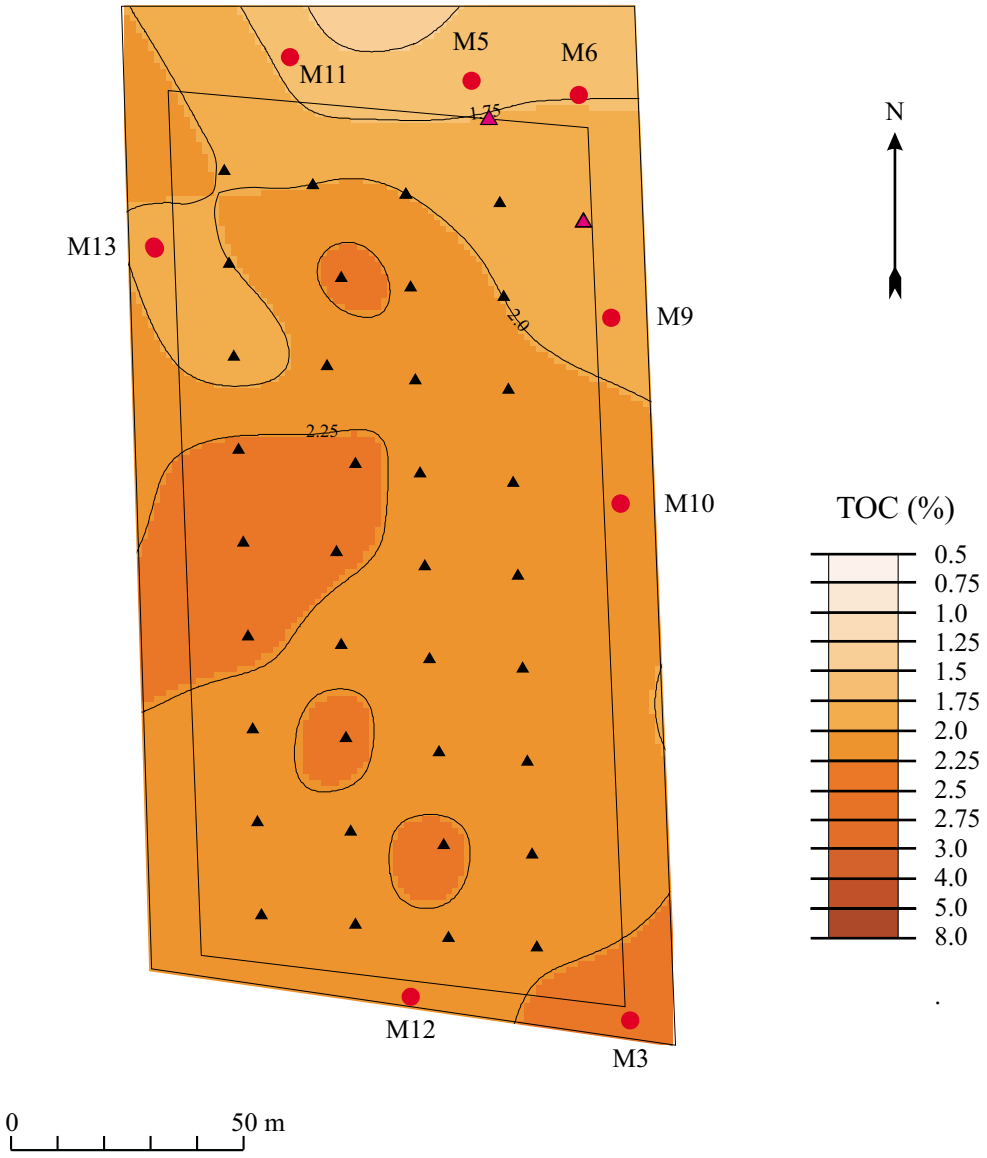


Figure A3.14. Map showing total organic carbon (TOC) content within the test field. Sampling points are indicated by ▲.

Pedological development

Pedological investigations have previously been carried out at Silstrup Experimental Station located 300 m southwest of the test field by Hansen (1976) and in relation to the Square Grid Profile (Statens Planteavlsforsøg, 1996) located 500 m to the south.

In both profiles at the test field the plough layer contains 18–25% clay. At a depth of 1 m the clay content is 43% in profile 1 (3093 East). The percentage of clay probably de-

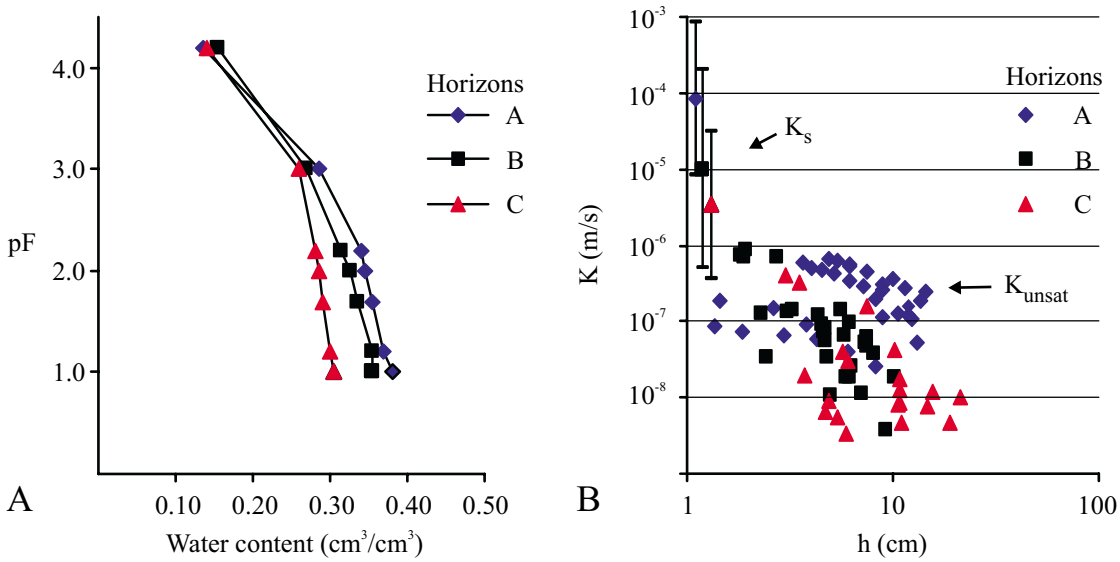


Figure A3.15. A) Retention curve based on values for the soil-water potential determined on the small soil core samples (100 cm^3). The data are the mean values from both profiles. B) The unsaturated hydraulic conductivity (K_{unsat}) as a function of soilwater potential in cm H_2O and the saturated hydraulic conductivity (K_s) determined on the large soil cores (6,280 cm^3).

reases towards the south since Hansen (1976) found 15% clay in the plough layer and over 24% clay in the underlying soil. At the Square Grid Profile the clay content is 12% in the topsoil and up to 27% at a depth of 120 cm. This picture is supported by the EM38 measurements (Figure A3.18A).

From a pedological point of view the change in clay content related to the parent material as well as to the different degrees of eluviation. The presence of a Bt horizon revealed by the occurrence of clay skins on peds in the profiles and in many of the soil cores is evidence of clay migration. Although evidence of clay migration could not be confirmed in these areas because the soil is cultivated, a high clay content is found just beneath the plough layer. The soils in these areas contain the weathered and brunified Bv horizons.

The base saturation of the soil is high due to the presence of chalk in the parent material and the high biological activity, both of which keep cations in circulation. The high base saturation can be maintained for a long time and provides the soil with a strong structure (Madsen, 1983). The C/N relation is low due to the high degree of decomposition.

The soil in the test field can be characterized as moderately mature with only slight eluviation in the NW areas to mature with more pronounced eluviation of both chalk and clay to some depth in the southern and eastern parts.

Soil hydrology

Soil cores (100 cm^3 and 6,280 cm^3) for the measurement of hydrological properties (soil water characteristics and hydraulic conductivity) were sampled at three levels corresponding to the A, B and C horizons.

The soil water characteristics of the nine small cores (100 cm^3) from each horizon are shown together with bulk density and porosity in Table A3.11 and Figure A3.15.

Table A3.11. Soil water characteristics determined on the small soil cores pF = $\log_{10}(-h)$.

Profile no.	Horizon	Depth cm	Water content at pF values cm^3/cm^3							Bulk density g/cm^3	Porosity[1] cm^3/cm^3
			1.0	1.2	1.7	2.0	2.2	3.0	4.2		
1 (3093)	Ap	15	0.39	0.38	0.36	0.35	0.34	0.28	0.13	1.42	0.46
	Bv	40	0.35	0.35	0.32	0.31	0.30	0.25	0.16	1.62	0.39
	BC(g)	150	0.30	0.30	0.29	0.28	0.28	0.26	0.16	1.77	0.33
2 (3094)	Ap	15	0.37	0.36	0.35	0.34	0.34	0.29	0.14	1.54	0.42
	Bv	40	0.36	0.36	0.35	0.34	0.33	0.29	0.15	1.59	0.40
	Cc	90	0.31	0.30	0.29	0.29	0.28	0.26	0.12	1.73	0.35

1) Assuming a particle density of 2.65 g/cm^3.

The soil in the A and B horizons gradually decreases in water content as a function of pF due to the relatively uniform pore size distribution, which is typical for a clayey/loamy soil. The majority of the pore are about 0.6 µm (tube-equivalent diameter), see Figure A3.16. The percentage of pores >12 µm is particularly low in the C horizon.

The saturated and unsaturated hydraulic conductivity determined on the large cores (6,280 cm^3) is shown in Figure A3.15. Unsaturated conductivity is low in all three horizons, with high inter-measurement variability in the A and C horizons. Due to the high variability in the A horizon within both the individual profiles and the field, it is difficult to establish a unique relationship between soil water potential (h) and hydraulic conductivity (k) in the horizon. The marked difference between near-saturated

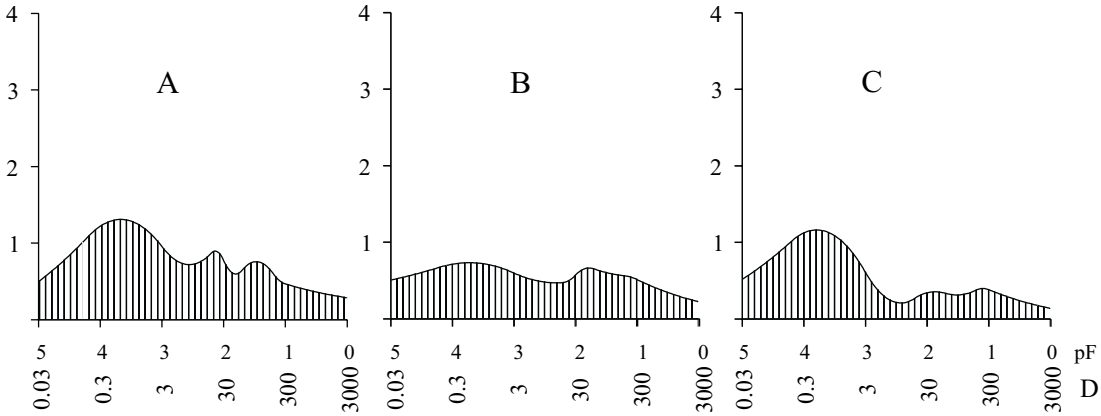


Figure A3.16. Pore size distribution measured (A, B, and C horizon) calculated from water retention data assuming the unity D=3000/10pF (D = pore diameter equivalent diameter, µm). A cubic spline interpolation procedure is used to yield discrete interpolate values on the sum curve obtained from the water retention curves. Abscissa: pF=log10(-h) in which h is the soil water potential in cm H_20. D = pore diameter, µm. Ordinate: percentage of pore volume per 1/10 pF-values, % v/v.

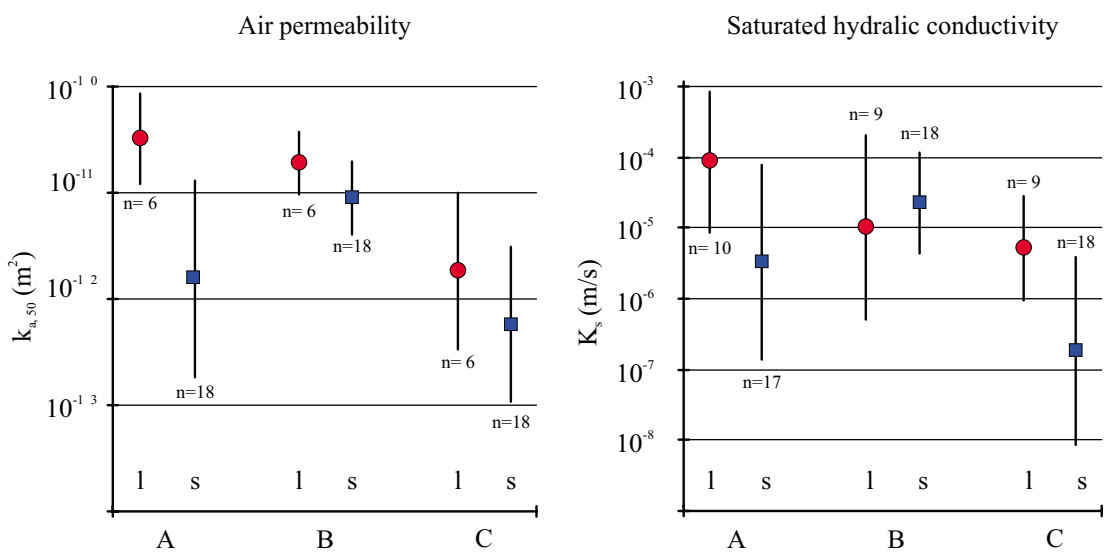


Figure A3.17. Air permeability at a water content of –50 cm H_20 ($k_{a,50}$) and saturated hydraulic conductivity (K_s) measured on large (6,280 cm^3) samples (●) and small (100 cm^3) samples (■).

hydraulic conductivity and saturated hydraulic conductivity indicates a high degree of direct piping (preferential flow) through macropores when the soil is fully saturated.

The measurements of saturated hydraulic conductivity and air permeability made using small (100 cm^3) or large (6,280 cm^3) soil samples differed markedly. This difference is probably related to the structure of the soil leading to a high dependence on sample size. With the large soil samples, infiltration takes place through a much larger soil area than is the case with the small soil samples and a greater number of macropores and other soil heterogeneities are therefore included.

A3.5 Geophysical mapping

Since destructive mapping methods are not accepted in the test field, it was decided to use EM-38, CM-031 and ground-penetrating radar (GPR). The EM 38 mapping was carried out on August 31 1999.

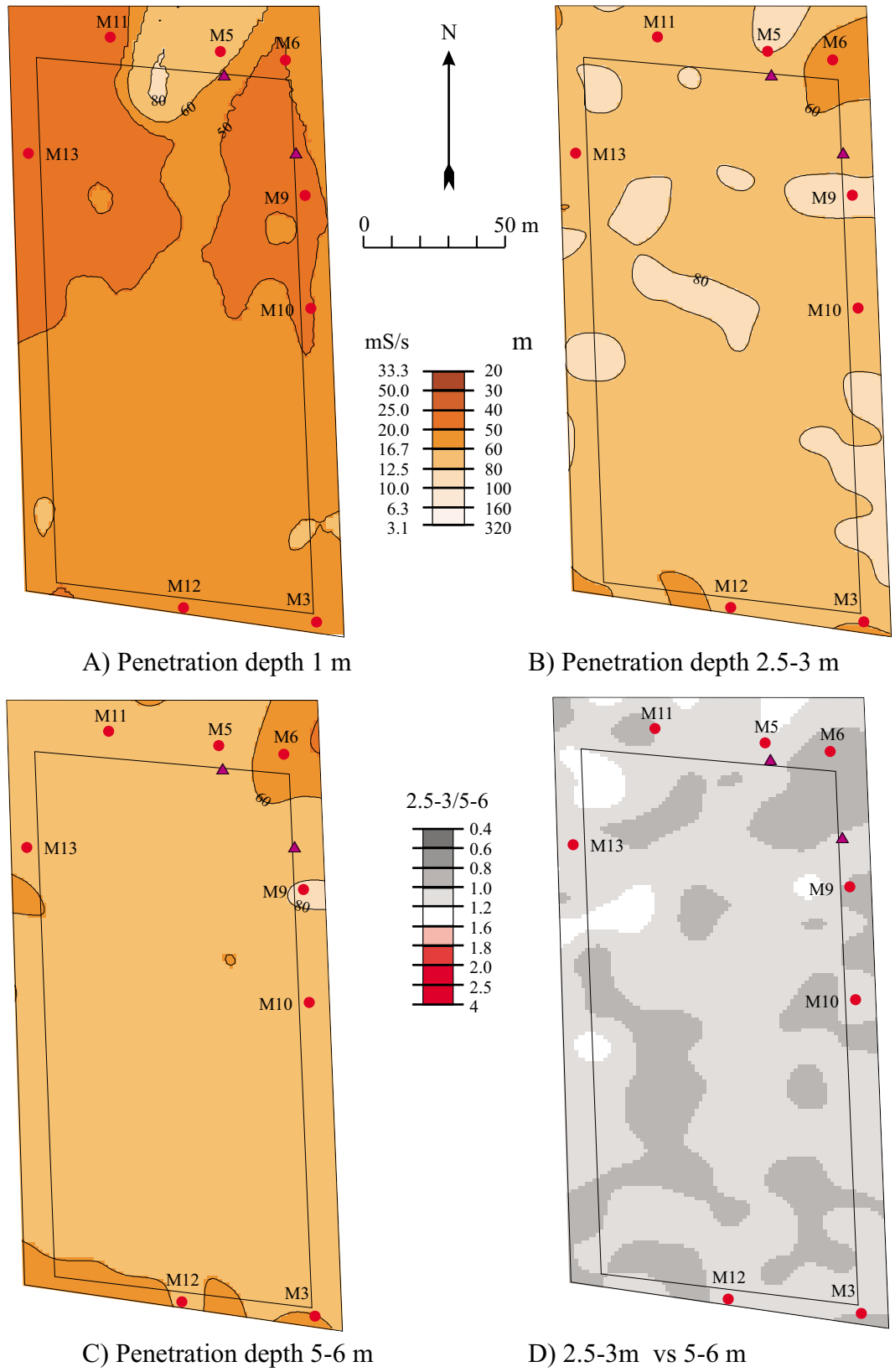
EM-38 mapping.

The EM-38 map found in Figure A3.18A reveals a rather homogenous texture pattern at Silstrup near the surface, i.e. the apparent resistivity ranges from 80 to 40 Ωm, with that of the majority of the area being 50 to 60 Ωm. In the northern end of the test field there are two areas with apparent resistivity in the range 40 to 50 Ωm indicating a higher clay content. In the areas with elevated apparent resistivity, the soil core and well data indicate the presence of clay and clay loam just below the topsoil.

CM-031 mapping

The test field has also been mapped with a CM-031 conductivity meter (Figure A3.18B, C and D). Figure A3.18B shows the apparent resistivity with a horizontal magnetic field penetrating 2-3 m. A homogeneous field can be identified with resistivity in the range 60 to 80 Ωm. According to Skov- og Naturstyrelsen (1987), resistivity is relatively high for a clay till, possibly due to the high $CaCO_3$ content of the till (>40% by weight).

The field is dotted with a number of smaller areas of elevated resistivity (80–100 Ωm), probably due to the presence of a more sandy till or sand lenses in the till. Figure A3.18C shows the apparent resistivity with a penetration of 5 to 6 m. These data reveal a completely homogenous geology with a resistivity between 60 and 80 Ωm indicating the



A) Penetration depth 1 m

B) Penetration depth 2.5-3 m

C) Penetration depth 5-6 m

D) 2.5-3m vs 5-6 m

Figure A3.18. Resistivity maps of the area. Map D shows the relative difference between map B and C and provides an idea about the homogeneity of the electrical properties to a depth of approx. 6 m b.g.s.

presence of a clay till. The relative difference between the vertical and the horizontal magnetic fields is shown in Figure A3.18D. Resistivity increases slightly with increasing depth, the opposite of what would be expected from the geological data. Again this may be attributable to the relatively high content of $CaCO_3$ in the unweathered clay till.

Ground-penetrating radar (GPR)

To detect any larger sand or gravel lenses or other geological anomalies and obtain information about internal structures such as bedding planes, etc., the area was mapped using ground-penetrating radar in a 20 to 30 m grid. The profiles revealed almost continuous cover with low penetration, interpreted as a clay till. Penetration of up to 4 m was obtained in a few spots, however. These data are in good agreement with the resistivity data.

Appendix A3.1. Cultivation and pesticide application history at Silstrup.

Year	Crop	Date	Pesticide brand	Dose per ha
1983	Spring barley	13.06.83	Bayleton	0.3 kg
		13.06.83	Propinox	2.0 l
1984	Winter barley	20.09.83	Tribunil	4.0 kg
		14.11.83	Topsin	0.8 l
		27.04.84	Sportak	1.0 l
		23.05.84	Tilt	0.5 L
1985	Winter wheat	20.11.84	Bayleton	0.5 kg
		20.11.84	Vegoran	1.75 l
		14.05.85	Cycocel	1.0 l
		14.05.85	M-prop-combi	3.5 l
		14.05.85	Sportak 45 ec	1.0 l
1986	Spring barley	29.05.86	Decis	0.3 l
	Undersown grass	29.05.86	Dinoseb	1.5 l
		29.05.86	Manganchelat	1.0 l
		29.05.86	Parathion	1.0 l
1987	Grass			
1988	Field bean	30.05.88	Dinoseb	1.2 l
		25.10.88	Roundup	3.0 l
1988	Spring barley	01.06.88	D-prop-mix	3.0 l
		28.06.88	Sportak 45 ec	0.5 l
1989	Fodder beet	27.04.89	Venzar	0.5 kg
		15.05.89	Betasana	2.0 l
		15.05.89	Goltix	2.0 kg
		01.06.89	Betasana	2.0 l
	Western part only	01.06.89	Fusilade	1.5 l
		01.06.89	Goltix	2.0 kg
		01.06.89	Pirimor	0.33 kg
		01.06.89	Sun Oil	1.0 l

Year	Crop	Date	Pesticide brand	Dose per ha
1990	Spring barley	15.05.90	Butytox	3.0 l
	Undersown grass	06.06.90	Tilt Turbo	0.5 l
1991	Grass			
1992	Winter wheat	21.10.91	Vegoran	1.25 l
1993	Spring barley	24.05.93	Butytox	3.0 l
	Undersown grass	08.06.93	Cyperb	0.2 l
		08.06.93	Sambarin	0.75 l
1994	Peas	24.05.94	Basagran 480	0.5 l
	Undersown grass	24.05.94	Cyperb	0.2 l
		24.05.94	Stomp SC	0.75 l
		17.06.94	Basagran 480	0.5 l
		17.06.94	Cyperb	0.5 l
		17.06.94	Stomp SC	0.75 l
		06.07.94	Decis	0.2 l
		10.10.94	Touch Down	2.5 l
1995	Spring barley	26.06.95	Butytox	3.0 l
	Undersown clover grass	26.06.95	Tilt Turbo	0.4 l
1996	1st year clover grass			
1997	2nd year clover grass			
1998	Winter wheat	21.10.97	IPU	1.0 l
		21.10.97	Stomp SC	1.5 l
		29.05.98	Bravo	0.2 l
		29.05.98	Mangansulfat	1.5 l
		29.05.98	Tilt EC	0.1 l
		19.06.98	Tilt Top	0.5 l
1999	Winter wheat	20.04.99	Express	0.0094 kg
		20.04.99	Oxitril	0.4 l
		25.06.99	Lissapol	0.1 l
		25.06.99	Express	0.0075 kg
		25.06.99	Tilt Top	0.4 l
		05.08.99	Roundup	2.0 l
		05.08.99	Team Up	4.0 l

Site Characterization and Monitoring Design

Annexe 4.

Site 4: Estrup

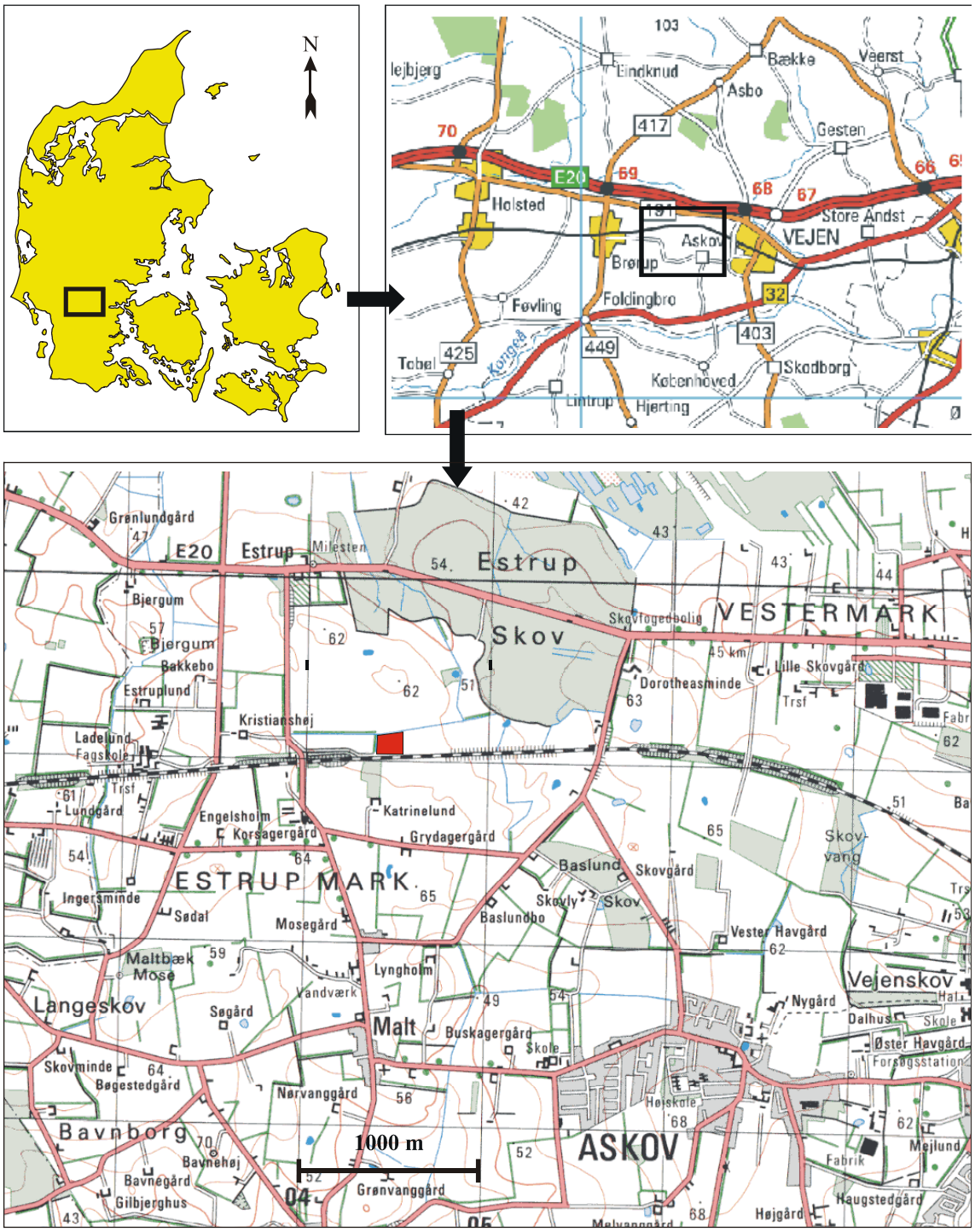


Figure A4.1. Location of the test field.

A4.1 Location, ownership and earlier cultivation and use

The test field is situated at Estrup west of Vejen in central Jutland (Figure A4.1). It is privately owned and leased by the Danish Institute of Agricultural Sciences (DIAS). The site characteristics are summarized in Table A4.1.

Table A4.1. Site characteristics.

Length and width of the test field	120 m x 96–112 m
Total area of the site, incl. buffer zone	1.8 ha
Area of the test field	1.26 ha
Municipality	Vejen
County	Ribe
Land registry no.	1av, Estrup Hovedgård, Malt
Ownership	Private, leased by DIAS

Earlier use

The area is leased from a private farmer and has previously been farmed as a normal field. As is apparent from Figure A4.2, the field has been farmland at least since 1938. Cultivation and pesticide application history at Estrup from 1993 to 1999 is summarized in Appendix A4.1.

A4.2 Technical installations

All installations at Estrup are numbered according to the code described in Section 3. In the present description, however, the site-specific code for Estrup, i.e. “4”, has been omitted for the sake of simplicity. The locations of all installations were selected on the basis of the drainage system and the groundwater flow pattern (Figure A4.3) and are shown in Figure A4.4.

Buffer zone

The buffer zone at Estrup is 10 m wide along the northern and western borders, 5 m wide along the southern border, where the railway runs, and 15 m wide along the eastern border.

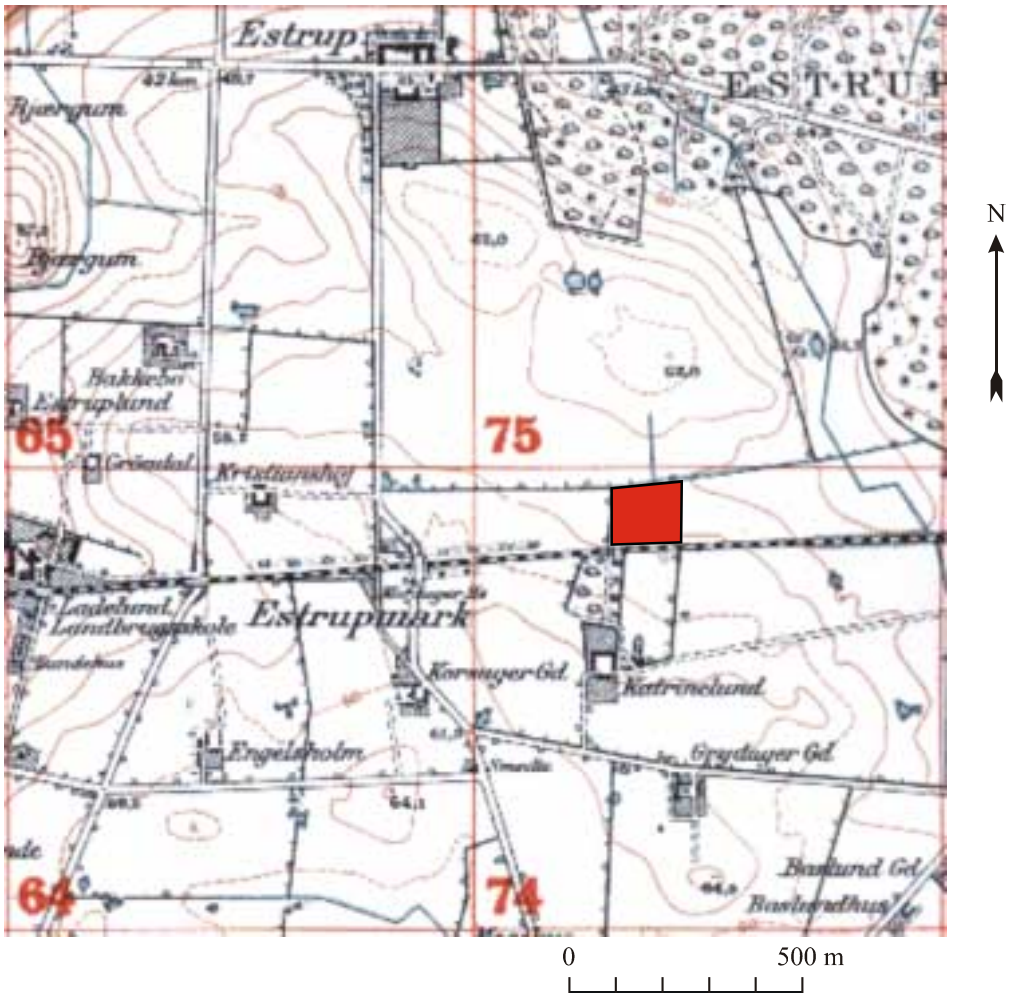


Figure A4.2. Topographic map 1:20.000 from 1938. The test field is marked as a red square.

Suction cups, TDR and Pt-100 sensors

The suction cups, TDR and the Pt-100 sensors in the eastern excavation (S1) were installed as described in Section 3.3.

The suction cups in the northern excavation (S2) were installed during deteriorating weather conditions, in a collapsing wall. Heavy precipitation combined with a water-bearing sand layer in the profile wall caused the wall in which the suction cups were installed to collapse several times during installation work. The hand-drilled installation holes were full of water, which made the clay and bentonite seals difficult to control. It is thus uncertain whether the clay and bentonite seals are actually in place. Because of the collapse of the profile wall, it subsequently became necessary to move the border of the test field 0.5–1.0 m to the south.

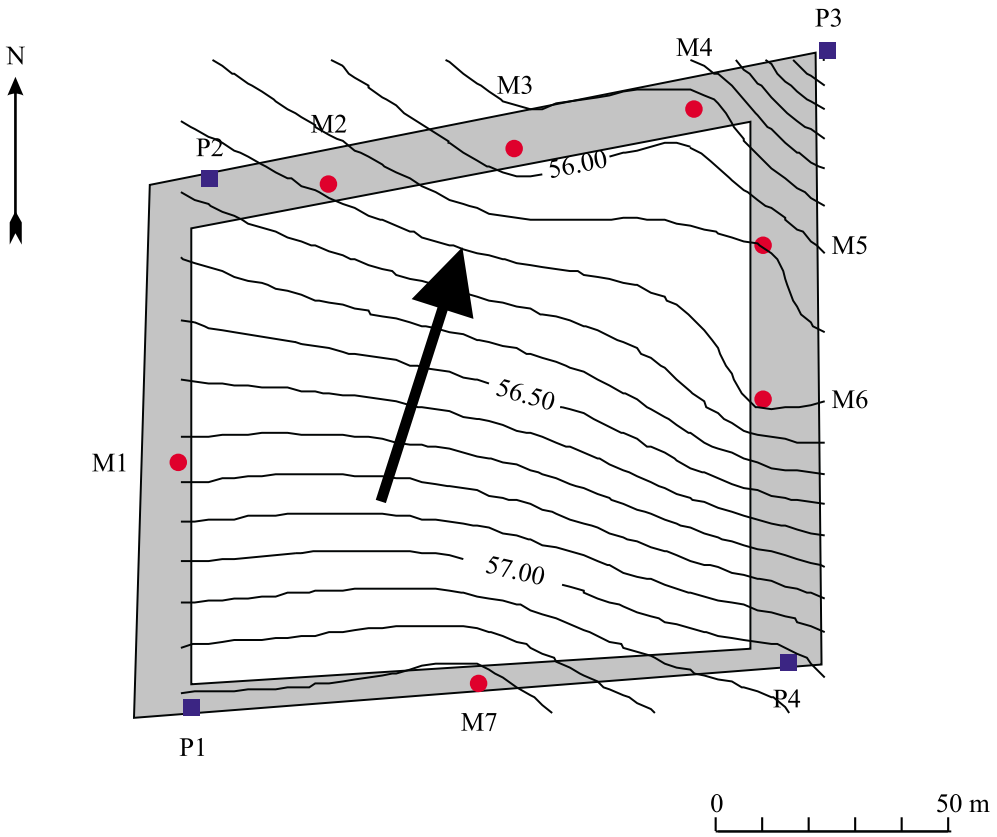


Figure A4.3. Potential head (m a.s.l.) at the site measured in February 2000 and the direction of the ground water flow.

Wells

Horizontal monitoring wells

Due to the geological conditions, only one of two planned horizontal wells was installed (Figure A4.4). Moreover, the length of the horizontal monitoring well was shortened to avoid drilling in sand.

The well H1 content of three 18 m screen sections and four 1 m bentonite seals were installed 3.5 m b.g.s. under the northeastern corner on November 30 1999. The length of the horizontal monitoring well below the test field was 70 m. The well was drilled from two 2.5 m deep excavations in order to keep the drill-water pressure down and avoid unnecessary damage to the penetrated lithologies.

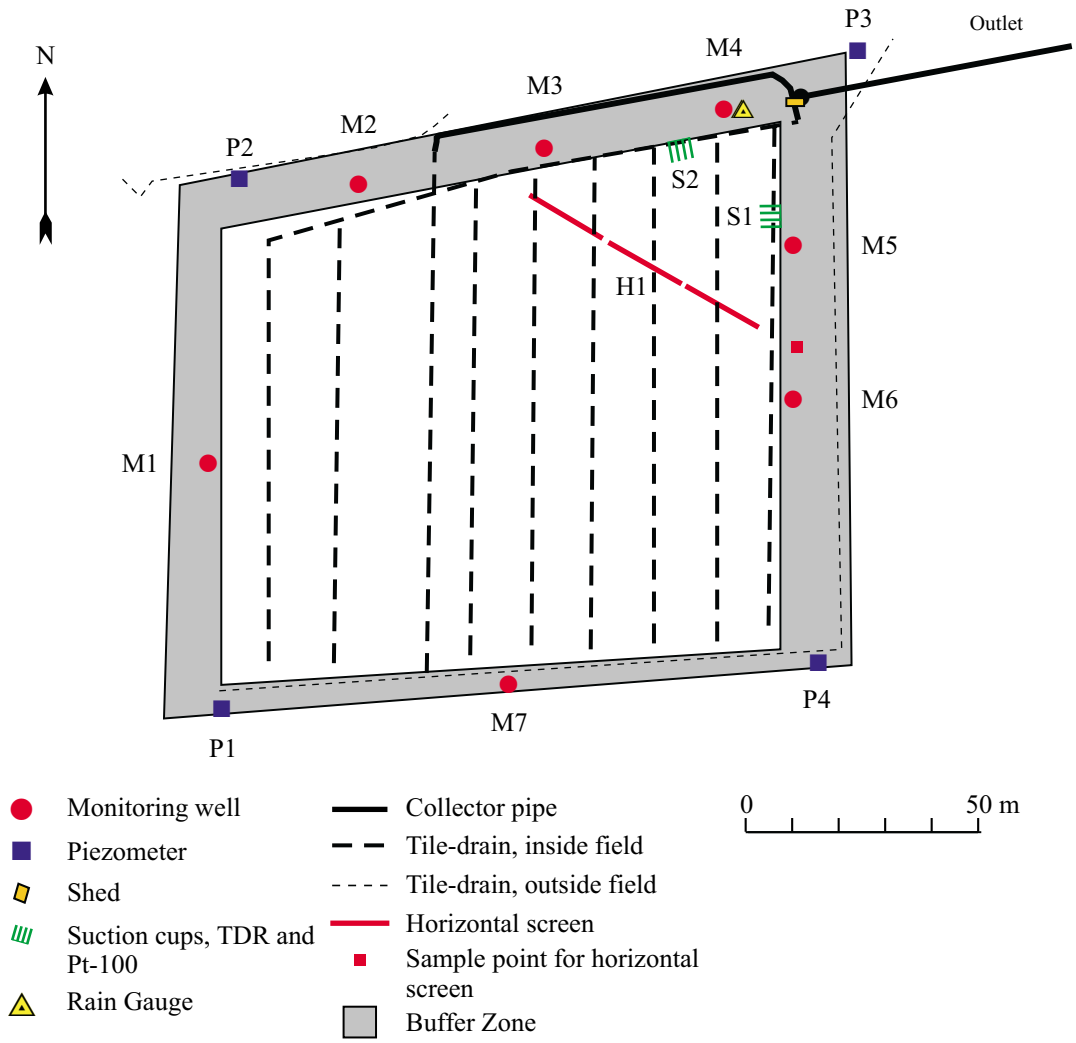


Figure A4.4. Sketch of the field showing the test and buffer zones and location of installations.

A second attempt was made to drill a horizontal well from a position 7 m west of M2 to 13 m north of M6, but the borehole had to be abandoned after 15 m of drilling in sand. The abandoned borehole was subsequently sealed with bentonite pellets.

Installation of the piezometers

Two wells each containing three piezometers were drilled on August 26 1999 and August 27 1999 in order to survey the geology and the groundwater head. Both these wells – P1 and P3 – penetrated clay, clay till and minor occurrences of sand. P2 and P4 were drilled in November 1999. In order to be able to monitor the regional groundwater head, P2 was drilled to 23.4 m b.g.s.

Table A4.2. Depth of the piezometer screens.

Well no.	DGU no.	Upper screen m b.g.s.	Middle screen m b.g.s.	Lower screen m b.g.s.
P1	132.1731	4.5–5.0	6.6–7.1	11.2–12.2
P2	132.1767	3.0–3.5	6.8–7.3	19.9–21.9
P3	132.1732	1.5–2.5	5.5–6.5	11.0–12.0
P4	132.1768	2.0–2.5	6.4–6.9	10.5–11.5

Monitoring wells

Seven monitoring well clusters (M1–M7) each consisting of four individual wells were installed in November 1999 (Figure A4.4). The technical specifications are described in Section 3.2.1.

Screen M4.3 in well cluster M4 was installed incorrectly as bentonite was present in the screen interval. The well was therefore reinstalled on 8 March 2000.

The screens in the monitoring well clusters are located at the following depths:

Mx.1: 1.5–2.5 m b.g.s.
Mx.2: 2.5–3.5 m b.g.s.
Mx.3: 3.5–4.5 m b.g.s.
Mx.4: 4.5–5.5 m b.g.s.

Drainage system

The drainage system is illustrated in Figure A4.4. The basis for the work with the drainage system was a hand-drawn sketch of the original drainage system made in 1965. The drawing map lacks any information regarding dimensions, depth or gradient of the drainpipes. Only the distance between drains was indicated on the map.

According to the map, there are eight parallel drains running northwards. These pipes join a main pipe that runs eastwards parallel to the ditch, making up the field boundary to the north. This main drain was detected in the northeastern corner of the field by a sondage and proved to be 6.5 cm in diameter, which is rather narrow for a main drain. The diameter of the main drain subsequently increased to 8 cm and finally to 10 cm, eventually exiting in an open ditch approx. 350 m east of the test field.

Some 50 m from the western border of the test field and parallel to the eight lateral drains, the map showed an additional 8 cm drainpipe starting close to the railway em-

bankment bordering the field to the south, with a side drain feeding into each side just a couple of meters from the railway. It was run straight to the north at a point where a 10 cm pipe delivers water from the neighbouring field to the west. The 10 cm pipe cuts through the northwestern corner of the field, thereby cutting a small triangle off the test field. Another 8 cm pipe exited in the ditch some 60 m further to the east. Insertion of a steel rod into this pipe revealed that it either terminates or is blocked 45 meters south of the ditch.

Since the project prohibits excavation work near or above the drainpipes within the test area, a thorough and more detailed inspection of the drainpipes was not possible.

New collector pipes and measuring chamber

A 350 m stretch of the ditch to the north of the test field was dredged and deepened to ensure unhindered outflow from the 10 cm pipe draining the field to the west as well as from the new drains established for the project.

The measuring chamber was located northeast of the test field. From here the water was led 95 m downstream to the east via a 160 mm PVC pipe that exited in the ditch. The reason for this extra run is that a more direct outlet further upstream would have necessitated an inconveniently deep ditch.

The discharge from the two 8 cm pipes that originally exited in the ditch was collected by an 85 m long, Ø 75 mm PE pipe running 1–2 m from the edge of the ditch. Water from the main drainage system was led to the chamber in a 5 m long, Ø 110 mm pipe. The two branches join in a T-junction right outside the chamber.

To cut off water entering the test field from the upstream side, a new drain was installed along the southern (along the railway) and eastern boundaries. The new drain consists of corrugated and perforated PVC pipes with an envelope of filter sand. It exits in the ditch northeast of the measuring chamber.

Dimensions of the outlet

The drained acreage of the test field amounts to 1.3 ha. The outlet from the measuring chamber consists of Ø 160 mm smooth PVC pipe, which should be more than sufficient. In order to ensure free flow in the drain, it is essential that the ditch is maintained in future.

Comments

The construction work was carried out in November 1999. During the installation of the cut-off drain south of the field, an additional small drainpipe was discovered running parallel to the field drains shown on the map. In addition, the upper ends of the two easternmost drains of the experimental field were found in the cut-off drain trench along the railway. All three drains were just 3.3 cm (5/4") in diameter. The spacing between the three was 13 m, which corresponds with the spacing stated on the map. In view of the small size of the main drain (6.5 cm), it seems to be part of the same drainage system and all 8 of the lateral drains inside the test field are probably of the same small diameter.

Narrow pipes of this size were used many years ago and, as far as we know, have not been used since 1932. The two 8 cm pipes that originally exited in the ditch, but which are now connected to the measuring chamber, seem to run in former ditches. The sequence of drainage events would normally be to get rid of open ditches first and thereafter initiate systematic drainage. From the pipes, though, the opposite would seem to be the case here.

The system of small pipes must be seen as the primary system, but old. The year 1965 written on the map must be interpreted as the time the drawing was made, probably in connection with inspection and maintenance of the drainage. Regardless of the age and capacity of the system, however, it is fair to state that runoff in all active drains is collected and led to the measuring chamber, and that all influx of water through drains from the uphill side has been cut off.

A4.3. Geology

Regional geology

Estrup is situated west of the Main Stationary Line on a hill island, sensu P.R. Barham in Stamp (1966), i.e. a glacial moraine preserved from the former glaciation – the Saalian, rising as a mature hill from an outwash plain of a later glacial epoch – the Weichselian. This means that the area has been exposed to weathering, erosion, leaching and other geomorphologic processes for the past 140,000 years: 25,000 years in the last interglacial period, the Eemian, a period when the climate was temperate, approx. 105,000 years during the Weichselian under varying glacial climates and 10,000 years during the Holocene under a temperate climate. This time span represents a full interglacial-glacial-interglacial cycle. East and north of the Main Stationary Line, the ice

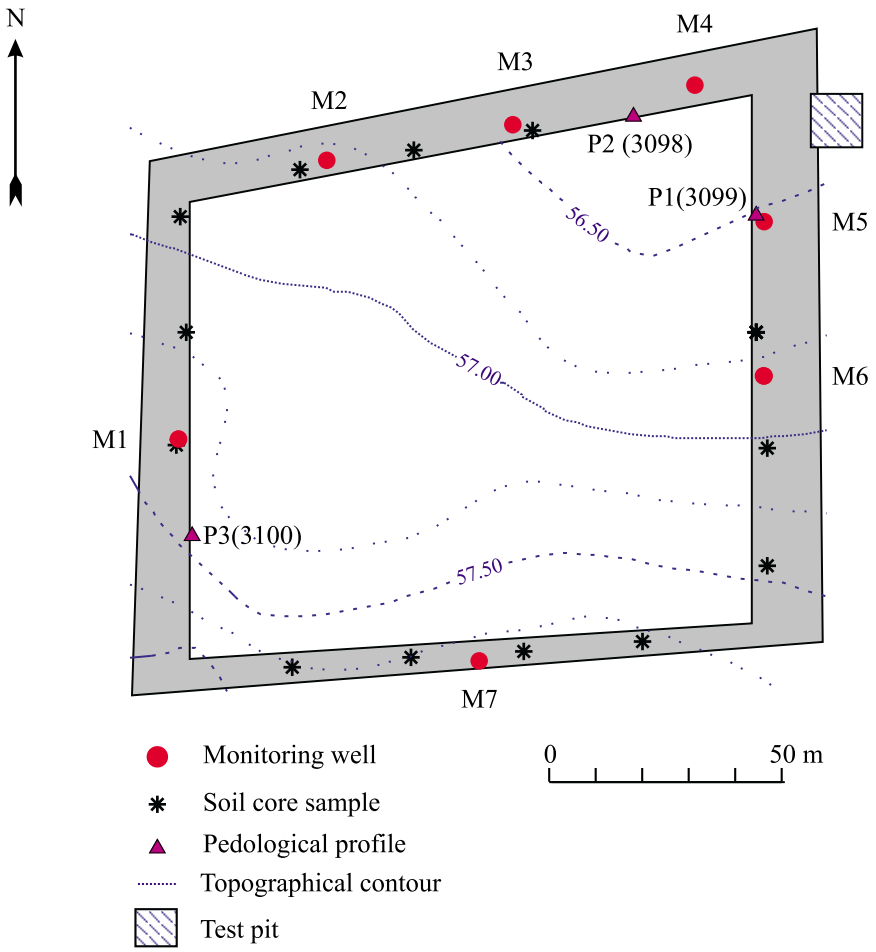


Figure A4.5. Topography at the site and location of soil cores, test pit and monitoring wells.

from the last glaciation – the Weichselian – melted approx. 12,000–15,000 years BP and landforming processes have only been active for this period. That means that the time spans during which the landscape has been subject to geomorphological and pedological processes differ east and west of the Main Stationary Line by a factor of 10 compared with the rest of the country.

According to Figure A4.6, the dominant sediment in the area is clay till that is probably Little Belt till formed during the late Saalian Paleobaltic advance (Houmark-Nielsen, 1987). The map of Quaternary sediments indicates that most of the test field is located on freshwater sediments from the Holocene. This is **not** the case, however, but rather an inaccuracy on the map.

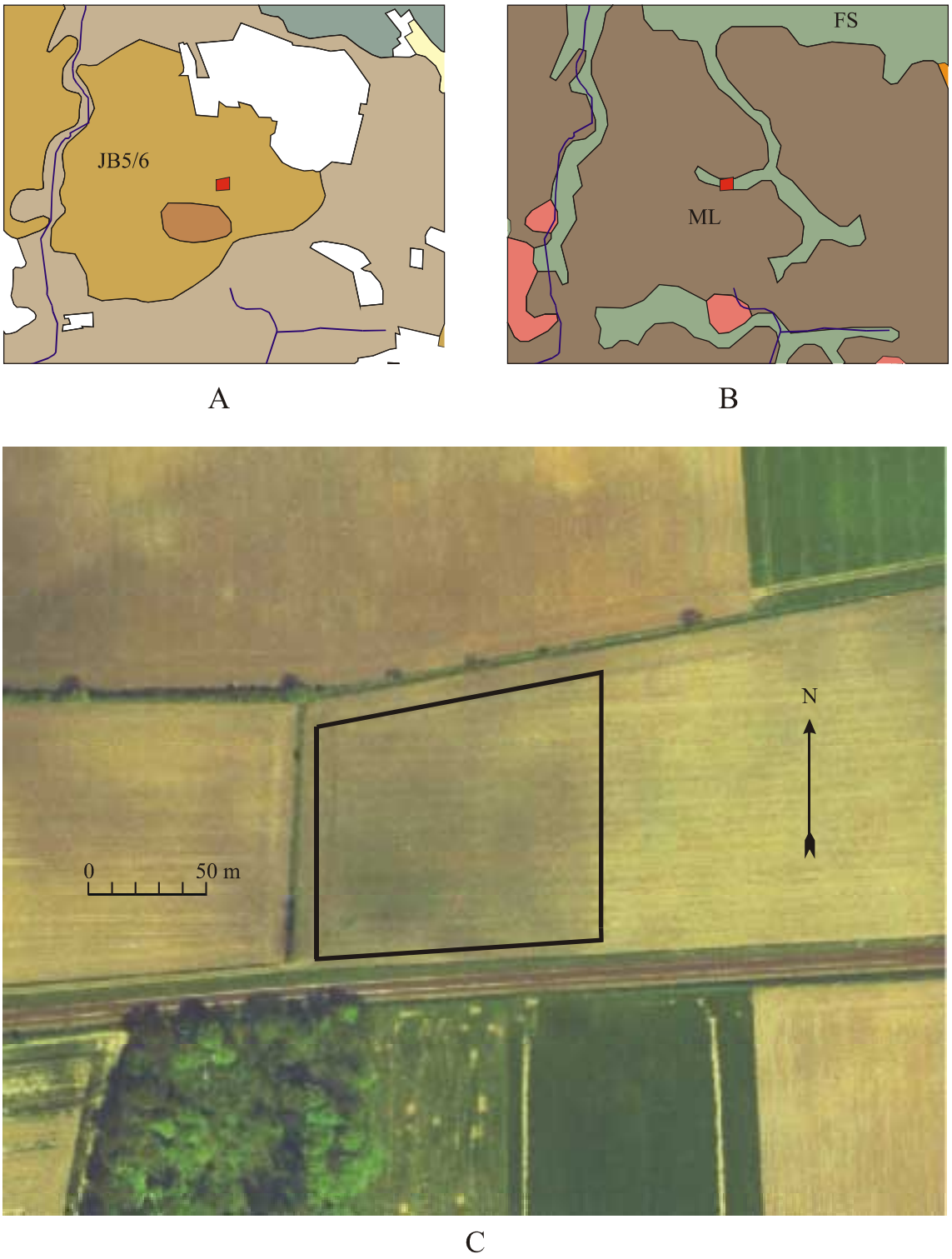


Figure A4.6. Location of the test field (red square) superimposed on: A) The soil type map. JB 5/6: Sandy loam B) Map of Quaternary sediments in Denmark, ML: Clay till, FS: Post-Glacial freshwater sand . C) An aerial orthophotograph, (Kampsax Geoplan, DDO1999

Geomorphology

The test field is located on a hill island 56 m a.s.l. The initial relief is eroded and does not reveal much about the original landscape left behind by the Saalian ice. Today the landscape can be described as a weakly undulating surface. The site slopes slightly (1.1%) towards the northeast, where it is bordered by a ditch (Figure A4.5).

Figure A4.6 shows the location of the test field superimposed on the Soil Classification map, the map of Quaternary sediments in Denmark (Hermansen and Jacobsen, 1998), and a 1999 orthophotograph. The dominant soil type in the area is a sandy loamy soil (JB5/6), whereas the dominant Quaternary sediment in the region is clay till (ML). The map incorrectly indicates that the majority of the test field is covered by Post-Glacial freshwater sand (FS). This is not the case, however, although some glaciofluvial sand bodies are present. Based on the orthophotograph, some inhomogenous appears to be in the soil properties inside the field.

Geology of the monitoring wells and piezometer wells

The monitoring wells and piezometers reveal a varied geology (Figures A4.7–A4.8), ranging from clay till to glaciofluvial sand and clay to Post-Glacial peat and fill material -sand - from the construction of the railway. The test field can be subdivided on the basis of the geology of the piezometer wells and monitoring wells combined with geophysical measurements.

In the southwestern corner, P1 contains clay till and minor components of silty till and sandy till to a depth of 12.4 m b.g.s. M1 contains clay till to a depth of 5.6 m b.g.s.

P2 and M2 contain mainly glaciofluvial sediments dominated by sand in the upper 7.4 and 5.5 m, respectively, but with some silt and clay layers. In P2 the sandy deposits rest on till deposits down to a depth of 23.4 m. The sand found in these wells constitutes one of three smaller basins found on the site.

The area covered by wells M3, M4 and M5 is dominated by clay till deposits with minor elements of glaciofluvial sand, possibly connected to the sand found in P2 and M2.

M6 mostly consists of glaciofluvial sand, once again containing a few layers of till. The sand body found in this well constitutes another of the three smaller basins found on the site.

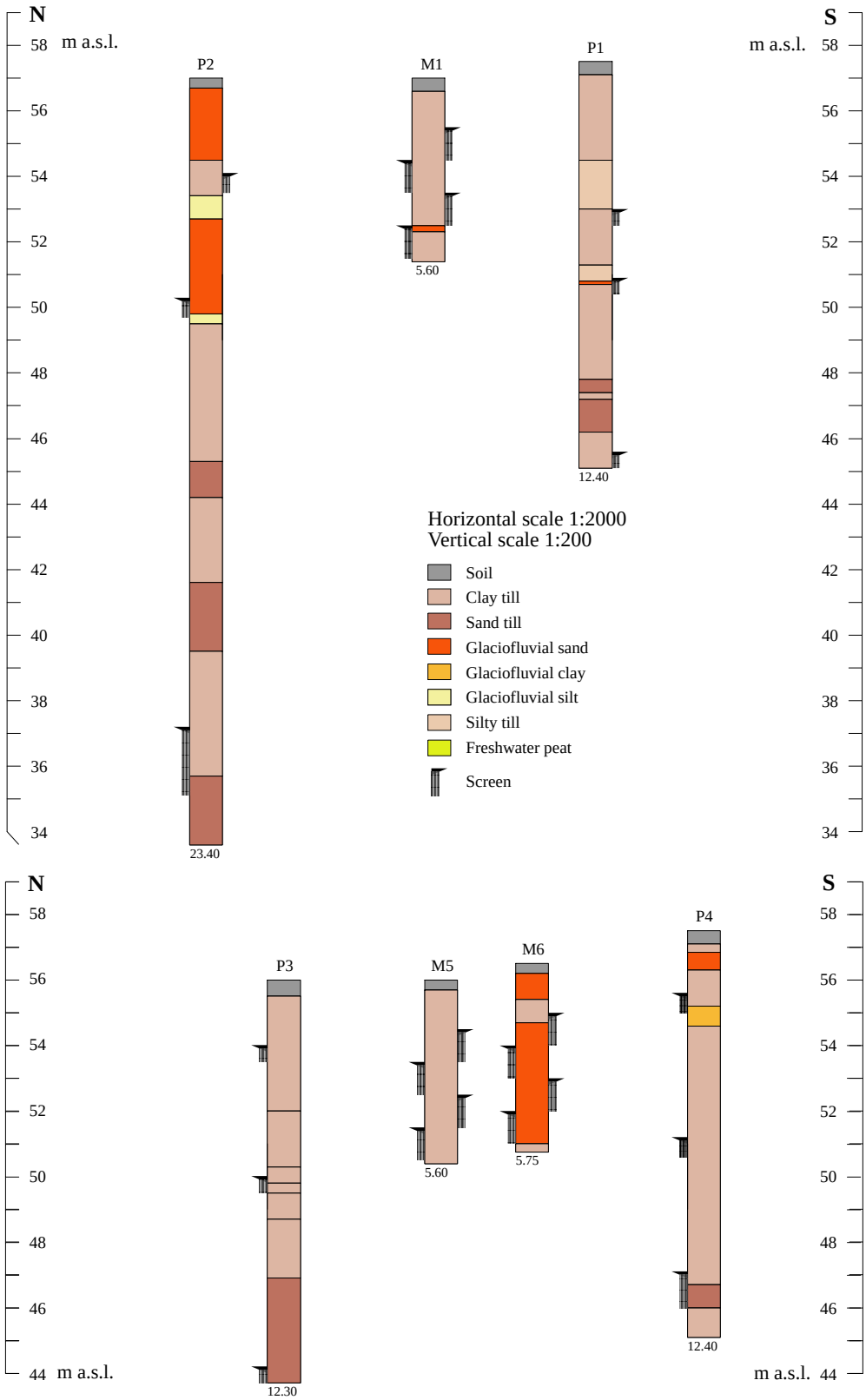


Figure A4.7. N-S cross sections based on wells at the site. The location of the wells is shown in Figure A4.4.

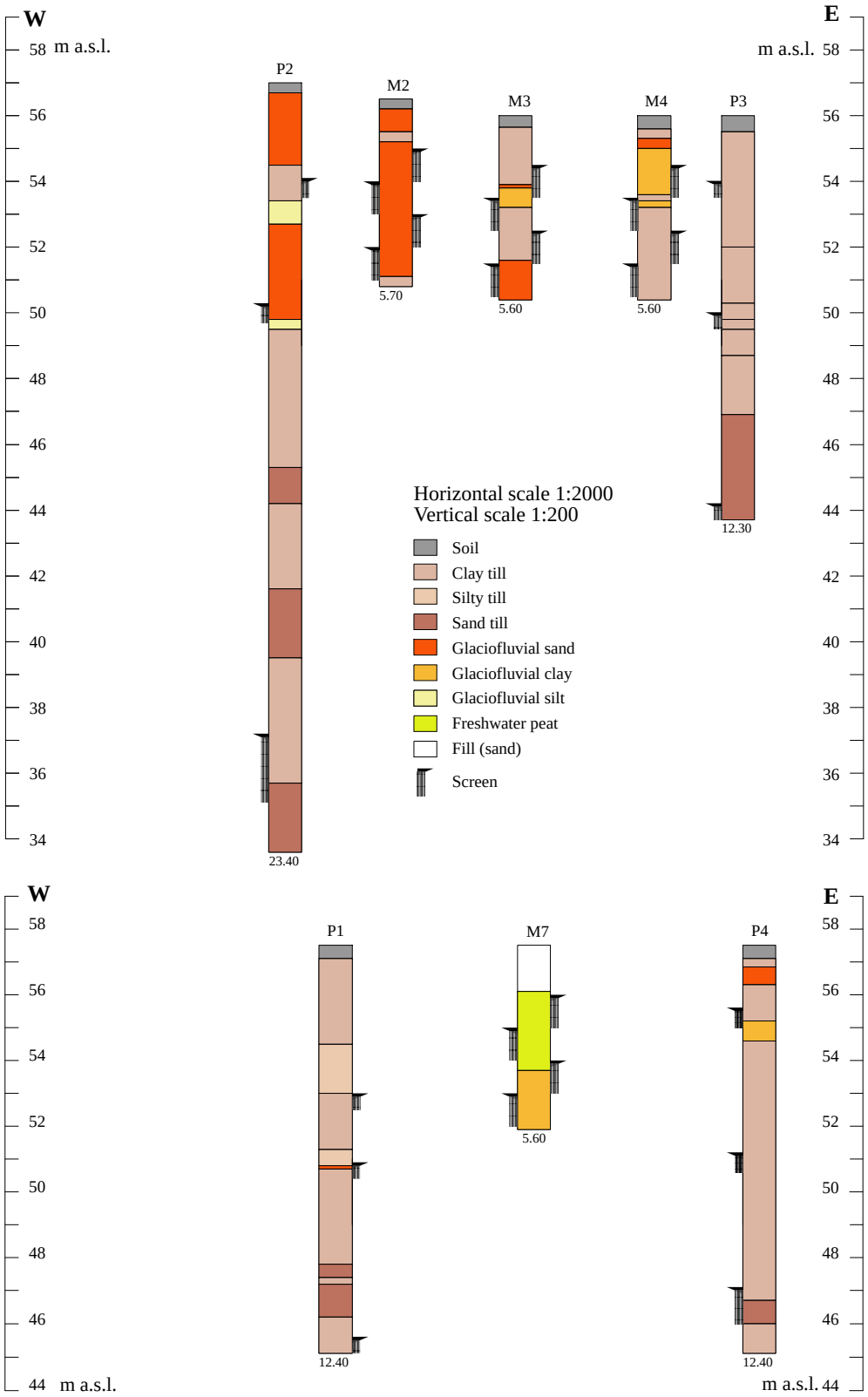


Figure A4.8. E-W cross sections based on wells along the southern and northern ends of the test field. The location of the wells is shown in Figure A4.4.

In M7 a small basin of postglacial peat was penetrated beneath 1.4 m of sandfill from the construction of the railway. Ground-penetrating radar and resistivity measurements revealed that the distribution of the peat is limited to a very small basin (10 m x 10 m). The peat found in this well constitutes the third of the three smaller basins found on the site.

Geology of the test pit

A test pit was excavated to 5 m b.g.s. using a backhoe in the buffer zone of the north-eastern corner of the test field for field vane tests, fracture descriptions and characterizations, fabric analyses, and lithological descriptions.

Unfortunately the subsequent drilling, digging and geophysical investigations revealed that the geology found in the test pit was only partially representative of that in the test field as a whole, although the geological variability is well represented in the test pit.

As it turned out, the east-facing profile were quite homogenous with more or less concordant units. In contrast, the south-facing profile revealed the rim of an interglacial or interstadial pond or lake as previously described for the area by Jessen and Milthers (1928). The lacustrine sediments found were calcareous, fine-grained and in some cases laminated. They served as a shield against leaching and dissolution of $CaCO_3$ such that calcareous till sediments are found at a much shallower depth in the south-facing profiles than in the east-facing profiles. The same phenomenon was detected in some drill holes. As there is no reason to believe that the lacustrine deposits found in the test pit occur inside the test field.

Samples were collected for grain size analysis, $CaCO_3$ content, clay mineral analysis, porosity/permeability, and exotic stone counts.

Lithological description

The depths given in Table A4.3 are average depths determined from the test pit, and correspond to the log in Figure A4.9–A4.11. The descriptions follow Larsen *et al.* (1995).

The south-facing test pit profile cut through the rim of a lacustrine basin containing the strata described in Table A4.4.

Table A4.3. Lithological description of the test pit at Estrup.

Depth m b.g.s.	Description	Sample no.
0.0–0.3	Top soil, sand, mix of clay, silt, and small mix of gravel, blackish brown. Noncalcareous.	DIAS
0.3–1.0	Clay till, strong mix of clay, mix of silt and sand, weak mix of gravel, some boulders. Numerous biopores, roots and burrows. Periglacial involutions, sand bodies in decimetre to meter scale veins and sand lenses. Strong brown to yellowish brown. Noncalcareous.	11008.
1.0–2.0	Clay till, sticky, strong mix of clay and silt, mix of sand, weak mix of gravel, biopores with clay skins. Brownish yellow with grey colouring around macropores. Noncalcareous.	11009.
2.0–3.70	Clay till, sandy, mix of clay silt and sand, some gravel. The till contains numerous chalk rafts. Fractures – horizontal as well as vertical – are abundant and covered with FeO and MnO. Iron oxides usually dominate but occasionally manganese oxides take over. The fractures seen in the profiles form a 3-dimensional pattern resembling that of a brick wall. The colour is light yellowish brown to pale brown with strong brown to yellowish red (rust coloured) haloes around the fractures. The sediment is calcareous or noncalcareous, depending on where in the pit the till is sampled.	11010 + 11011.
3.70–3.90	Sandy till, strong mix of sand, mix of silt and clay, homogenous, strong brown calcareous or noncalcareous, depending on where in the pit the till is sampled.	11017
3.90–5.0	Clay till, sandy, mix of clay silt and sand, some gravel. The till contains several chalk rafts. Fractures – horizontal as well as vertical – are abundant and covered with iron and manganese oxides and hydroxides. The fractures form a 3-dimensional pattern resembling that of a brick wall. The colour is light yellowish brown to light brownish grey with strong brown to yellowish red (rust coloured) haloes around the fractures. The sediment is calcareous or noncalcareous, depending on where in the pit the till is sampled.	11014 + 11015 + 11016

Table A4.4. Lithological description of lacustrine sediments found in the south-facing profile of the test pit.

Depth m b.g.s.	Description
1.0–1.5	Fine-grained or noncalcareous homogenous sticky clay with a gyttja component, mix of silt, weak mix of sand, light yellowish brown and brownish yellow. Lower limit is very irregular with a 1 m topography caused by “chimneys”. This sediment is a product of alteration from the underlying unit.
1.5–1.8	Fine-grained calcareous homogenous sticky clay with a gyttja or marl component.
1.8–2.1	Fine layers of clay silt and fine sand, laminated on a mm to cm scale, yellowish brown and greyish brown, calcareous, thickness increasing towards the east. This unit rests on a clay till.

The pedological profile 3 (3100 Estrup west) dug in the buffer zone between P1 and M1 in the southwestern corner (2 m x 3 m, 1.85 m deep) (Figure A4.13) revealed glaciofluvial sand resting on rafted Tertiary micaceous clay at a depth of 1.15 m. The Tertiary clay was penetrated with a hand corer revealing that it was approx. 30–40 cm thick resting on glaciofluvial sand. This indicates that the clay as well as the sand has been glacially dislocated as described by Pedersen (1989).

Fracture description

In order to develop a conceptual model of the fracture systems and macropores in the test field, fracture orientation at various depths and fracture position and frequency were measured in the test pit for calculation of fracture parameters according to Klint and Gravesen (1999). The data are presented in Figures A4.10 and A4.11. The fracture analysis was supplemented by measurement of the till fabric and orientation of chalk rafts in order to clarify the stratigraphic relationships in the test pit (Figure A4.9).

In the upper 2 m of the profiles the clay till was so sticky and plastic that preparation of the fractures for measurement was impossible. Nonetheless, fractures and macropores were present. In general, the fracture systems at Estrup are dominated by postdepositional fractures, probably originating from desiccation and cryogenic processes as described by Washburn (1979).

The orientation of the fractures 2.5 m b.g.s. revealed an apparently random system. The number of large fractures is too low for any systematic relationships to be determined. Of the 40 fractures described at 2.5 m b.g.s., all were straight with an element of randomness. Their surfaces were irregular on a cm scale, rough on a mm scale.

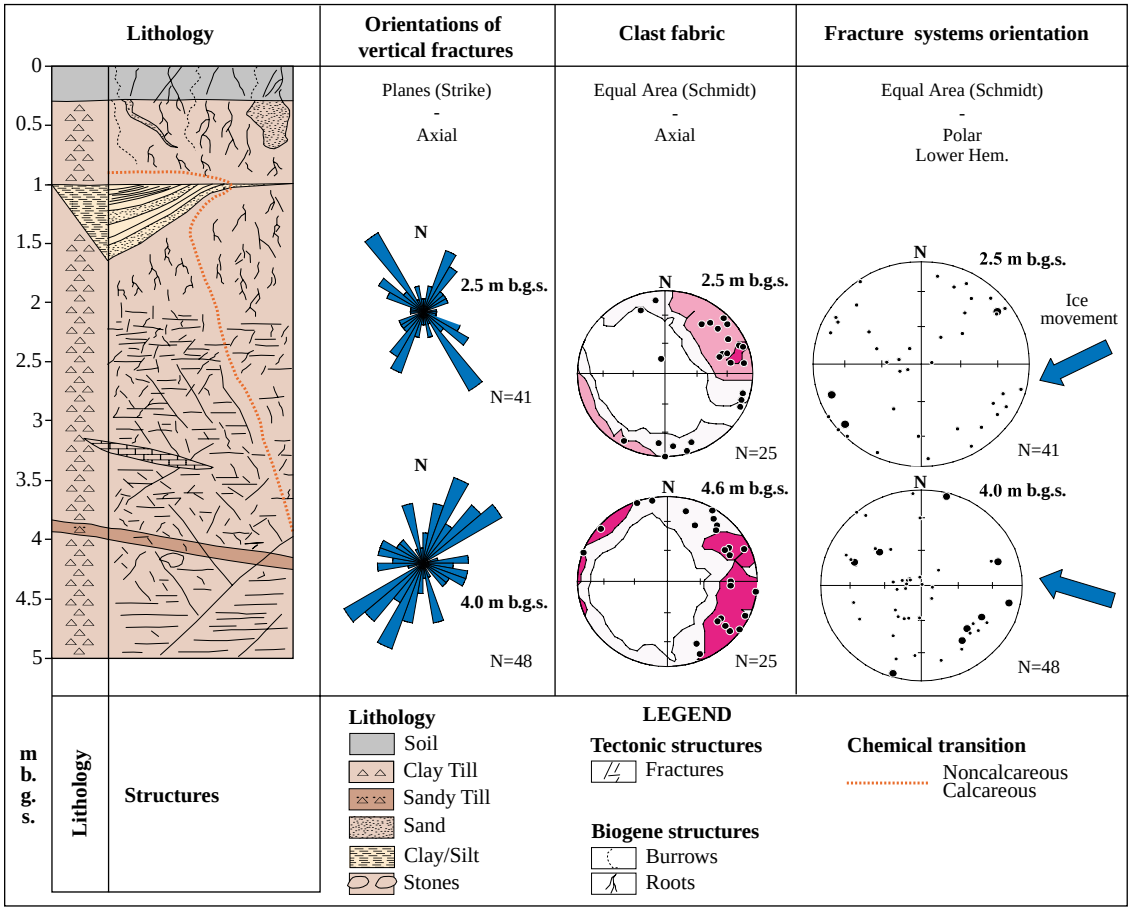


Figure A4.9. Lithology, fracture orientation, clast fabric data and interpreted ice movement direction.

At 4.0 m b.g.s. the orientation of the large fractures is random, as is that of the smaller fractures, although the latter are grouped. The fractures are straight, with an irregular surface on a cm scale and rough on a mm scale. Their surface cover are dominated by iron oxides, with some manganese oxides.

Fracture geochemistry

Three depth-dependent types of coating could be observed on the fracture surfaces in the test pit.

I. 0.25–1.3 m b.g.s.: The macropores and fractures were coated with clay skins and organic matter. At depths below 0.5 m b.g.s., some Fe and Mn oxides and hydroxides were also observed.

II. 1.3–2.2 m b.g.s.: Some fractures and macropores are coated with light grey reduced material.

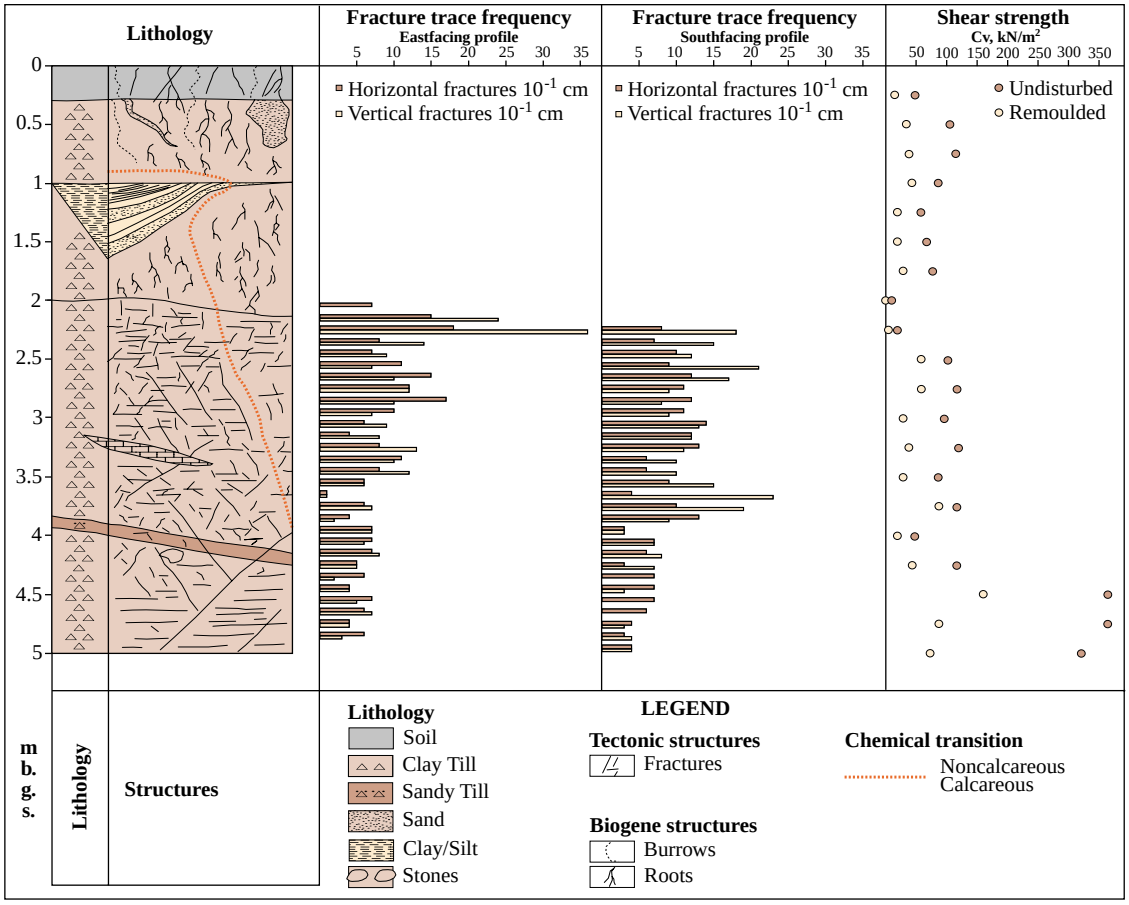


Figure A4.10. Lithology, fracture trace frequency and shear strength in the test pit.

III. 2.2–5.0 m b.g.s.: The fractures had Fe and Mn oxide and hydroxide cover or precipitate. Compared to the other sites in the programme, there were considerably more precipitated oxides on the fracture surfaces at Estrup. The halo was red.

Clast fabric analysis:

The clast fabric analyses at 2.5 and 4.6 m b.g.s. clearly indicate deformation from an easterly direction.

Field vane tests

The field vane tests revealed values ranging from 10 to 120 kN/m^2 in the upper 4.25 m. From 4.50 to 5.0 m the values increase to more than 300 kN/m^2 reflecting the transition from noncalcareous to calcareous.

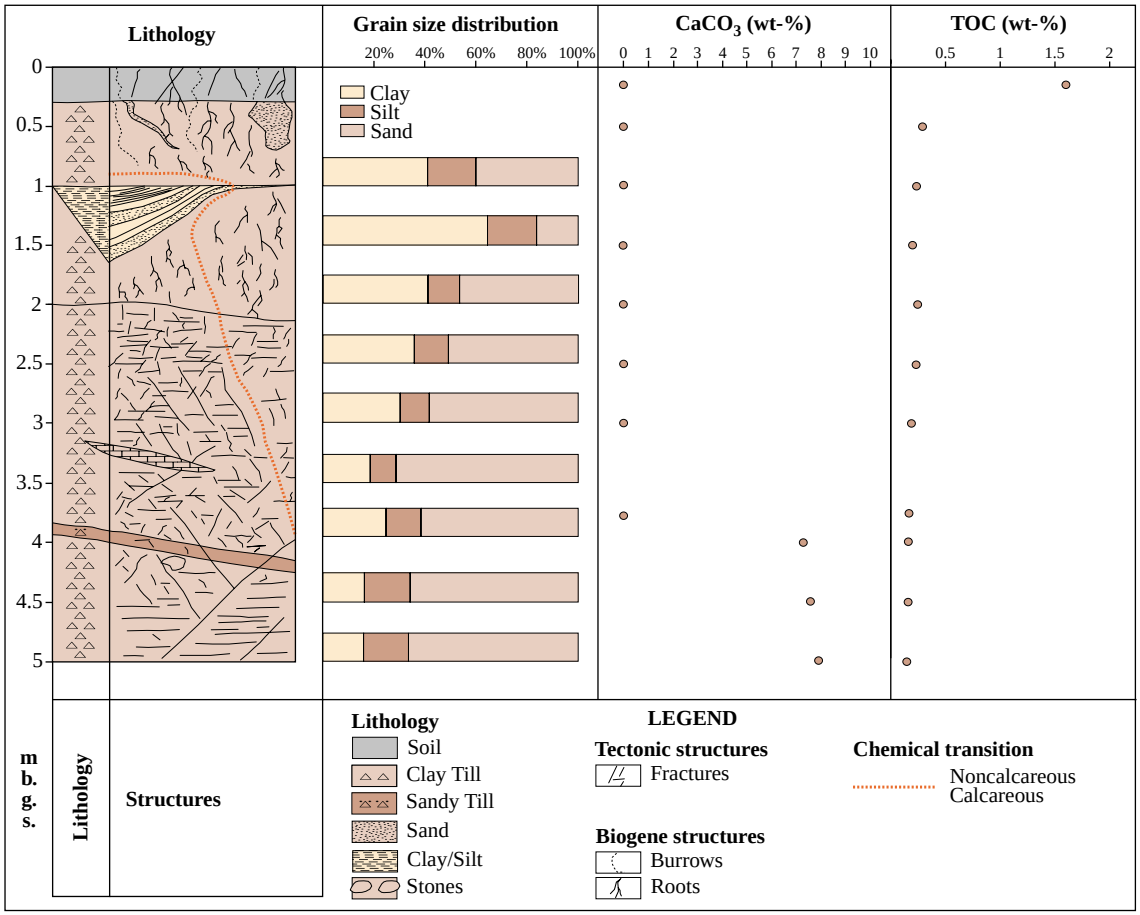


Figure A4.11. Lithology, grain size distribution and $CaCO_3$ and total organic carbon (TOC) content in the test pit. Grain size fractions larger than 2.0 mm are not included in the grain size analysis.

Laboratory analysis

Grain size analyses

Well samples were collected for every 0.5 m. One sample was collected from each layer in order to describe the lithological variation found in the wells. In order to illustrate the geological variation at the test site, four of these samples were submitted for laboratory analysis. All grain size analysis data are shown in Table A4.5.

Table A4.5. Texture analysis of sediment from the test pit and selected wells.

	Grain size in mm							
Depth and location m b.g.s.	<0.002	0.002–0.020	0.02–0.63	0.63–0.125	0.125-0.20	0.20–0.5	0.5–2.0	Sediment
Test pit								
1.00	40.9	10.7	8.2	17.6	6.4	10.7	5.4	Clay till
1.50	64.6	13.8	5.2	5.6	4.0	5.3	1.4	Clay till
2.00	41.1	9.6	2.6	13.9	11.0	15.9	5.9	Clay till
2.50	35.9	9.6	3.7	14.9	12.5	17.2	6.3	Clay till
3.00	30.4	8.3	3.1	15.9	13.7	21.3	7.5	Clay till
3.50	22.0	13.0	5.1	16.1	13.7	21.6	8.6	Clay till
3.75	18.7	5.3	4.5	12.9	14.9	31.2	12.5	Clay till
4.00	24.8	8.1	5.6	14.7	13.5	23.7	9.6	Clay till
4.50	16.4	9.9	8.0	15.9	14.2	25.3	10.3	Clay till
5.00	16.1	10.5	7.1	16.7	14.9	24.3	10.5	Clay till
Wells								
M4 (2.00)	44.2	24.2	6.2	7.7	5.7	8.4	3.6	Glaciofluvial clay with silt lamina
M4 (5.60)	11.6	40.2	5.0	12.0	10.1	15.3	5.8	Clay till
M6 (2.50)	1.3	4.1	3.8	10.4	15.3	38.7	26.4	Glaciofluvial sand
M1 (3.50)	33.7	51.1	4.1	3.0	2.6	3.9	1.6	Clay till

Data from GEUS Sediment Laboratory. Some of the fractions were determined by linear interpolation.

Table A4.6. Total organic carbon (TOC) and $CaCO_3$ content in sediment samples from the test pit and selected wells.

Locality	Depth m b.g.s.	TOC %	$CaCO_3$ %	Sediment
Test pit	1.0	0.24	<0.1	Clay till
Test pit	1.5	0.20	<0.1	Clay till
Test pit	2.0	0.25	<0.1	Clay till
Test pit	2.5	0.23	<0.1	Clay till
Test pit	3.0	0.19	<0.1	Clay till
Test pit	3.5	0.17	<0.1	Clay till
Test pit	3.75	0.17	<0.1	Sandy till
Test pit	4.0	0.16	7.3	Clay till
Test pit	4.5	0.16	7.6	Clay till
Test pit	5.0	0.15	7.9	Clay till
Wells				
M4.4	2.0	0.31	36	Glaciofluvial clay
M4.4	5.6	0.36	23	Clay till
M6.4	2.5	0.13	<0.1	Glaciofluvial sand
M1.4	3.5	0.78	24	Clay till
M7.4	2.5	50	<0.1	Peat, Post_Glacial

Data from GEUS Sediment Laboratory.

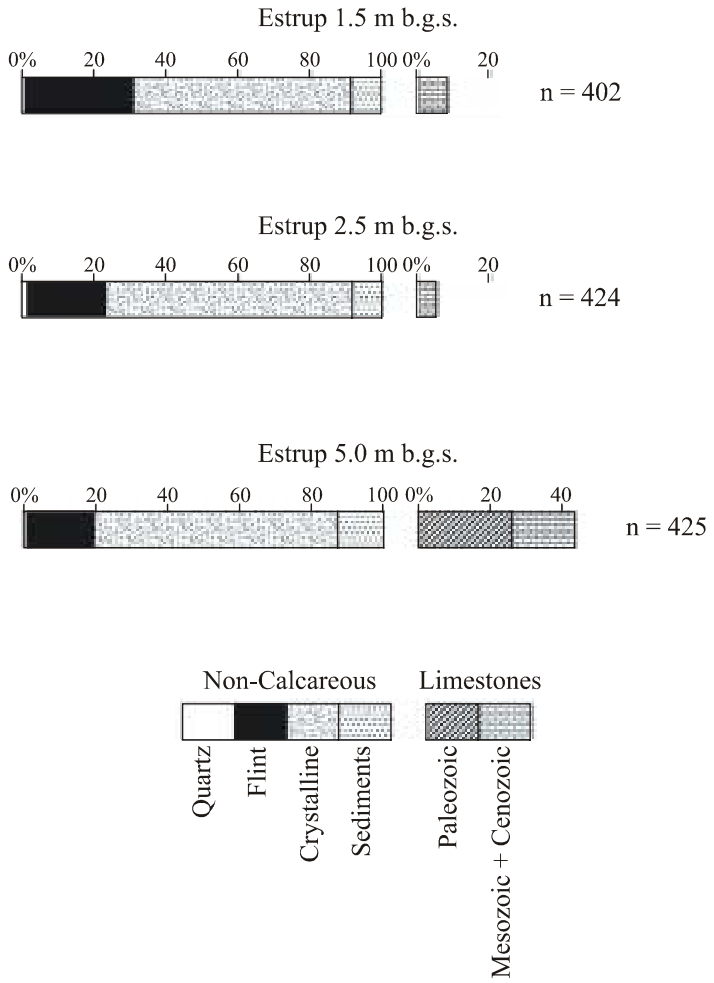


Figure A4.12. Fine gravel analysis from three levels in the test pit. n is the number of grains counted.

Clay mineral analysis

Clay minerals were analysed in test pit samples collected at 2.5, 3.5 and 4.75 m b.g.s. The composition of all three samples was the same, the clay fraction (< 2 μm) being dominated by smectite, but also containing vermiculite, illite, kaolinite and quartz.

Fine gravel analysis

Fine gravel was counted on three samples from the test pit excavation (Figure 4.12). Two different fine gravel compositions were seen. Since the samples collected at 1.5 and 2.5 m b.g.s. were both from above the calcareous-noncalcareous boundary, there are significantly fewer calcareous clasts in these samples than in the sample from 5.0 m b.g.s. The composition of the noncalcareous clasts indicates that only one till unit is present, and that leaching dissolution and other soil processes are responsible for the lithological differences seen in profiles east-facing profile.

Total organic carbon (TOC) and $CaCO_3$ content

The TOC and $CaCO_3$ data are shown in Table A4.6. The data from the test pit reveal normal clay till values. $CaCO_3$ has leached to a depth of nearly 4 m b.g.s., this being attributable to the long period of exposure.

Porosity and horizontal permeability

For determination of porosity and permeability, 100 cm^3 samples were collected from the test pit using stainless steel cylinders. Considerable variation was seen in all parameters (Table A4.7). The samples taken from the upper 2 m revealed high porosity that decreased with depth, probably reflecting a change in weathering and the high clay content. The saturated hydraulic conductivity measurements are within the range reported for clay till by other authors (e.g. Rosenbom *et al.*, 2000).

Table A4.7. Special core analysis data from the test pit.

Plug no.	Depth	Plug type	Liquid permeability	Saturated hydraulic conductivity	Porosity	Grain density
	m b.g.s.		mD	10^{-9} m/s	cm^3/cm^3	g/cm^3
1	1	2	0.021	0.20	0.43	2.700
2	2	2	0.006	0.06	0.45	2.697
3	3	2	0.05	0.48	0.31	2.675
4	4	2	0.335	3.24	0.32	2.675

Data from GEUS Core Laboratory.

A4.4 Pedology

The pedological field work at Estrup was carried out from November 22 to 24 1999. Three soil profiles were excavated (Figure A4.5) and 14 soil cores were collected to a depth of 1.0 m in the buffer zone. Inside the test field, 30 samples were taken from the topsoil (0–25 cm).

Table A4.8. Description of profile 1 (3099 Estrup East).

Soil classification, DK	Pseudogleytypilessive	**Soil classification, USDA**	Abruptic Argiudoll
Parent material	Clay till	**Profile depth**	150 cm
UTM	32U NG Easting 504515 Northing 6149124	**Drainage class**	Moderately well drained
Landform	Hill island	**Groundwater level**	230 cm
Map sheet	1213 III SV	**Vegetation**	Stubble
Elevation	56 m DNN	**Maximum rooting**	Approx. 120 cm
Topography	Very gently undulating	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	23.11.99

Profile description

Ap (0–26 cm)
Very dark greyish brown (10YR 3/2f) clayey silty sand, containing humus, a few small mainly rounded and unweathered stones of mixed type, artificial liming, frequent small roots, a few wormholes and root channels, moderate coarse subangular structure, weak sticky consistency, clear smooth boundary.

Bt(g) (26–45cm)
Light olive brown (2.5Y 5/3 f) heavy clay with many vertically striped large conspicuous diffuse spots of reddish brown (7.5YR 6/8 f), humus poor, a few small mainly rounded and unweathered stones of mixed type, some small roots, a few wormholes and root channels, moderate coarse prismatic structure, weak sticky consistency, spotted thick coatings of clay minerals and humus in root channels and on aggregate peds, gradual wavy boundary.

Bt(g)2 (45–121 cm)
Greyish brown (2.5Y 5/2 f) heavy clay with many vertically striped large marked diffuse spots of strong brown (7.5YR 5/6 f), humus poor, a few small mainly rounded and unweathered stones of mixed type, a few small soft rounded Fe oxide and Mn oxide and hydroxide nodules, calcareous mainly as powder, a few small roots, a few wormholes and root channels, moderate coarse prismatic structure, sticky consistency, very little spotted thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.

Cc (121–150 cm)
Yellowish brown (10YR 5/4 f) heavy clay with lots of vertically stripes of medium size clear spots of light brownish grey (10YR 6/2 f), humus poor, a few small mainly rounded and unweathered stones of mixed type, strongly calcareous, mainly as powder, very strong and coarse angular structure, sticky consistency.

Remarks	The Bh horizon: Minor depressions containing dark coloured material with 2–5 cm big iron concretions in the bottom, possibly traces of the roots of windfelled trees. The bottom of the Bt horizon (20–30 cm thick) is covered with two large stones. The B horizon: Wormholes and root channels are lined with humus and clay minerals. A chalk raft was exposed in the excavation from 144 to 154 cm.

Table A4.9. Description of profile 2 (3098 Estrup North).

Soil classification, DK	Pseudogleytypilessive	**Soil classification, USDA**	Aquic Argiudoll
Parent material	Clay till	**Profile depth**	150 cm
UTM	32U NG Easting 504489 Northing 6149145	**Drainage class**	Moderately well drained
Landform	Hill island	**Groundwater level**	230 cm
Map sheet	1213 III SV	**Vegetation**	Stubble
Elevation	56 m DNN	**Maximum rooting**	Approx. 70 cm
Topography	Flat, gently undulating	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	22.11.99

Profile description

Ap (0–27 cm)
Very dark greyish brown (10YR 3/2 f) clay, a few small mainly rounded stones, especially unweathered, artificial liming, some small roots, 1–10 wormholes and root channels per dm^2, moderate subangular structure with medium big aggregates, brittle consistency, clear smooth boundary.

Ap2 (27–40 cm)
Very dark greyish brown (10YR 3/2 f) clay, a few small mainly rounded stones especially unweathered, a few small roots, 1–10 wormholes and root channels per dm^2, moderate subangular structure of medium big aggregates, brittle consistency, clear wavy boundary.

BE(g) (40–62 cm)
Brown (10YR 4/3 f) clayey silty sand with a few rounded thin clear spots of strong brown (7.5YR 5/8 f) and secondary spots of light olive brown (2.5Y 5/3 f), a few small and medium stones, mainly rounded and unweathered, a few small soft rounded Fe oxide and hydroxide nodules, very few small roots, 1–10 wormholes and root channels per dm^2, weak fine subangular structure, very brittle consistency, clear diffuse boundary.

2Bt(g) (62–114 cm)
Brownish yellow (10YR 6/8 f) very heavy clay with many vertical stripes of thin marked clear spots of light olive grey (5Y 6/2 f), a few small and medium size stones mainly rounded and unweathered, a few thin soft rounded Fe oxide and hydroxide nodules, 1–10 wormholes and root channels per dm^2, strong very coarse angular structure, firm consistency, mottled moderately thick coatings of clay minerals in root channels and on aggregate peds, clear diffuse boundary.

3Cg (114–150 cm)
Grey (2.5Y 6/1 f) light clayey sand with a yellowish brown (10YR 5/6 f) band of iron precipitations on top of the horizon, no stones, structure-less, loose consistency.

Remarks	The Bt(g) horizon is occasionally cut by narrow sand-filled vertical fractures. There is a layer of stones in the border between the Bt(g) horizon and the 3Cg horizon.

Table A4.10. Description of profile 3 (3100 Estrup West).

Soil classification, DK	Pseudogley typilessive	**Soil classification, USDA**	Fragiaquic Glossudalf
Parent material	Glaciofluvuial sand	**Profile depth**	180 cm
UTM	32U NG Easting 504395 Northing 6149055	**Drainage class**	Moderately well drained
Landform	Hill island	**Groundwater level**	240 cm
Map sheet	1213 III SV	**Vegetation**	Stubble
Elevation	56 M DNN	**Maximum rooting**	Approx. 80 cm
Topography	Very gently undulating	**Author**	Søren Torp
Slope	0–1°	**Date of description**	23.11.99

Profile description

Ap (0–28 cm)
Black (10YR 2/1 f) light clayey silty sand, containing humus, a few small mainly rounded unweathered stones of mixed type, artificial liming, frequent small roots, 1–10 wormholes and root channels per dm^2, moderate subangular structure with aggregates of medium size, nonsticky consistency, abrupt smooth boundary.

Bs/Bhs (28–58 cm)
Yellowish brown (10YR 5/8 f) light clayey sand with many prominent big clear spots of black (5YR 2.5/1 f) and secondary spots of yellowish brown (10YR 5/4 f), a few small mainly rounded unweathered stones of mixed type, humus poor to containing humus, a few soft and hard medium big nodules of Fe oxides and hydroxides with mixed form, a few small roots, moderate angular structure with aggregates of medium size, nonsticky consistency, strongly discontinuous weak cemented spodic horizon and placic horizon 1–10 cm thick, continuous plate structure fragipan, very little mottles of thick humus coatings between the grains of sand, gradual irregular boundary.

Bt(g) (58–115 cm)
Brownish yellow (10YR 6/8 f) clayey sand with lots of branded big clear spots of greyish brown (2.5Y 5/2 f), texture band of sand, humus poor, a few small mainly rounded unweathered stones of mixed type, moderate subangular structure with coarse aggregate, weak sticky consistency, gradual wavy boundary.

2C (115–185 cm)
Black (7.5YR 2.5/1 f) heavy clay with lots of rounded big marked diffuse spots of dark grey (5Y 4/1 f), texture band of sand, humus poor, nearly no stones, massive structure, very sticky consistency.

Remarks	From 30–115 cm the structure of the profile shows signs of incubations from the last Ice Age. The horizon is thus messy with a chaotic texture, colour and an irregular soil development. The Bhs horizon is irregular cemented by placic layers, humus, iron minerals and small areas of brittle fragipan. Humus is found in chimneys and contains pores and roots.

Table A4.11. Soil texture analysis from the pedological profiles.

Pro. no.	Hor. no.	Horizon	Depth	Soil texture (mm) %							$CaCO_3$	OM[1]
											%	%
			cm	<0.002	0.002–0.02	0.02–0.63	0.63–0.125	0.125–0.2	0.2–0.5	0.5–2		
1	1	Ap	9–19	13.8	12.7	10.7	11.4	11.2	28.6	8.9	–	2.7
1	2	Bt(g)	32–42	36.3	15.3	3.7	7.5	9.6	21.0	6.0	–	0.5
1	3	Bt(g)2	64–74	33.0	15.9	4.5	8.7	8.4	21.8	7.5	–	0.2
1	4	Cc	125–135	31.1	24.9	1.5	2.4	1.2	1.6	0.8	36.1	0.5
1	5	Chalk	144–154	–	–	–	–	–	–	–	81.4	0.22
2	1	Ap	10–20	20.0	15.0	11.6	6.8	11.5	24.2	6.8		4.1
2	2	Ap2	35–45	19.8	14.2	11.7	9.6	10.4	22.8	8.6		2.9
2	3	BE(g)	51–61	11.8	5.2	6.0	10.0	16.0	35.0	15.5		0.5
2	4	2Bt(g)	85–95	50.2	18.0	1.0	6.2	5.8	13.3	5.1		0.3
2	5	3C	124–135	7.0	2.3	1.0	4.7	15.3	53.6	15.9		0.1
3	1	Ap	10–20	10	7.1	12.9	11.0	11.6	34.1	7.9	–	5.5
3	2	Bs	36–46	9	4.7	4.0	10.9	13.8	44.1	12.9	–	0.8
3	3	Bt(g)	77–87	12	4.3	2.9	11.6	20.6	37.1	10.9	–	0.4
3	4	2C	164–174	39	24.1	12.8	12.3	0.9	0.6	0.3	–	10.1

1) OM: Organic matter, OM = 1.72 x TOC. Analysed by DIAS.

Table A4.12. Soil chemistry of samples from the pedological profiles.

Pro. no	Hor. no	N_{total}	C/N	P_{total}	pH[1]	K	Na	Ca	Mg	Total bases	H+	CEC	Base sat.	Fe (Ox)	Al (Ox)
		%		mg/kg					cmol/kg				%	mg/kg	
1	1	0.12	13	380	6.53	0.23	0.09	14.1	0.53	15	–	12.1	100	2044	808
1	2	0.05	6	144	6.34	0.37	0.11	13.6	0.9	15	–	13.9	100	4144	1748
1	3	0.03	4	242	6.55	0.3	0.11	14.2	1.63	16.2	0.56	16.8	97	2294	1034
1	4	0.05	6	475	7.52	0.3	0.17	18.5	0.91	19.9	–	19.7	100	2290	568
1	5	0.02	6	348	7.72	0.07	0.07	12.1	0.25	12.5	–	6.6	100	546	126
2	1	0.18	13	542	7.75	0.4	0.1	11.5	0.72	12.7	7.77	20.5	62	2114	812
2	2	0.12	14	352	6.36	0.29	0.09	10.5	0.42	11.3	5.12	16.4	69	1040	1160
2	3	0.04	7	171	6.32	0.17	0.04	5.23	0.22	5.66	4.84	10.5	54	1182	690
2	4	0.05	3	109	6.35	0.41	0.16	18	2.99	21.5	5.59	27.1	79	2484	1412
2	5	0.02	3	37	6.36	0.06	0.09	2.09	0.18	2.42	3.18	5.6	43	216	385
3	1	0.19	17	646	7.03	0.23	0.1	20.3	0.39	21	–	15	100	1648	1024
3	2	0.04	12	108	6.59	0.19	0.17	4.74	0.18	5.28	4.92	10.2	52	1730	1340
3	3	0.03	8	50	4.24	0.24	0.07	4.75	0.21	5.27	3.93	9.2	57	1702	916
3	4	0.15	39	153	4.47	0.54	0.35	11.5	5.34	17.7	22.8	40.5	44	1576	2934

1) pH determined in $CaCl_2$ solution. Analysed by DIAS.

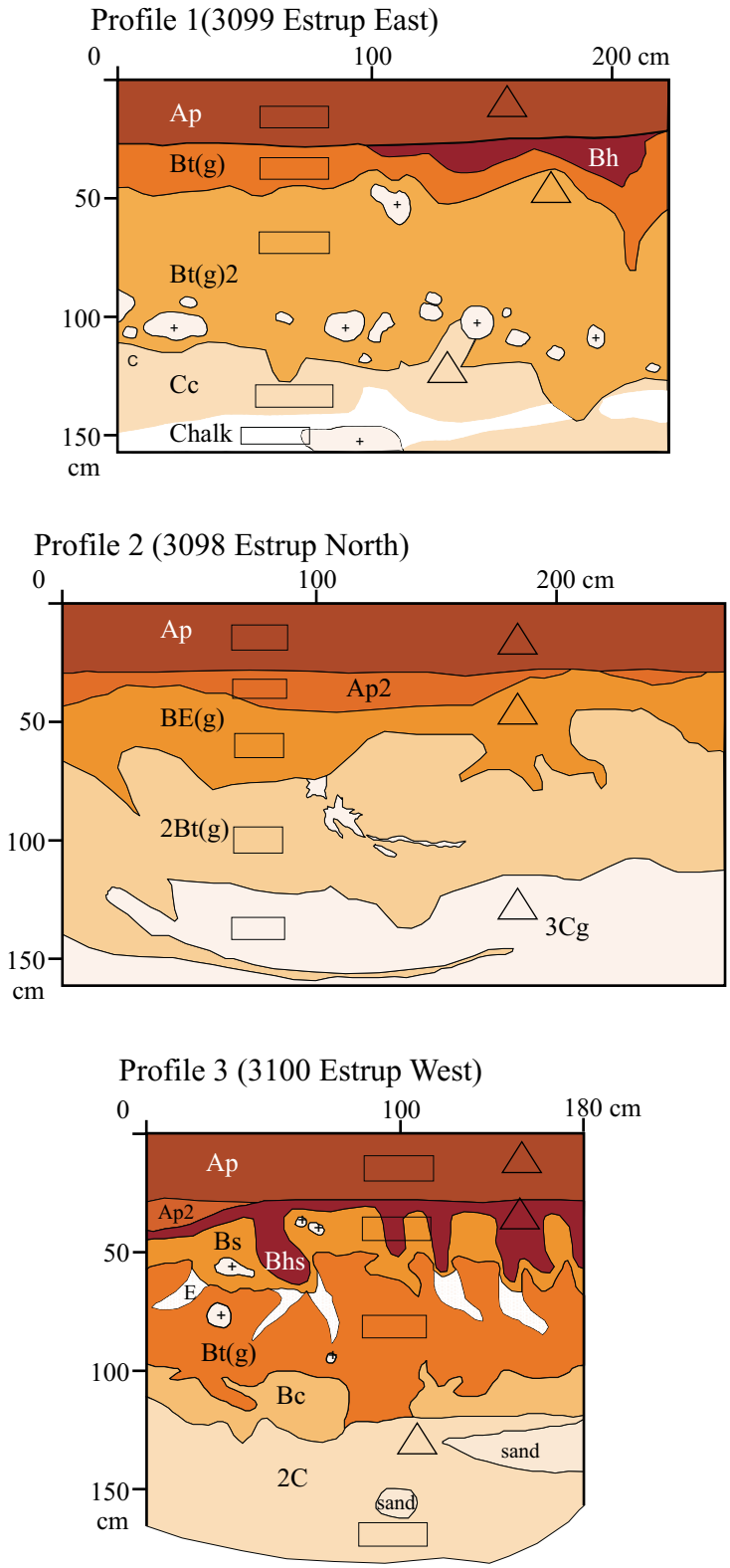


Figure A4.13. Schematic drawings of profiles showing horizon distribution. Rectangular boxes indicate sampling points for soil texture and soil chemistry. Triangular boxes indicate sampling points for hydrological analysis. White areas with + symbolise stones.

Profile description

The pedological descriptions of the three profiles are summarized in Tables A4.8, A4.9 and A4.10. The profile horizons are shown in Figure A4.13. The profile laboratory data (grain size, texture, organic matter, nutrients and major cations) are summarized in Table A4.11, and A4.12.

In Table A4.13 the profiles are classified according to both "A Pedological Soil Classification System Based on Danish Soils" (Madsen and Jensen, 1985) and USDA Soil Taxonomy (Soil Survey Staff, 1999).

Table A4.13. Classification of the profiles.

Profile no.	Danish Soil Classification	USDA Soil Taxonomy
1 (3099 East)	If the profiles have an E horizon and a Bt horizon they are Lessive soils. Hence Typilessive. Because of the gley, they are **Pseudogleytypilessive**.	The high base saturation and the content of organic matter make the soil a Mollisol. Because of the illuvial argillic horizon it is an Argiudoll. As the increase in clay exceeds 20%, the soil is an **Abruptic Argiudoll**.
2 (3098 North)	do.	The high base saturation and the content of organic matter make the soil a Mollisol. Because of the illuvial argillic horizon it is an Argiudoll. Because there are redox spots, the soil is an **Aquic Argiudoll**.
3 (3100 West)	The sandy texture class and a Bhs horizon will make this soil a Podsol and a Typipodsol. The Pseudogley makes it a Pseudogleytypipodsol. Because there is an illuvial Bt horizon, it is a **Lessive Pseudogleytypipodsol**.	Unlike the other two profiles the soil does not have a high base saturation in the upper 125 cm. The value is considered a little overestimated by the oxalate method. In view of the profile morphology it is considered not to be a Mollisol. The order is Alfisols and the suborder Udalfs. Because there is a Glossic, the soil is a Glossudalf. With fragic soil properties and redodepletions the soil is thus an **Fragiaquic Glossudalf**.

Soil cores from the buffer zone

In the northeastern part of the area (approx. 20% of the site), the soil profile is as found in profiles 1 and 2. In the rest of the area, except for a small edge in the south, the profile is bisequem with podsolized sandy topsoil and a more pseudogleyed clay till underneath.

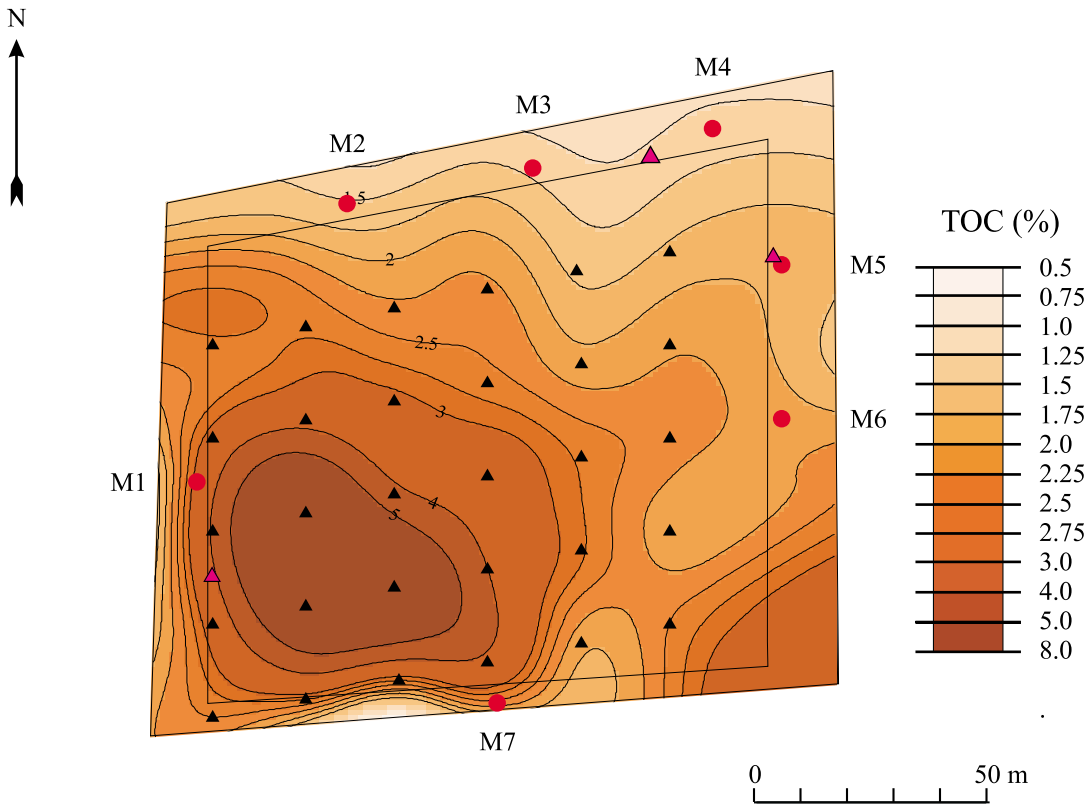


Figure A4.14. Map showing total organic carbon (TOC) content within the test field. Sampling points are indicated by ▲.

The southwestern part of the buffer zone (5–10% of the area) has heavy clay to a depth of approx. 1 m.

Total carbon mapping

The samples from the topsoil inside the field were only analysed for total organic carbon (TOC), which varied between 1.7 and 7.3% (dry weight). Three extreme values are found in the southwestern part of the field. The content is lowest in the northeastern part of the field (Figure A4.14).

Pedological development

The long exposure of the soil to weathering during the last interglacial-glacial-interglacial cycle has resulted in acidification, decalcification and the transport of clay and organic matter, thus resulting in leached upper horizons. The texture varies most in the southwestern part of the test field. The parent material seems to consist of a varied till containing both rafts of chalk, clay with elevated TOC values (0.7%) and a clay

content >50%. In addition, areas of well-sorted sand are present. Under the periglacial conditions during the last Ice Age, the soil (0–150 cm) was probably modified and disturbed by periglacial phenomena such as *in situ* involution and fissure filling attributable to deep frost penetration and the freezing and thawing of interstitial waters in the active layer (Eyles, 1983). Very randomly distributed vertical sand-filled fissures are present that range in size from a few millimetres to tens of centimetres. The fissures were probably made when water-filled sand was injected into the overlying clay during freezing expansion. The distribution of these fissures in the area is unknown. The net result is very uneven particle size distribution through the profiles, as exemplified by the particle size distribution in profile 2 (3098 Estrup North).

The pedological development in the area is typical for leached soils. The horizon order is typically A, E, Bt and C or, in the case of the more leached areas, A, E, Bhs, Bt and C. In parts where the parent material was sand with a low clay content or the degree of leaching was higher, podsolization has started in the topsoil and the soil profile was a bisequem. The remaining of the podsol could be seen as Bhs horizons in the western profile and in some of the soil cores. The presence of a discontinued cemented placic horizon shows that the podsolization processes have been active for some time. The occurrence of small basins with iron concretions just under the plough layer seen in profile 3 (3100 Estrup West) and in some of the soil cores is evidence of temporary, water-filled puddles. The origin of these small basins is unknown, but they may be puddles formed by the roots of wind-felled trees (Langohr, 1993). The leaching results from degradation of the top of the illuvial horizon with interfingering of eluvial material into the Bt horizon, referred to as a Glossic horizon in the USDA Soil Taxonomy. The presence of heavy calcareous clay near the surface is unusual for old soils from the Saale Ice Age, which are usually deeply leached, and could be attributable to the very high content of chalk in the shape of rafted material in the till and the presence of sand-filled fissures draining the bulk of the water away. Below this lies the Bt horizon at depths ranging from 40 to 80 cm. The illuvial horizon gives rise to a perched water table of pluvial origin in the matrix. The phenomenon called pseudogley is the result of moderately reducing conditions where the soil iron (FeII) forms grey vertical stripes in a redbrown matrix. In the dry season the iron does not remain in the ferrous state, but is reoxidized to form patches of concretion (Duchafour, 1979).

Artificial liming results in a reversed pH in the chalk-free profiles. The base saturation varies markedly in the three profiles. Base saturation is near 100% in the profile with chalk rafts (Profile 1, 3099 Estrup East) but at the medium level of just over 50% in the

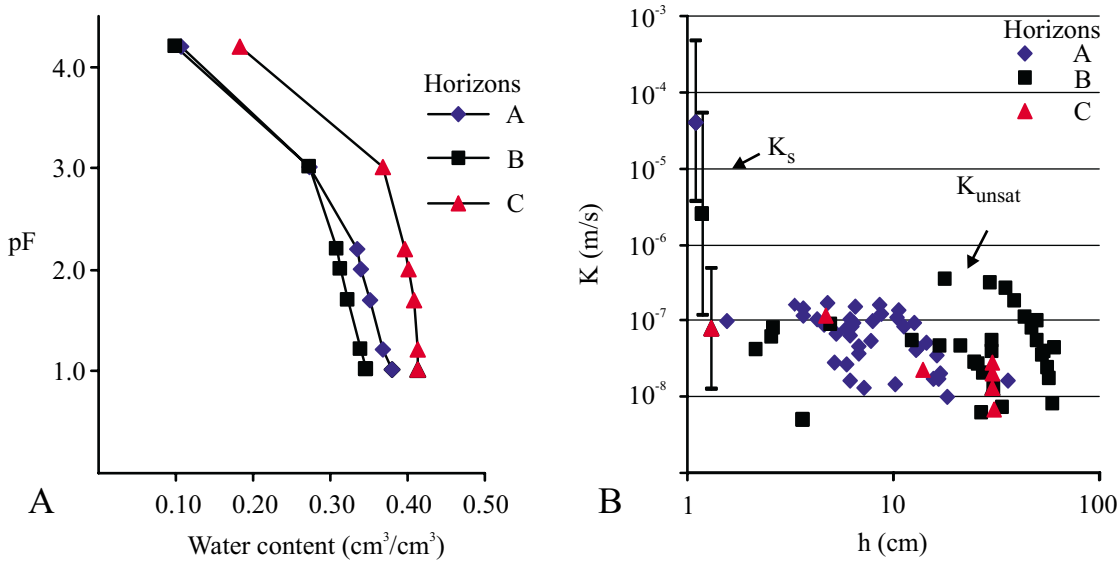


Figure A4.15. A) Retention curve based on values for the soil-water potential determined on the small soil core samples (100 cm^3). The data are the mean values from three profiles. B) The unsaturated hydraulic conductivity (K_{unsat}) as a function of soil ater potential in cm H_2O and the saturated hydraulic conductivity (K_s) determined on the large soil cores (6,280 cm^3).

other two profiles. The organic matter content in profile 3 (3100 Estrup West) in the Ap horizon (5.50%) reflects the fact that the profile is low-lying with humus built up.

The pedology of the area reflects the very varied textures and the varied geological parent material as well as the periglacial processes that have been taking place. The picture is one of abrupt change with podsolized topsoil horizons over a partly degraded illuvial horizon.

Soil hydrology

Soil cores (100 cm^3 and 6,280 cm^3) for the measurement of hydrological properties (soil water characteristics and hydraulic conductivity) were sampled at three levels corresponding to the A, B and C horizons.

The soil water characteristics of the nine small cores (100 cm^3) from each horizon are shown together with bulk density and porosity in Table A4.14 and Figure A4.15.

Because of its high clay content, the soil in the B and C horizons tends to swell markedly when absorbing water, a property that complicated the calculation of the soil water characteristic for the two horizons. The soil has a high water-holding capacity until pF 3 (-1,000 cm H_2O). The majority of the pores are about 0.6 µm (tube-equivalent diame-

ter). The percentage of pores >20 µm is particularly low in the C horizon (Figures A4.16).

Table A4.14. Soil water characteristics determined on the small soil cores, pF = $\log_{10}(-h)$

Profile no.	Horizon	Depth cm	Water content at pF values cm^3/cm^3							Bulk density g/cm^3	Porosity[1] cm^3/cm^3
			1.0	1.2	1.7	2.0	2.2	3.0	4.2		
1 (3099)	Ap	15	0.35	0.34	0.33	0.31	0.30	0.24	0.09	1.56	0.41
	Bt(g) [2]	36	0.33	0.32	0.31	0.30	0.29	0.26	0.20	1.73	0.35
	Cc [2]	122	0.37	0.37	0.36	0.36	0.35	0.33	0.22	1.78	0.33
2 (3098)	Ap	15	0.37	0.36	0.34	0.33	0.33	0.27	0.13	1.56	0.41
	BE(g) [2]	50	0.38	0.38	0.37	0.37	0.37	0.33	0.06	1.67	0.37
	3Cg [2]	122	0.45	0.45	0.45	0.44	0.44	0.41	0.02	1.59	0.40
3 (3100)	Ap	15	0.42	0.41	0.39	0.38	0.38	0.31	0.10	1.42	0.46
	Bhs [2]	38	0.33	0.32	0.29	0.27	0.27	0.23	0.04	1.69	0.36
	2C [2]	120	0.42	0.42	0.42	0.41	0.40	0.37	0.31	1.55	0.42

1) Assuming a particle density of 2.65 g/cm^3.
2) Tendency to swell.

The saturated and unsaturated hydraulic conductivities determined on the large cores (6,280 cm^3) are shown in Figure A4.15. Because of heterogeneity in the B and C horizons and the low conductivity in the C horizon, it is difficult to establish a unique relationship between pressure potential (h) and hydraulic conductivity (k) for the two horizons. The marked difference between near-saturated hydraulic conductivity and saturated hydraulic conductivity in the A and B horizons indicates a high degree of direct piping (preferential flow) through macropores when the soil is fully saturated.

The measurements of saturated hydraulic conductivity and air permeability made using small (100 cm^3) and large (6,280 cm^3) soil samples differed markedly (Figure A4.17). This difference is probably related to the structure of the soil leading to a high dependence on sample size. With the large soil samples, infiltration takes place through a much larger soil area than is the case with the small soil samples and a greater number of macropores and other soil heterogeneities are therefore included.

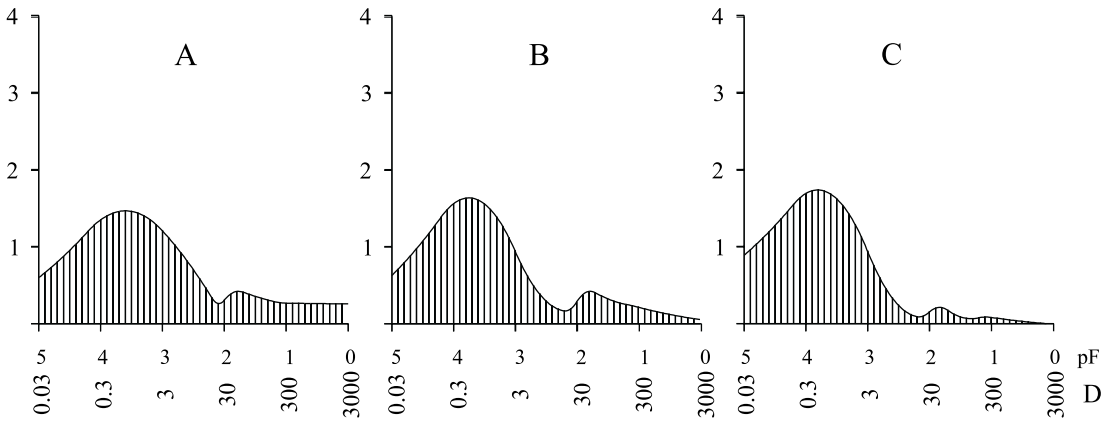


Figure A4.16. Pore size distribution measured (A, B, and C horizon) calculated from water retention data assuming the unity D=3000/10pF (D = pore diameter equivalent diameter, µm). A cubic spline interpolation procedure is used to yield discrete interpolate values on the sum curve obtained from the water retention curves. Abscissa: pF=log10(-h) in which h is the soil water potential in cm H_20. D = pore diameter, µm. Ordinate: percentage of pore volume per 1/10 pF-values, % v/v.

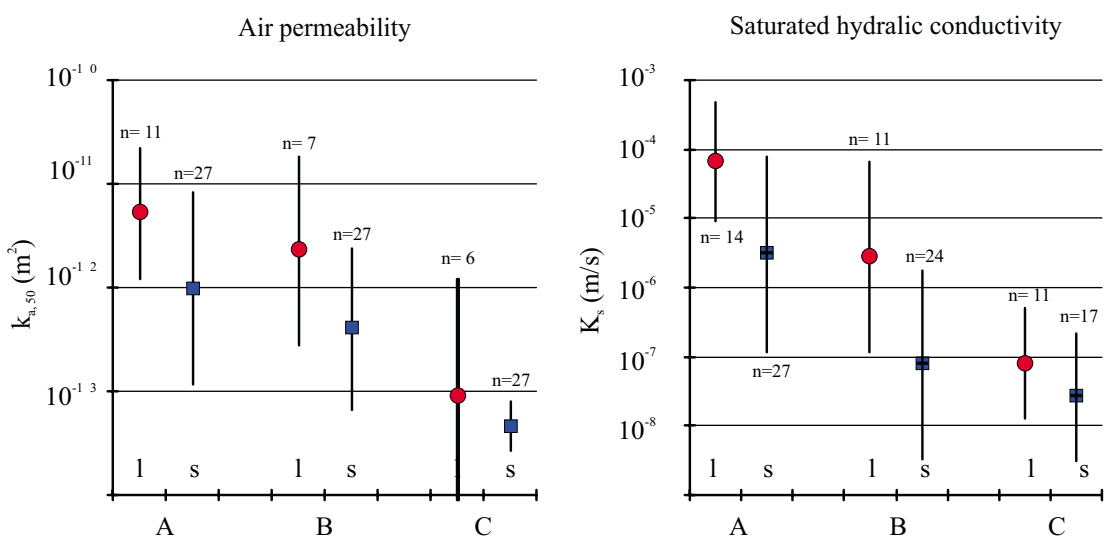


Figure A4.17. Air permeability at a water content of –50 cm H_20 ($k_{a,50}$) and saturated hydraulic conductivity (K_s) measured on large (6,280 cm^3) samples (●) and small (100 cm^3) samples (■).

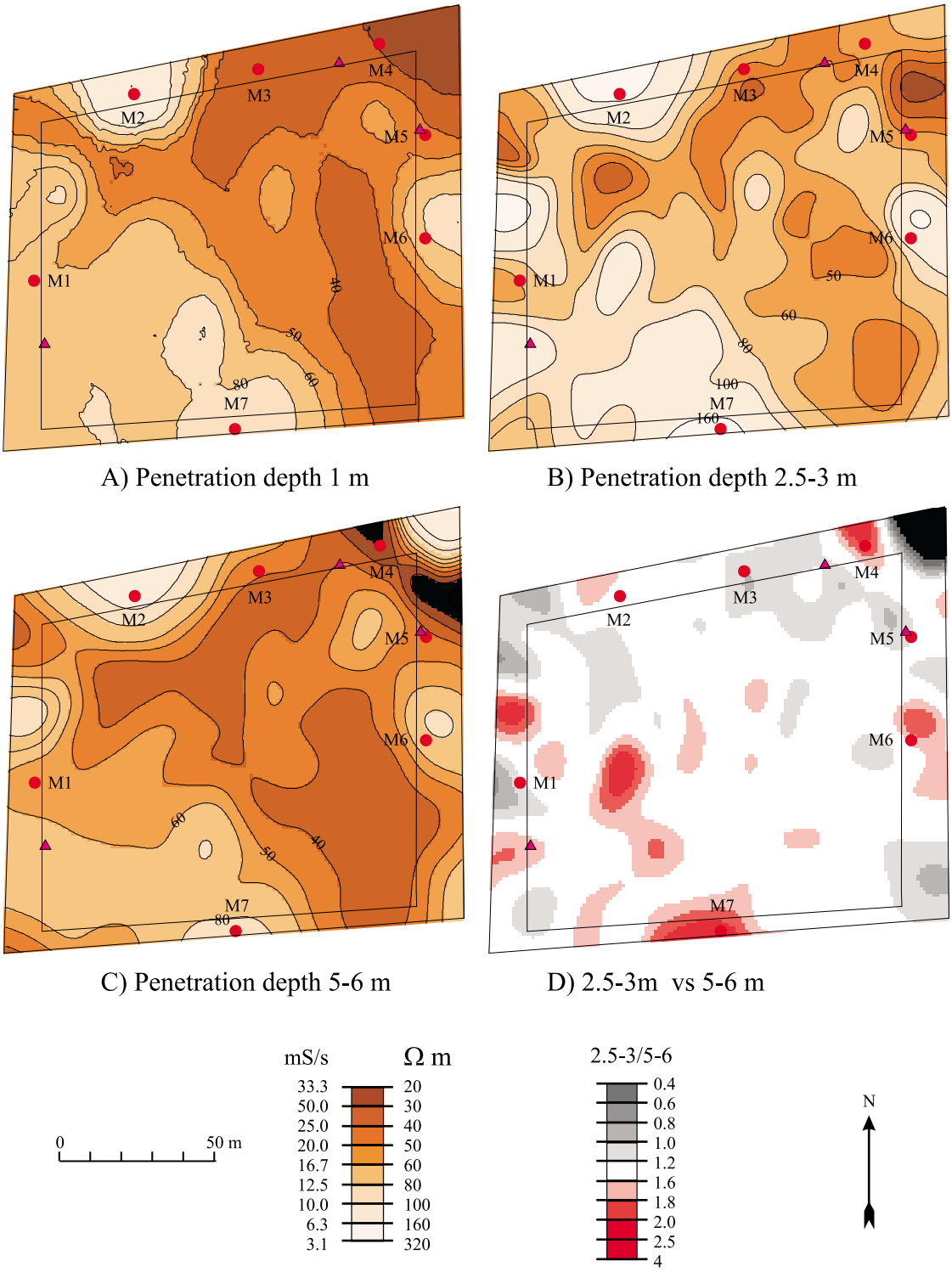


Figure A4.18. Resistivity maps of the area. Map D shows the relative difference between map B and C and provides an idea about the homogeneity of the electrical properties to a depth of approx. 6 m b.g.s.

A4.5 Geophysical mapping

Since destructive mapping methods are not accepted in the test field, it was decided to use EM-38, CM-031 and ground-penetrating radar (GPR). The EM38 measurements were made on August 29 2000.

Conductivity meter, EM 38 and CM-031 mapping.

The EM-38 map (Figure A4.18A) and the CM-031 maps (Figure A4.18B-D) show that the resistivity in the test field is variable, ranging from 20–300 Ωm. The area can be subdivided into three subareas on the basis of the conductivity properties:

1. An area of high resistivity in the southwestern corner and around well M6 where the resistivity decreases with increasing depth, thus indicating sand over clay.
2. An area towards the northeast with relatively low resistivity, probably reflecting an area with clay till. A "ridge" with low resistivity running from well M3 to the south-eastern corner can be observed in Figure A4.18 A–B.
3. An area around well M2 where the resistivity is high from the surface to a depth of more than 6 m, thus reflecting the presence of sand from the surface downwards.

Ground-penetrating radar (GPR)

To detect any sand or gravel lenses or other geological anomalies the area was mapped using ground-penetrating radar in a 20 x 30 m grid (Figure A4.19). The map is in good agreement with the conductivity map and the well data. The following features are apparent in the GPR profiles: An area in the southwestern corner with sand on top of clay till, and a clay cover over the northeastern part of the test field. Several minor areas with enhanced penetration were detected in the field, which is in good agreement with both the geoelectrical data and with the well data.

GPR profile 3 located close to well M7 where the peat was found is shown in Figure A.4.20. Unfortunately, it is not possible to distinguish between peat and sand.

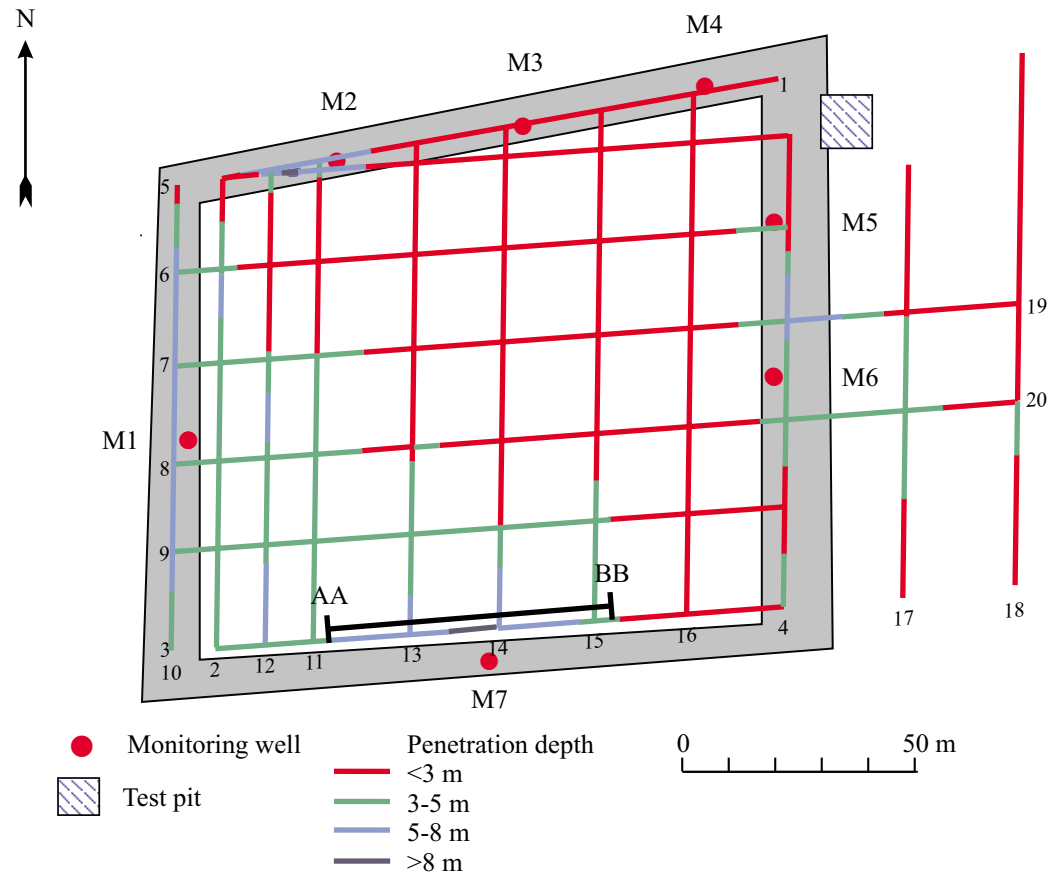


Figure A4.19. Map showing the penetration depth.

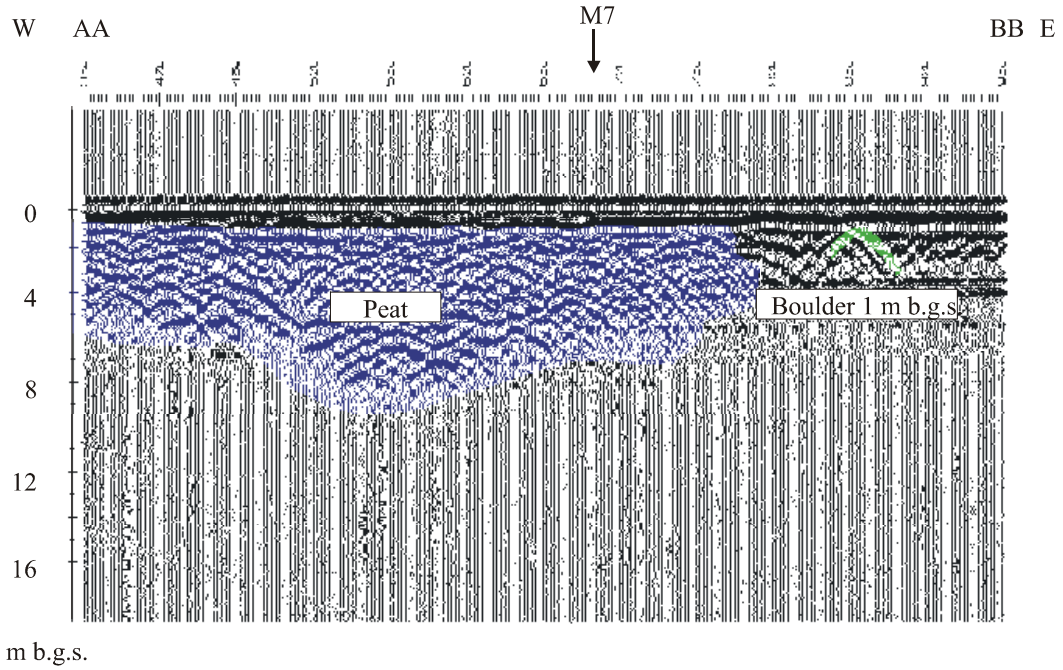


Figure A4.20. Ground penetrating radar profile, line no 3. The section AA to BB is show on Figure A4.19.

Appendix A4.1. Cultivation and pesticide application history at Estrup.

Year	Crop	Date	Pesticide brand	Dose per ha
1993	Winter wheat	20.10.93	Mylone Power	0.75 l
	(Haven)	20.10.93	Tolkan	1.5 l
		01.04.94	Manganese sulphate	4.0 kg
		15.05.94	Tilt Top	0.3 l
		20.06.94	Tilt Top	0.3 l.
1994	Winter wheat	15.10.94	Stomp SC	1.0 l.
	(Ritmo)	15.10.94	Tolkan	2.0 l
		25.04.95	Tilt Top	0.3 l.
		15.05.95	Tilt Top	0.2 l
		05.06.95	Tilt Top	0.2 l.
		20.06.95	Tilt Top	0.3 l.
1996	Spring barley	21.05.96	Kemifam Pro Fl	0.377 l.
	Undersown grass	21.05.96	Ariane S	0.943 l.
	(Meltan-.Tivoli T)	25.05.96	Manganese sulphate	1.415 kg.
		05.07.96	Tilt Top	0.4 l.
1997	Winter wheat	07.10.97	Stomp SC	1.0 l.
	(Ritmo)	07.10.97	Tolkan	0.5 l.
		01.05.98	Corbel	0.203 l.
		01.05.98	Ally	0.0057 kg.
		20.05.98	Tilt Top	0.2 l.
		11.06.98	Corbel	0.179 l
		11.06.98	Amistar	0.34 l
1999	Spring barley	05.04.99	Potassium chloride	132.1 kg.
	(Optic)	18.05.99	Express	0.0075 kg.
		18.05.98	Oxitril	0.283 l.
		01.06.98	Manganese sulphate	2.358 kg.
		07.06.98	Tilt Top	0.250 l
		01.07.98	Tilt Top	0.187 l

Site Characterization and Monitoring Design

Annexe 5.

Site 5: Faardrup

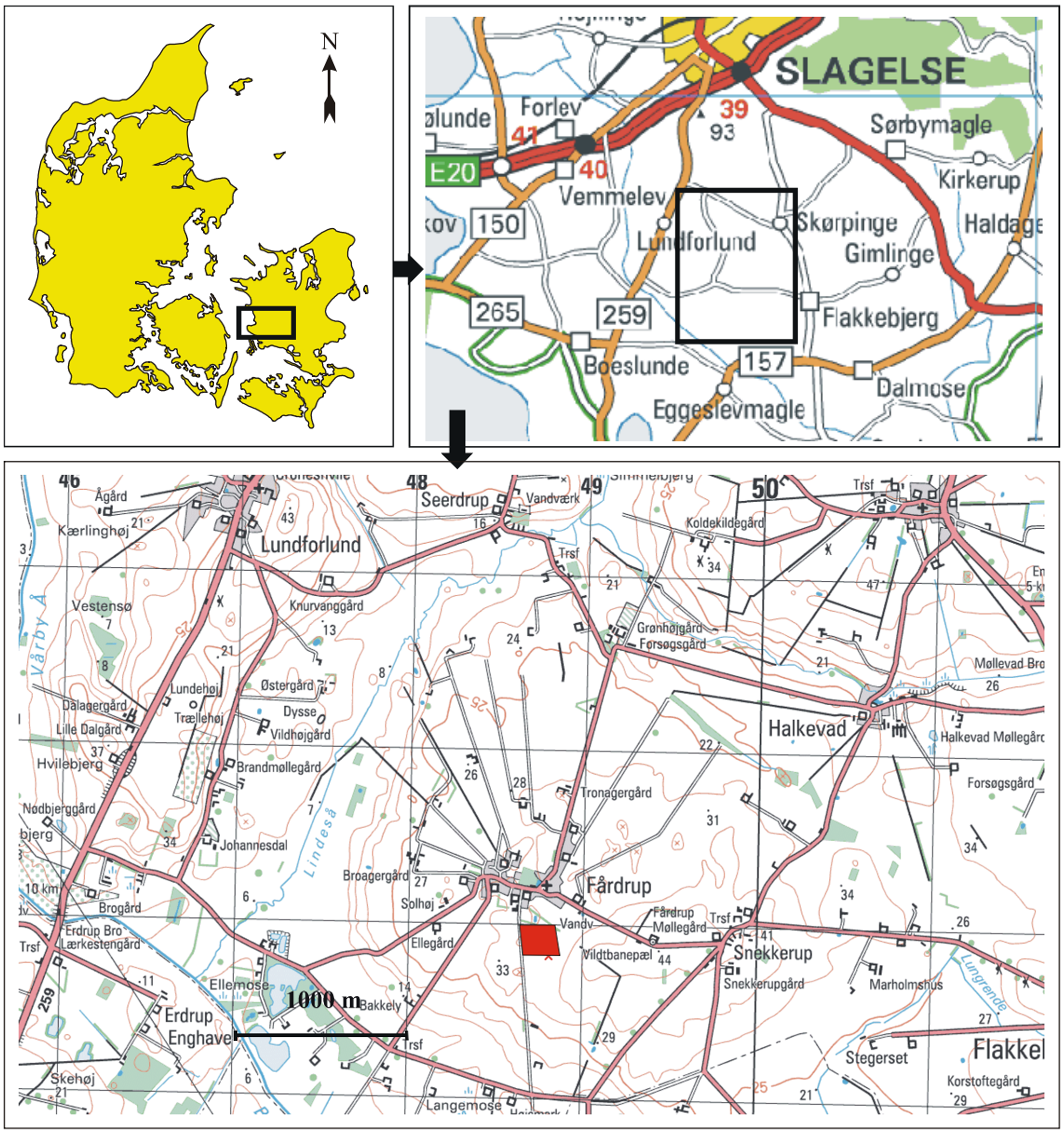


Figure A5.1. Location of the test field.

A5.1 Location, ownership and earlier cultivation and use

The test field at Faardrup is located on Zealand, 8.5 km south of the city of Slagelse (Figure A5.1) and approx. 3 km from the Danish Institute of Agricultural Sciences (DIAS) research centre at Flakkebjerg. It is privately owned and leased by DIAS. The site characteristics are summarized in Table A5.1.

Table A5.1. Site characteristics.

Length and width of the test field	164 m x 152 m
Total area of the site, incl. buffer zone	3.3 ha
Area of the test field	2.33 ha
Municipality	Hashøj
County	Vestsjælland
Land registry no.	6a, Fårdrup By, Fårdrup
Ownership	Private, leased by DIAS

Earlier use

The area is leased from a private farmer and has previously been farmed as a normal field. As is apparent from Figure A5.2, the field has been farmland at least since 1940. A 1944 map of the drainage system indicates the presence of a dirt road in what is now the southern buffer zone (Figure A5.4). This road is no longer visible on the surface, and no traces have been encountered during the field work. However, the field work revealed a tapwater pipe that intersects the southeastern corner of the field. Cultivation and pesticide application history at Faardrup from 1995 to 1999 is summarized in Appendix A5.1.

A5.2 Technical installations

All installations are numbered according to the code described in Section 3. In the present description, however, the site-specific code for Faardrup, i.e. “5”, has been omitted for the sake of simplicity. The locations of all installations are shown in Figure A5.4.

Buffer zone

The width of the buffer zone is >11 m along the northern border, 12 m along the western border where the road adds a further 4 m to the buffer zone, 17 m along the eastern border and >11 m along the southern border.

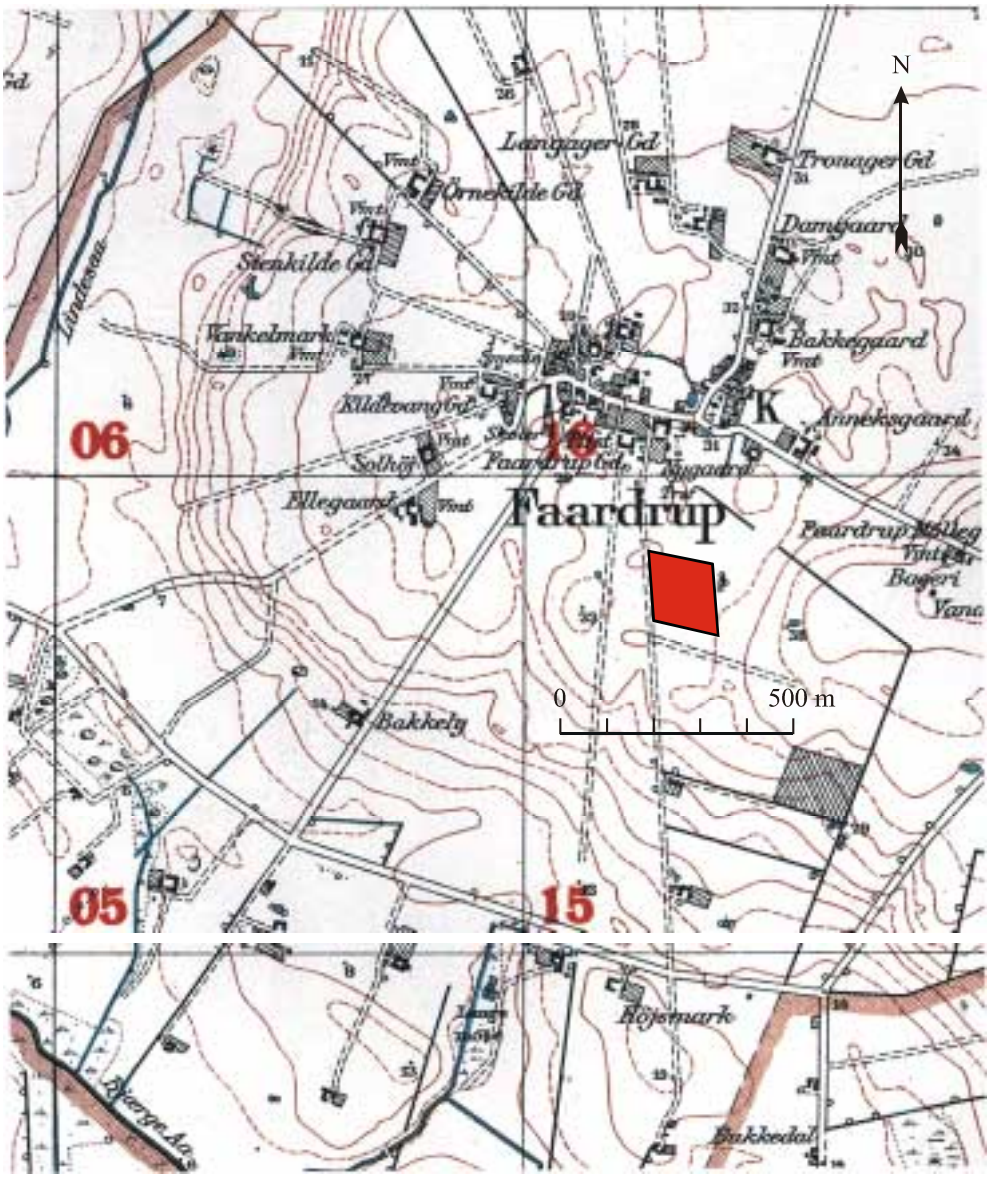


Figure A5.2. Topographic map 1:20.000 from 1940. The test field is marked as a red square.

Suction cups, TDR and Pt-100 sensors

The suction cups at Faardrup were installed as described in Section 3.3 except for the following deviations:

- The distance from the corner of the test field to the first suction cup was approx. 10 m rather than 20 m as stated in Section 3.3.
- The suction cups installed 1 m b.g.s. were placed at a horizontal distance of 1.0 m from the edge of the field rather than 2 m as stated in Section 3.3.
- The suction cups installed 2 m b.g.s. were placed at a horizontal distance of 1.5 m from the edge of the field rather than 2.5 m as stated in Section 3.3.

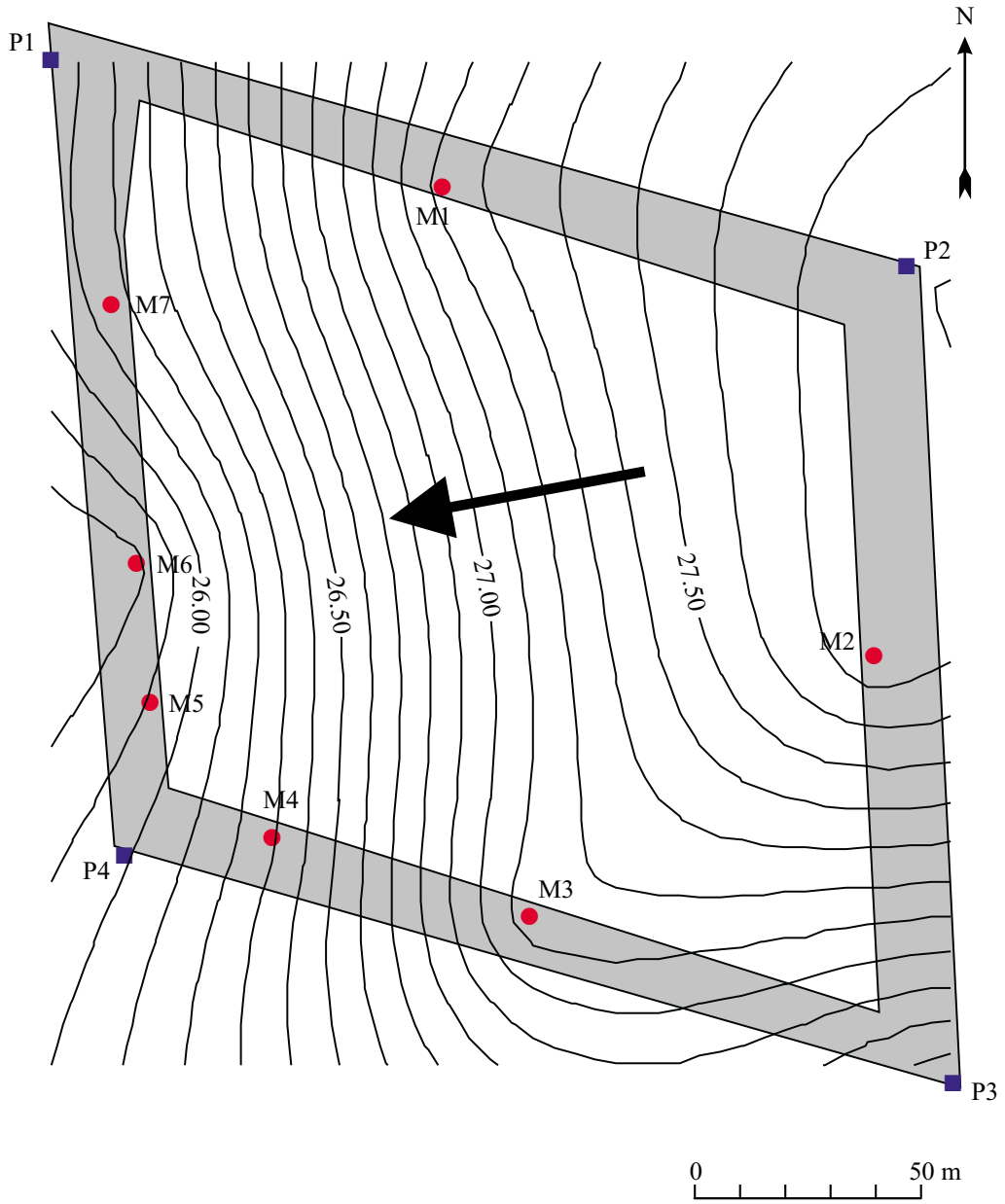


Figure A5.3. Potential head (m a.s.l.) at the site measured in November 1999 and the direction of the ground water flow.

- The installation holes were drilled manually with a hand auger.
- A ¾" garden hose was sliced open and used as cable duct.

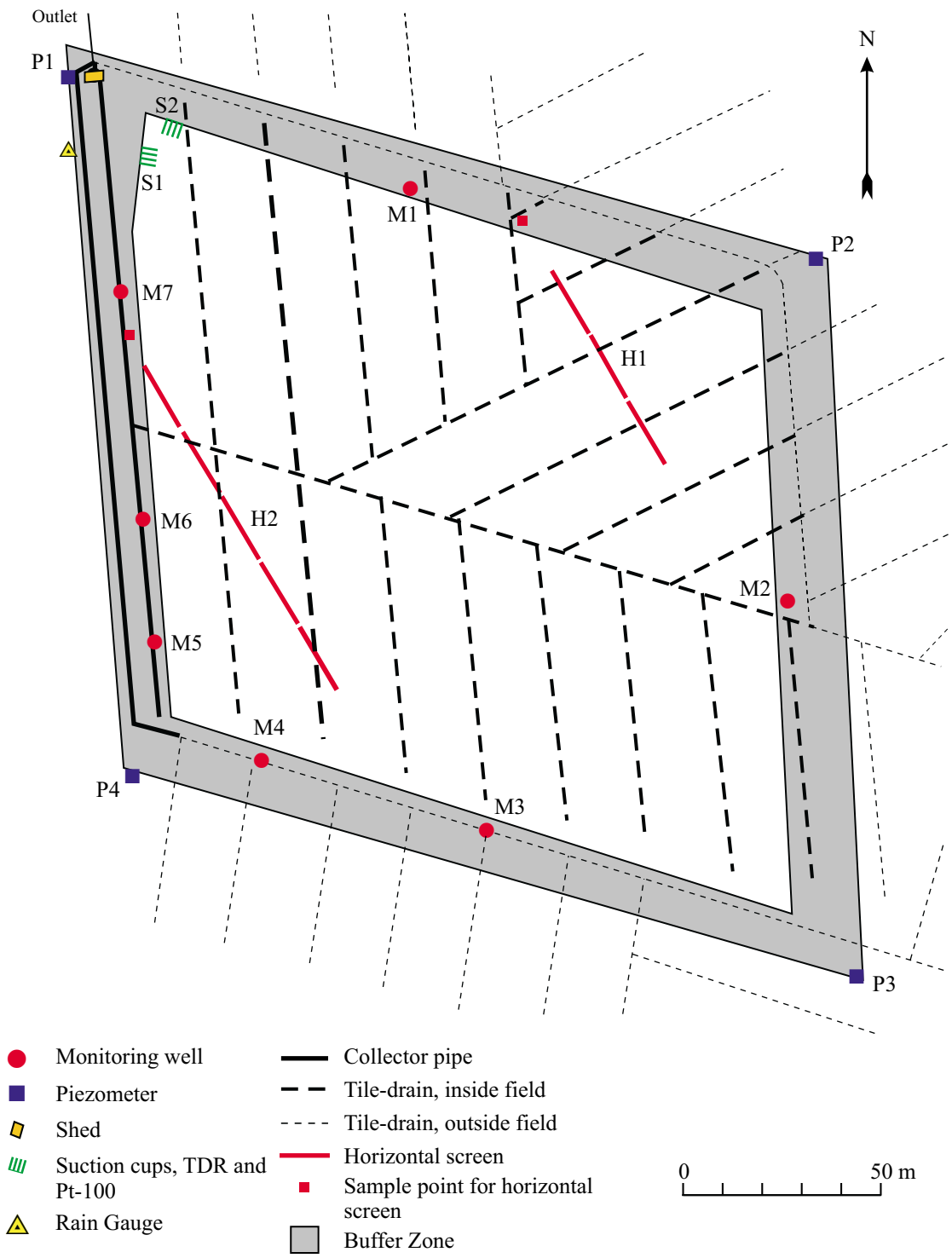


Figure A5.4. Sketch of the field showing the test and buffer zones and location of installations.

Wells

Horizontal sampling wells

Two horizontal sampling wells were installed at Faardrup from June 1 to 10 1999 (Figure A5.4). Both wells were intended to consist of five 18 m screens separated by 1 m long bentonite seals, total length 96 m including a 1 m bentonite seal at each end.

Well H2 intersects the southwestern corner of the field. The overall drilled length of the well is 158 m, of which 110 m lie under the test field. The first filter is located 1 m from the edge of the field and 8 m from the sampling site.

H1 was drilled under the northeastern corner of the field. It intersects the northern edge of the test field 104 m from the northwestern corner and intersects the eastern edge 90 m from the northeastern corner. The overall drilled length is 160 m, of which 120 m lie under the test field.

Due to technical difficulties, however, H1 only consists of three 18 m long screens separated by 1 m bentonite seals. During installation, two 18 m screens – H1.4 and H1.5 – and two bentonite seals got stuck in the casing, and had to be removed. As a result, H1 only consists of the remaining three 18 m screen sections. The functioning screens are the three northernmost screens designated H.1.1, H.1.2 and H.1.3. The first filter is located approx. 10 m along the horizontal well from the border between the buffer zone and the test field and 14 m from the sampling site.

According to the drilling company's log, the screens and bentonite seals are located 3.35 to 3.70 m b.g.s. The target was 3.5 m b.g.s. The samples are taken from the northern end of the H1.

Installation of piezometers and monitoring wells

All wells at Faardrup were drilled as cased wells with a 6" (152 mm) solid stem auger except for some sandy intervals below the groundwater head, where a bailer was used.

To monitor the groundwater head, four wells each containing three piezometers were placed in each corner of the test field (Figure A5.4). The depth of each piezometer is given in Table A5.2.

Table A5.2. Location of the piezometers.

Piezometer	DGU no.	Upper screen m b.g.s.	Middle screen m b.g.s.	Lower screen m b.g.s.
P1	215. 920	2.5–3.0	6.5–7.0	10.5–12.0
P2	215. 963	3.0–3.5	5.5–6.0	9.3–9.8
P3	215. 964	2.5–3.0	6.2–6.7	12.7–13.2
P4	215. 965	3.0–3.5	5.5–6.0	11.6–11.9

Monitoring wells

The monitoring wells are grouped in seven clusters of four, numbered clockwise from the northwestern corner of the field: M1…..M7. The exact location of each monitoring well cluster is shown in Figure A5.4. All screens are Ø 63 mm, 1 m screens.

The monitoring well screens of all seven clusters are located at the following depths:

Mx.1: 1.5–2.5 m b.g.s.
Mx.2: 2.5–3.5 m b.g.s.
Mx.3: 3.5–4.5 m b.g.s.
Mx.4: 4.5–5.5 m b.g.s.

Two different monitoring well cluster designs are in use at Faardrup. Well clusters M1, M2, M6 and M7 are installed pair-wise in two separate Ø 60 cm, 1 m tall concrete manhole rings with electroplated steel covers. Well clusters M3, M4 and M5 are installed as four wells in one Ø 60 cm, 1 m tall concrete manhole ring.

The monitoring wells were drilled from the surface to a depth of 1.5 m b.g.s. using a 6" (152 mm) solid stem auger. Casing was used if necessary. In a few wells, a bailer was used to clean the bottom of the borehole before installation of the screen. When drilling from a depth of 1.5 m b.g.s. downwards, A-tubes were used to obtain intact samples for a high-quality geological description. After the A-tube was retrieved, the interval was drilled again with the 6" solid stem auger in order to open the borehole to the desired diameter. Coring with A-tubes is a time-consuming drilling method, as every interval cored with an A-tube has to be re-drilled using the auger.

Even relatively small stones and pebbles will stop the A-tube after perhaps only 5 cm of penetration. After each failed attempt, the interval has to be drilled first with the auger and thereafter with the A-tube. Because of the difficulty involved, the A-tubes were only used at Faardrup.

Drainage system

The existing drainage system.

The basis for the work was a map made by Hedeselskabet on April 1st 1944. The map indicates the presence of a traditional systematic drainage system. The elevations on the map are assumed to still apply.

The whole system drains to an inspection chamber at the northern boundary of the area, from where the water flows in an 18 cm main drainpipe to the village of Faardrup. The conditions further downstream were not investigated.

The drainage water from the test field and the adjacent fields is collected in a 15 cm main drain, running along the western border of the area. The drainage system in the test field is a "herringbone system" with a collector drain that runs down westwards from the hills in the east, crosses the middle of the field and into the 15 cm main drain. All the drainpipes are clayware – Ø 5.5 cm i.d. laterals and Ø 6.5 cm and 10 cm i.d. collector drains. The slope decreases down through the system and is only 1.8‰ in the 15 cm main drain.

It was decided that the flow measurements should be made using Thompson weir placed in chambers comprised of Ø 125 cm rings. This construction design requires a level difference of at least 20 cm through the structure, as well as a permanent free flow downstream. As these conditions were not met, pumps were installed in connection with the measuring chamber.

Measuring chamber and pumps

The water from the test field is collected by interception of the 6" pipe, from where it is led to a Ø 125 cm chamber with a 30° Thompson notch. From here the water flows to a similar Ø 125 cm chamber equipped with two 0.75 kW submerged pumps each with a capacity of 4–5 l sec^{-1} ha^{-1}. The water is pumped to a third chamber (Ø 100 cm) with its outlet connected to the old Ø 15 cm main drain. An initial (a few metres) section of the latter between the inlet and the outlet connections was removed to ensure that the water is properly cut off and runs through the measuring structure.

The two pumps run alternately when discharge is low, and simultaneously when one pump is insufficient. Two pumps were chosen rather than one in order to increase reliability in the event of pump failure, ensure the possibility of maintenance without cessation of operations, and in view of the limited capacity of the main pipe downstream of the measuring chamber.

The pipes used in connection with the measuring chamber/pump chamber are smooth PVC pipes. Although PVC might contain chemical impurities, it was agreed to nevertheless use it since only a few metres of the pipes are included in the system upstream of the measuring chamber, where sampling takes place.

Dimensions of drainage system

According to diagrams of water flow in pipes, the capacity of the main pipe downstream of the measuring chamber is around 1 l sec^{-1} ha^{-1} estimated for the catchment as a whole provided there is free flow and that the pipes are in good condition and free of sediment. A capacity of 1 l sec^{-1} ha^{-1} is commonly used for agricultural drainage systems in Denmark.

In extreme situations, in particular when surface runoff has accumulated in depressions on the field, runoff can be several-fold greater than 1 l sec^{-1} ha^{-1}. The installed pumps thus have a maximum capacity of approx. 3 l sec^{-1} ha^{-1}.

Since the capacity of the pumps exceeds that of the drainpipe downstream of the measuring chamber, there is a risk of ponding. If the water level rises above the soil surface, it will flow over the top of the 100 cm inspection chamber and run along the surface in a northerly direction away from the test field. The test field drainage system is only isolated from the above-mentioned downstream main drainpipe by a soil column, however. Thus if there is a difference in water head for longer periods, water will flow back towards the test field through the soil layers.

The cut-off drainpipe.

To isolate the test field drainage system, cut-off drainpipes were installed.

The neighbouring drains, south of the test field, constitute a smaller, independent drainage system. Prior to the study, it exited in the top end of the 15 cm main drain in the southwestern corner of the test field. This system was disconnected at this point, and the water led downstream in a new pipe installed along the western boundary, parallel to the old main. As the purpose is to convey the water around and away from the test field, a watertight pipe was used consisting of a 113/145 mm corrugated PVC pipe. The slope is only 1.0‰.

A second cut-off drain was installed to the north and the east of the test field. In this case, the purpose was to prevent water from running into the test field from its upstream side. We therefore used perforated, corrugated pipes with an envelope of gravel. Any existing drains intersected were closed with a brick towards the test field, and their up-

stream parts were connected to the new pipe via a T-junction. The slope of this second cut-off pipe is 5‰ or more.

Both cut-off drains exit to the 100 cm inspection chamber, which receives the pump outlet from the new measuring chamber and pump chamber.

Comments

All of the construction work was carried out during April and May 1999.

A5.3 Geology

Regional geology

Over the past decade a research programme focusing on pesticide leaching in fractured till has been carried out at the DIAS research centre at Flakkebjerg, 3 km from Faardrup. Considerable data are therefore available concerning the regional geology of the area. As Faardrup is situated only 3 km from Flakkebjerg and is assumed to have a similar geological setting to Flakkebjerg, the present description is partially based on the Flakkebjerg data.

The area around Faardrup and Flakkebjerg is dominated by an undulating clayey till plain 30 m a.s.l. that is dotted with smaller hills up to 45 m a.s.l. The till plain is cut by erosional valleys. To the west and south the landscape drops relatively abruptly towards the two streams Lindes Å and Bjerge Å (10 m a.s.l.). To the north the area drops towards the upper reaches of Lindes Å.

The surface geology is dominated by clay till deposits covered by 30–40 cm of topsoil. The surface geology varies locally and detailed surface mapping in the Flakkebjerg area has revealed smaller areas with sandy till deposits and glaciofluvial sand, clay and gravel deposits, as well as Post Glacial peat and gyttja (personal communication; Knud Erik Klint, GEUS). As the geomorphology at the Faardrup site is comparable to that of the Flakkebjerg area, it is reasonable to expect the same features at Faardrup (Klint and Gravesen, 1999).

A regional model of the area has been presented based on well and field studies (Henriksen *et al*., 2000) according to which the majority of the area is covered by a 5–20 m

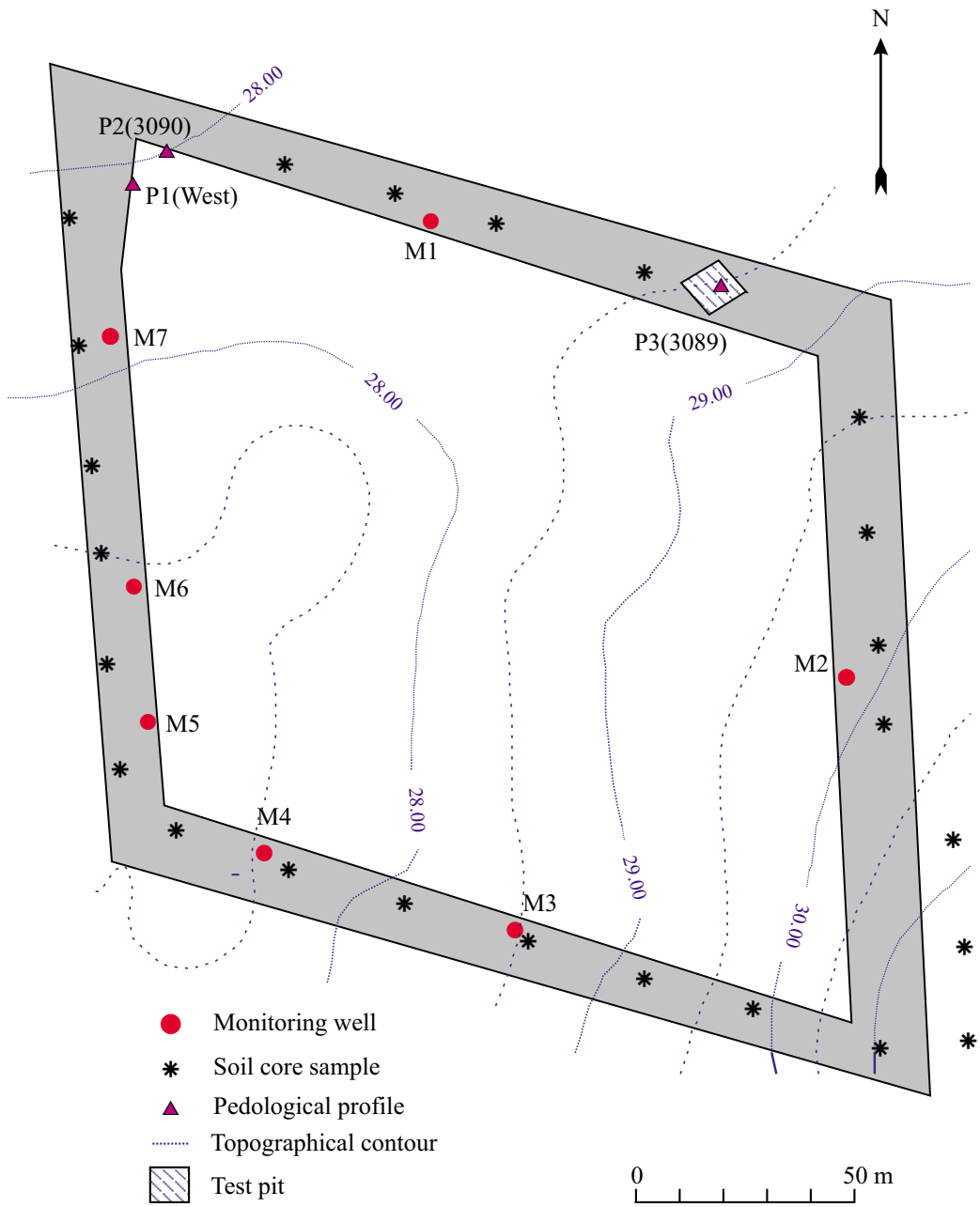
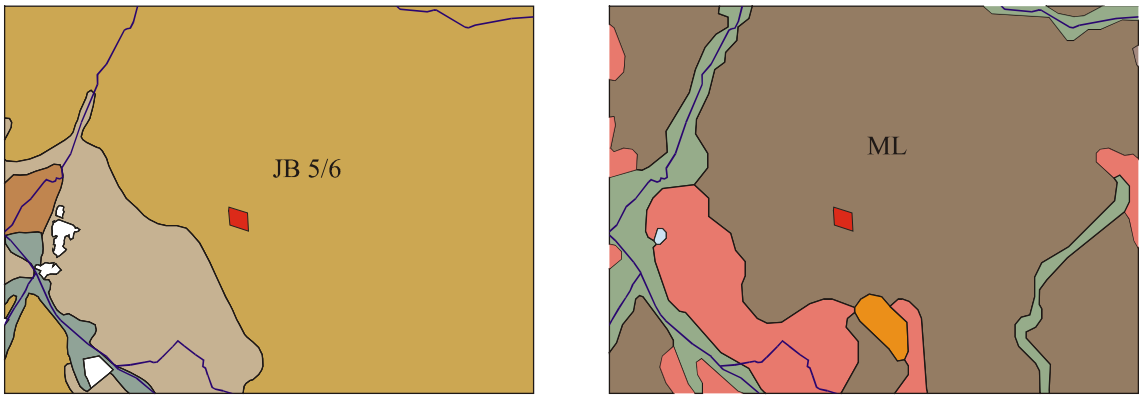
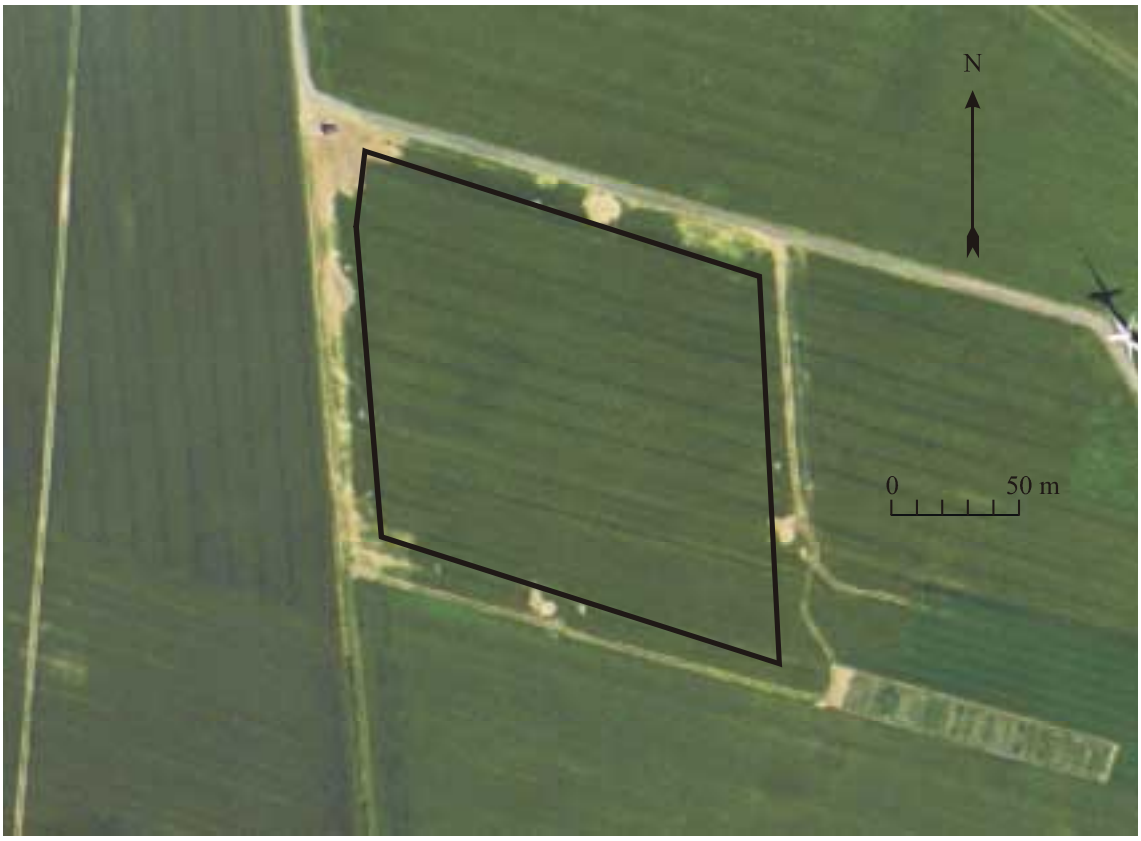


Figure A5.5. Topography at the site and location of soil cores, test pit and monitoring wells.

thick clay till deposit except where it is cut by erosional valleys. In the valleys glaciofluvial and Post Glacial limnic sediments dominate. The clayey till cover consists of a young Baltic till unit, possibly a Belt Sea Till, of varying thickness, deposited by a Baltic ice advance in the Upper Weichselian. Under the Belt Sea till lies a Mid Danish till deposited by the N-E advance (Houmark-Nielsen 1987). The Mid Danish till was detected in most but not all wells in the area separated by a relatively thin, 0.5–5 m thick, glaciofluvial sand unit.



A B



C

Figure A5.6. Location of the test field (red square) superimposed on: A) The soil type map. JB 5/6: Sandy loam. B) Map of Quaternary sediments in Denmark, ML: Clay till. C) An aerial orthophotograph (Kampsax Geoplan, DDO1999).

Beneath this till cover there is a 2–15 m thick glaciofluvial sand deposit. This was probably deposited as a proglacial sandur corresponding to the N-E advance and is regarded as a regional aquifer. Under the sand, a number of older till units with related sand deposits are found. The age of these older units is uncertain, but they could be of a Middle Weichselian or possibly Saalian age.

The Pre-Quaternary surface consists of Paleocene limestone located 10–20 m b.s.l., that is regarded as a regional aquifer.

Geomorphology

As seen in Figure A5.1, the test field is situated close to the top of the hill on which the village Faardrup lies. The field slopes gently towards the west with an average gradient of approx. 1.7%. The slope is slightly greater in the eastern part of the field. In the western part of the field, there is a small oval 50 m x 30 m depression with a negative relief of 0.5–1.0 m (Figure A5.5).

The test field is shown superimposed on the Soil Classification map, the map of Quaternary sediments in Denmark and an orthophotograph in Figure A5.6. The field is placed in an area dominated by sandy loam soil (JB 5/6). The map of the Quaternary sediments indicates that the dominant sediment type is clay till. Based on the orthophotograph, the field appears to be homogenous.

Geology of the monitoring wells and piezometer wells

As seen in the geological cross sections based on the information from the wells (Figures A5.7 and A5.8), clay till (ML) is the dominant sediment at Faardrup. Minor variations in the cross sections include sandy till and minor components of glaciofluvial sand and gravel. The geology found in well M6 differs from the other wells at Faardrup in that alternating layers of glaciofluvial sand and glaciolacustrine clay dominate.

Colour changes in the till indicate variations in the redox conditions. Grey colours indicate reduced conditions whereas brown colours indicate oxidized conditions. Based on colour changes, three different zones can be recognized. In most wells, an upper zone with yellowish brown and brownish yellow colours is found from below the topsoil to a depth of 2.5–5 m b.g.s. Below this, a suboxic zone with greyish brown till is present to a depth of 4–6 m b.g.s. This zone is typically 0.2 to 0.5 m thick. Below this there is a lower zone with olive grey and grey-coloured till.

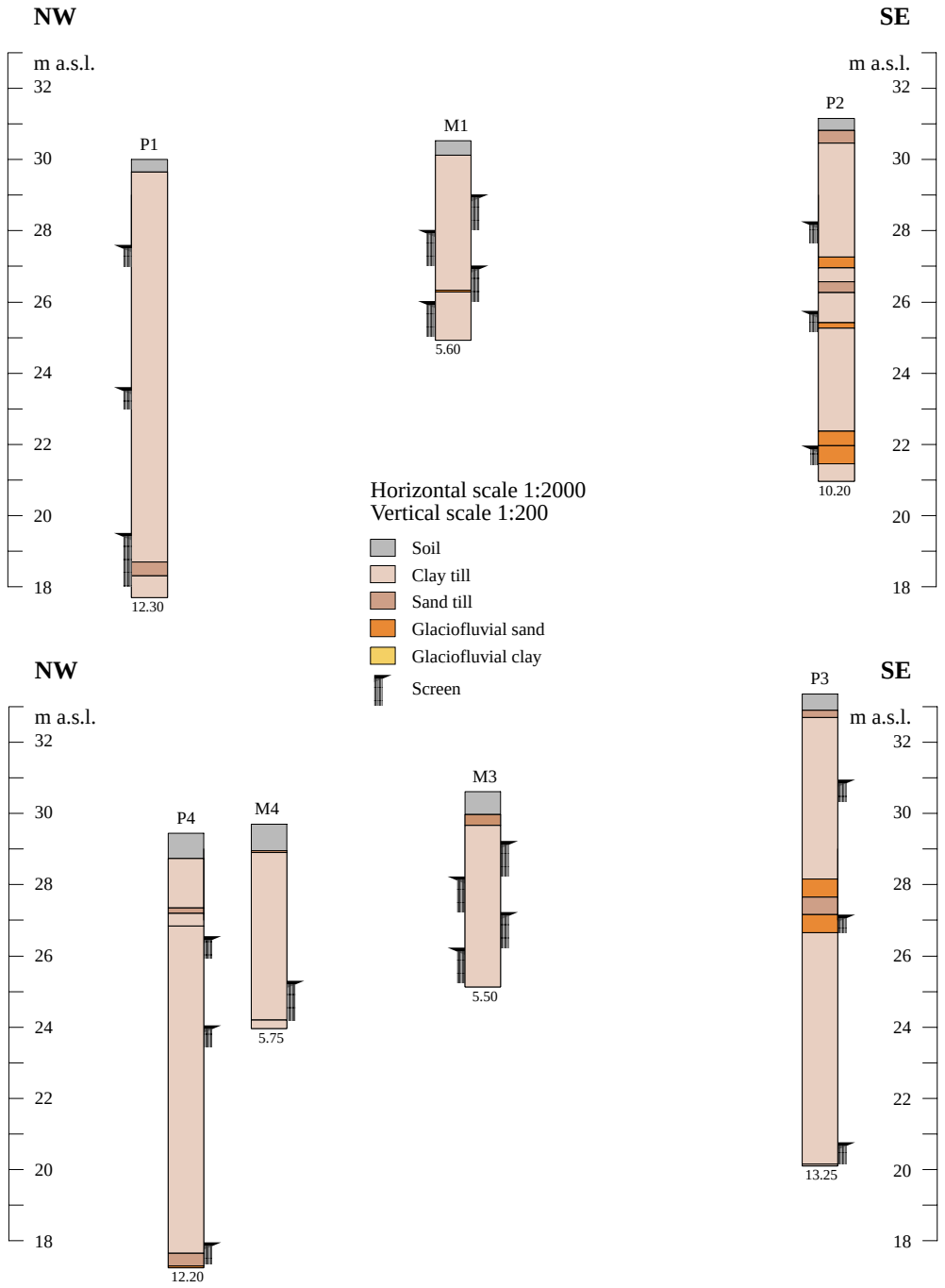


Figure A5.7. NW-SE cross sections based on wells at the site. The location of the wells is shown in Figure A5.4.

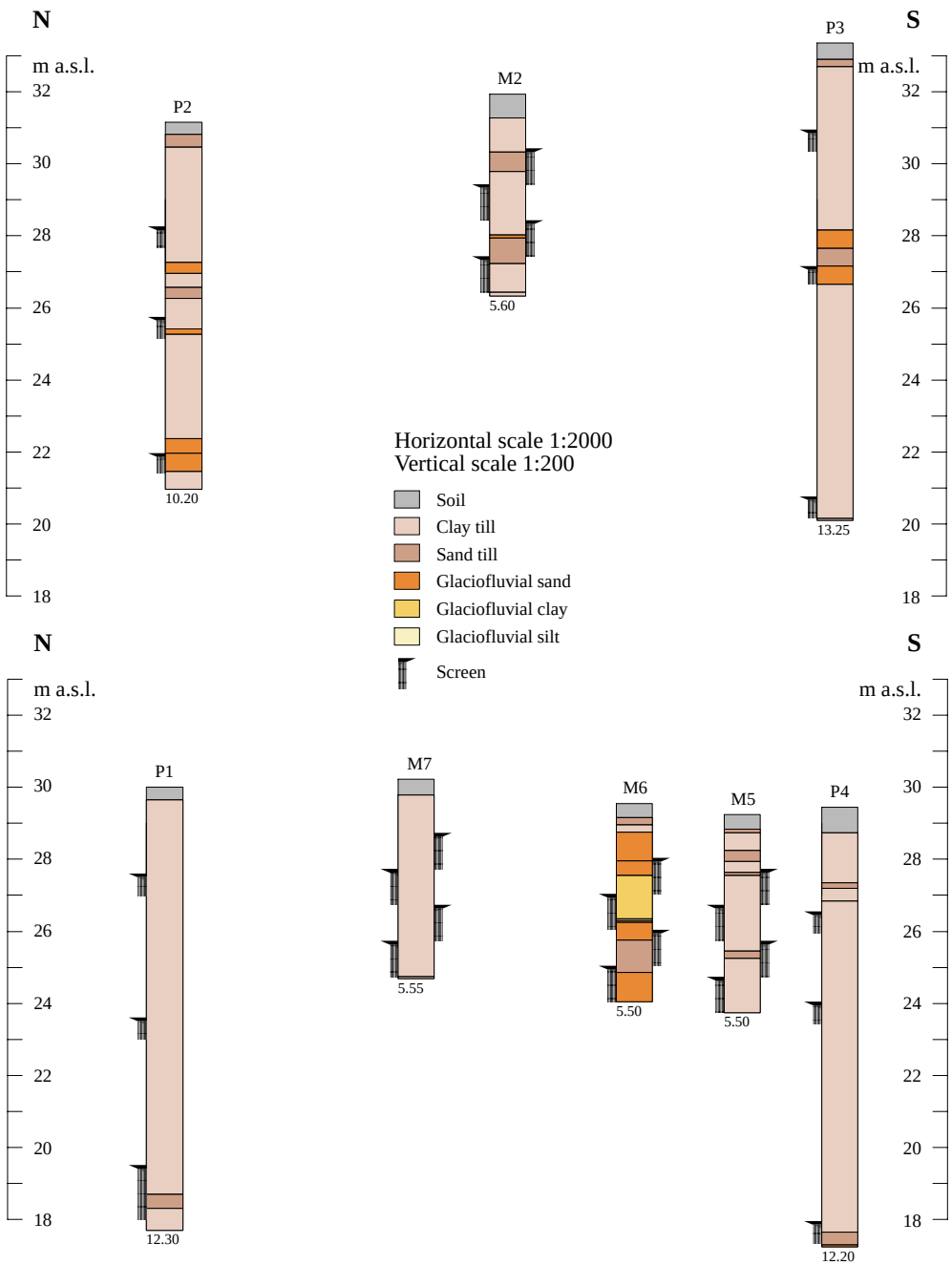


Figure A5.8. N-S cross sections based on wells along the eastern and western ends of the test field. The location of the wells is shown in Figure A5.4.

Geology of the test pit and drainage ditch excavations

A test pit was excavated to 5.5 m b.g.s. using a backhoe in the buffer zone of the north-eastern corner of the test field for lithological description, fracture descriptions and characterization, fabric analysis and field vane tests.

Samples were collected for grain size analysis, $CaCO_3$ content, total organic carbon (TOC), clay mineral analysis, porosity/permeability, and exotic stone counts.

Lithological description

The depths given in Table A5.3 are average depths determined from the test pit, and correspond to the log in Figure A5.9–A5.11. The descriptions follow Larsen *et al*. (1995).

Table A5.3. Lithological descriptions from the test pit at Faardrup.

Depth m b.g.s.	Description	Sample no.
0–0.4	Topsoil. Sand mixed with clay silt and gravel, numerous burrows, root channels and desiccation cracks, visible organic material, non-calcareous, very dark greyish brown.	DIAS Profile 3089
0.4–1.1	Clay till with sand veins and bodies. Clay strongly mixed with sand, clay mixed with silt, gravel and boulders, noncalcareous. Numerous fractures and desiccation cracks, the latter decreasing with depth. Numerous burrows and root channels that decrease in number towards the bottom of the unit. Clay skins and root traces on fractures. Light olive brown.	DIAS Profile 3089
1.1–2.4	Clay till with some sand veins and lenses. Clay mixed with silt, strong mix of sand and weak mix of gravel and few cobbles. Fissile, i.e. heavily fractured horizontally and subhorizontally on a 0.5–1.0 cm scale. Brownish yellow with grey colouring around fractures and haloes around roots. Calcareous (16–20% weight), wet, water-bearing.	10929 10930
2.4–4.0	Clay till with folded sand veins and lenses. Clay mixed with silt, strong mix of sand and weak mix of gravel and cobbles, olive brown with iron and manganese oxide coating on and around fractures and sand veins. Some sand veins have weak red colouring as well as iron oxide, calcareous, moist.	10907 10886
4.0–4.3	Clay till with numerous sand lenses, veins and gravel. Clay strongly mixed with sand, clay mixed with silt, gravel and a few cobbles. Calcareous; the matrix has a $CaCO_3$ content of approx. 20% while more significant sand veins contain approx. 3% $CaCO_3$ The matrix colour changes in this interval from olive brown to dark olive grey. Sand lenses and some fractures are coloured weak red and rust-coloured, moist.	10885 (sand-vein)
4.3–5.7	Clay till, with few sand veins and lenses. Clay with strong mix of sand, mix of silt, gravel and few cobbles. Dark olive grey, calcareous (20%), moist.	10883

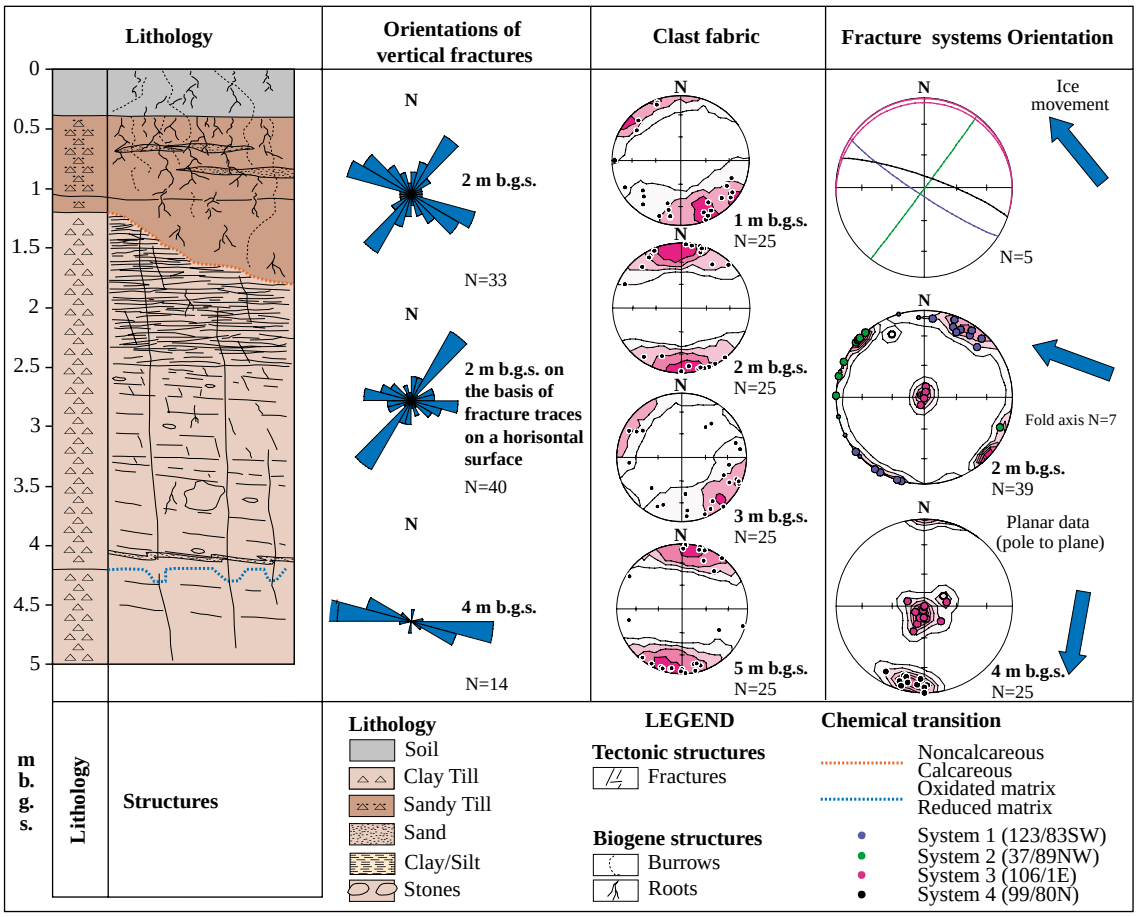


Figure A5.9. Lithology, fracture orientation, clast fabric data and interpreted ice movement direction.

Fracture description

In order to make a conceptual model of the fracture systems and macropores in the test field, fracture orientation at various depths and fracture position and frequency were measured in the test pit.

Four different fracture systems are distinguished and described with regard to spacing, orientation and occurrence, the data are presented in Figure A5.9 and the main fracture systems identified. Besides the fracture analysis, fabric in the till and fold axis in folded sand veins were measured in order to describe the stratigraphic relationships in the test pit excavation.

In the upper meter, agricultural processes, bioturbation and desiccation cracks dominate to a degree that obscure the systematic fracture systems. Four fracture systems has been recognized at Faardrup (Figure A5.9).

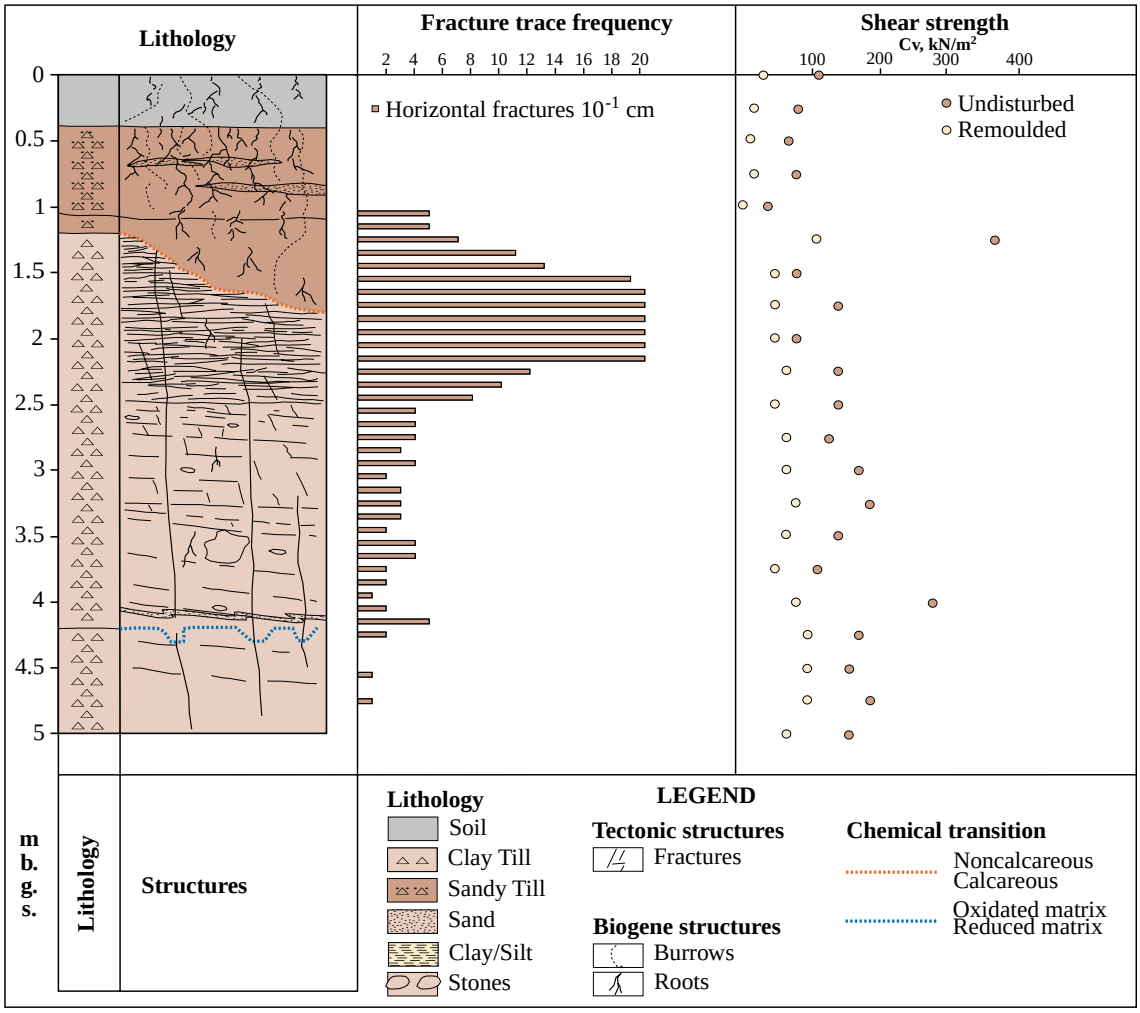


Figure A5.10. Lithology, fracture trace frequency and shear strength in the test pit.

System 1: Vertical fractures with orientation strike/dip 123°/80° SW indicating deformation from the northeast. This fracture system can be recognized from 1 m to 5.5 m b.g.s. The spacing of system 1 fractures, the most prominent fracture system, was 35–40 cm at 2 m b.g.s. and 3.5 m b.g.s. Fracture system 1 was visible throughout the excavation to 5.5 m b.g.s.

System 2: Vertical fractures with orientation strike/dip of 37°/89° NW indicating a deformation from southeast and/or desiccation. This fracture system occurred between 1.0 m and 3.0 m b.g.s.

System 3: Horizontal and subhorizontal fractures with orientation strike/dip of 106°/1° E indicating a shear-related deformation or possibly a freeze-thaw process, as described by Washburn (1979). This fracture system is most intensive at 1.8–2.3 m b.g.s., where the till becomes fissile due to the large number of fractures.

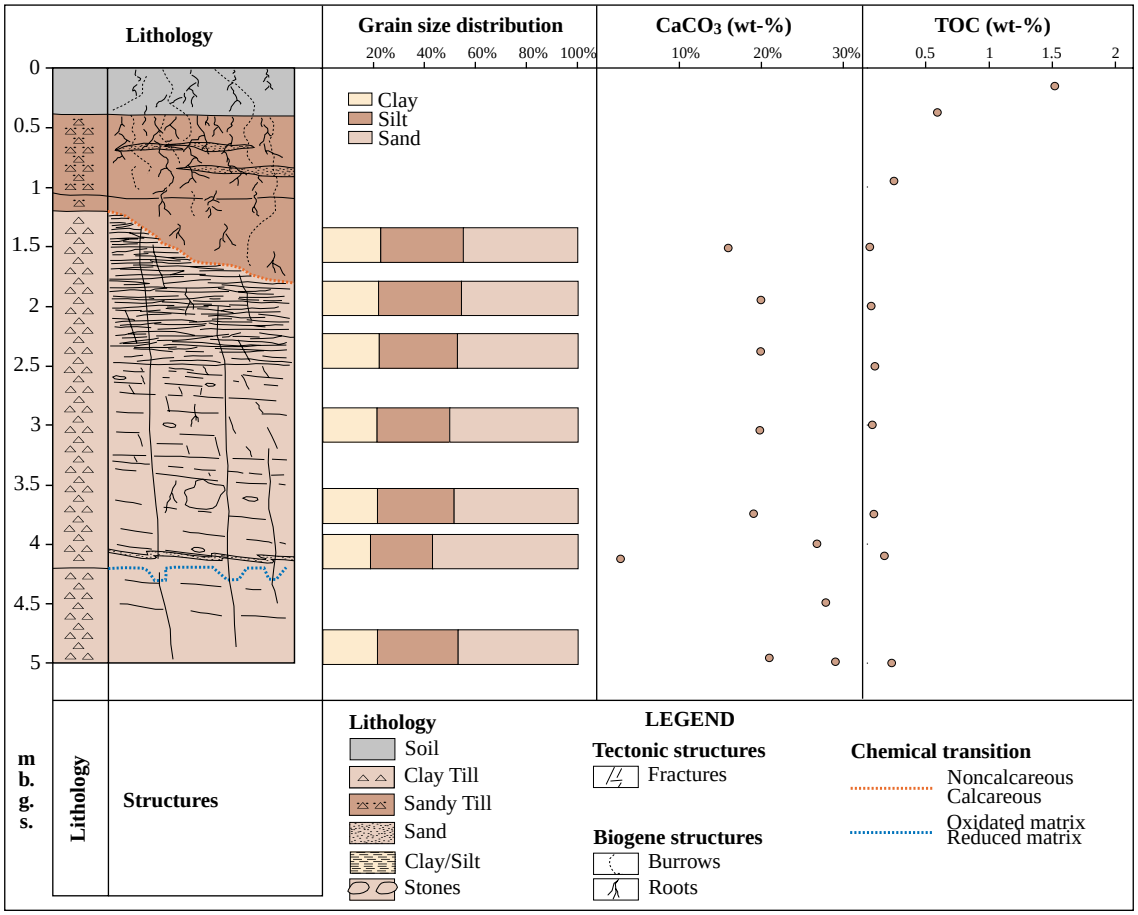


Figure A5.11. Lithology, grain size distribution and $CaCO_3$ and total organic carbon (TOC) content in the test pit. Grain size fractions larger than 2.0 mm are not included in the grain size analysis.

System 4: Consist of nearly vertical fractures with orientation strike/dip of 99°/80° N. The spacing was 35-40 cm, it was regular and the fractures reached well in to the reduced till. The orientations of fracture system 1 and 4 is approximate equal and it is likely that the formation of the two fracture systems is related.

During field work it was observed that most of the water entering the test pit excavation derived from this intensely horizontally fractured zone. This fractured zone probably acts as a drainage system and may be present under a large part of the test field.

Fracture geochemistry

From a geochemical point of view, the fractures can be divided into 5 depth-dependent units. These data are field observations and primarily based on the matrix colour and colour changes from fracture surfaces into the matrix.

I. 0.3–1.5 m b.g.s. A unit in which fractures are coated with clay skins and traces of topsoil can often be seen in large aperture fractures. Root traces are abundant on fracture surfaces. Most of the fractures are caused by desiccation. This unit stretches from the bottom of the topsoil 30–40 cm to approx. 1.2–1.5 m b.g.s. The lower extent of this unit more or less coincides with the change from non-calcareous to calcareous till.

II. 1.5–2.5 m b.g.s. The most obvious feature of this unit is a grey colouration of the matrix around hydraulically active fractures and macropores. A zone of 1–2 cm around the fracture is reduced-grey while this zone is in turn bordered by a 1 cm thick zone of rust-coloured matrix. The reduced conditions are attributable to oxygen consumption in connection with degradation of organic matter. Although the majority of the horizontal and subhorizontal fractures show no visible geochemical alteration, the intense fracture pattern indicates that the entire matrix is probably oxidized.

III. 2.5–4.1 m b.g.s. Hydraulically active fractures are coated with iron and manganese oxides. The matrix is olive brown, but shows signs of increased oxidation in a narrow unit (5 cm) around the fractures, reflected as brownish yellow and yellowish brown colouration.

IV. 4.1–5.0 m b.g.s. In this unit the hydraulically active fractures have a thin coating of iron and manganese oxides. The matrix around the fractures exhibits signs of oxidation up to 5 cm from the fractures.

V. 5.0–5.5 m b.g.s. A unit found in the bottom of the test pit excavation where there is no coating or signs of alteration on the fracture surfaces.

Clast fabric and fold axis analysis

Clast fabric analysis was performed at four depths, 1.0, 2.0, 3.0 and 5.0 m b.g.s. (Figure A5.9). The upper three measurements indicate deformation in southern or southeastern direction, whereas the analysis at 5.0 m b.g.s. could be the result of a northeasterly deformation. All fold axis measurements made on thin folded sand veins reveal deformation from an easterly or east–southeasterly direction.

Comment on the drainage ditches

The geological variation present in the drainage ditches is well reflected in the test pit and the profiles, except for the area near well cluster M6, where glaciofluvial sand was encountered (see the grain size analysis, Table A5.4).

Laboratory analyses

Grain size analysis

Grain size analysis has been carried out on 15 samples from the site (Table A5.4). The till typically consists of 19–23% clay, 25–35% silt, 40–50% sand and 2–7% gravel.

Table A5.4. Texture analysis of sediment from the test pit and from selected wells.

	Grain size in mm							
Depth and location m b.g.s.	<0.002	0.002–0.020	0.02–0.63	0.63–0.125	0.125–0.200	0.20–0.5	0.5–2.0	Sediment
Test pit								
1.50	22.9	25.1	7.2	17.6	11.8	10.7	4.8	Clay till, oxidized
2.00	21.9	26.2	6.2	16.4	11.6	12.0	5.7	Clay till, oxidized
2.50	22.3	23.8	6.6	18.7	12.5	10.9	5.1	Clay till, oxidized
3.00	21.1	21.8	7.0	19.1	13.0	12.1	5.9	Clay till, oxidized
3.75	21.5	23.3	6.8	19.2	12.8	11.5	5.0	Clay till, oxidized
4.10	18.7	16.3	8.0	14.0	12.0	17.6	13.4	Sand vein in till
5.00	21.6	23.6	8.0	18.0	12.3	11.2	5.3	Clay till, reduced
Wells								
P4 (2.50)	23.7	19.5	6.1	19.9	12.7	12.0	6.1	Clay till, oxidized
P4 (4.50)	31.5	16.1	5.7	16.1	12.2	12.3	6.1	Clay till, suboxic
P4 (6.50)	23.7	24.3	6.3	16.3	12.5	11.2	5.7	Clay till, reduced
P4 (8.50)	19.6	26.6	9.1	15.3	11.2	11.7	6.5	Clay till, reduced
P4 (10.50)	24.5	20.7	5.1	16.3	12.7	13.5	7.3	Clay till, reduced
P4 (12.50)	9.2	12.4	8.5	16.3	17.7	25.2	10.8	Sandy till, reduced
M6 (2.50)	36.9	50.7	9.5	1.9	0.5	0.5	0.2	Glaciolacustrine clay
M7 (5.50)	16.4	23.3	11.7	16.9	12.4	12.7	6.7	Clay till
Drainage ditch west (1.80)	5.1	14.2	14.9	23.1	16.7	18.0	8.0	Glaciofluvial sand

Data from GEUS Sediment Laboratory. Some of the fractions were determined by linear interpolation.

Clay mineral analysis

Clay mineral analysis was carried out on three samples from the test pit. The clay fraction (<2 µm) in the till at Faardrup is dominated by smectite – but also contains vermiculite, illite, kaolinite and quartz. In one sample from 2.25 m b.g.s., chlorite was also found. According to Ernstsen (1998), this is a normal clay mineral composition for this region.

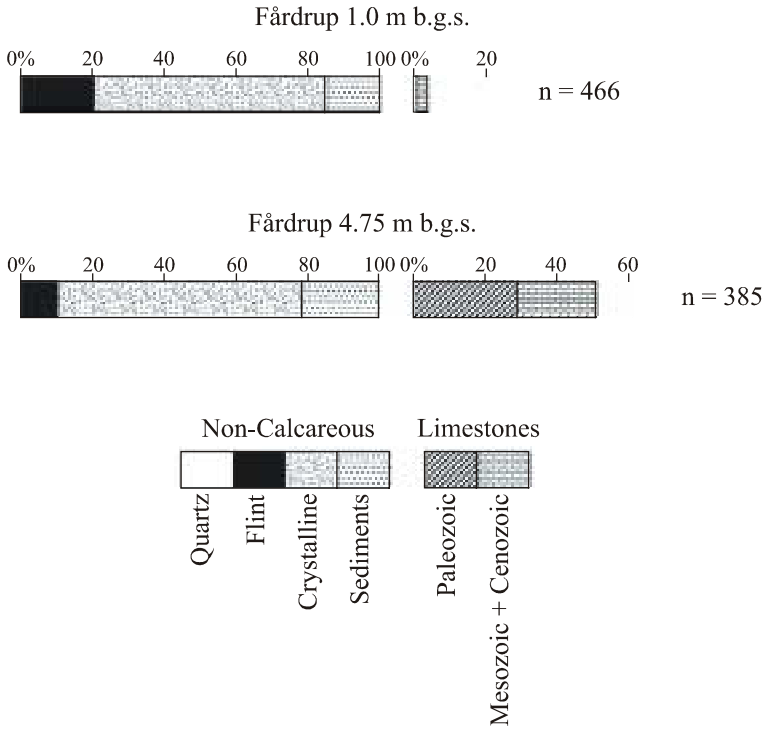


Figure A5.12. Fine gravel analysis from two levels in the test pit. n is the number of grains count.

Fine gravel analysis

Exotic stone counts have been performed on two samples from Faardrup using the Dutch method (Figure A5.12) – one from the sandy till 1 m b.g.s. and one from the clay till 4.75 m b.g.s. Because of dissolution, the content of calcareous gravel particles is lower in the sample from 1 m b.g.s. than in that from 4.75 m b.g.s. The composition of the samples was otherwise more or less similar, and there is no justification for subdividing the till based on the fine gravel analyses.

Total organic carbon (TOC) and $CaCO_3$ content

With most samples the calcium carbonate content was 19–21% by weight, which is normal for the region (Table A5.5 and Figure A5.11).

Two samples deviate from this pattern: The $CaCO_3$ content of the sample from 1.5 m b.g.s. is 16%, probably due to dissolution caused by meteoric water, while that of the sample from 4.1 m b.g.s. in a sand layer is 3.0%. The latter can be explained in two ways: either the sand layer is a palaeo-surface with a shallow weathering zone, possibly connected to an interstadial, or it is hydraulically active with resultant dissolution of $CaCO_3$.

As would be expected, the total organic carbon (TOC) of the samples from Faardrup was low (Figure A5.11), ranging from 0.06% to 0.23 % by weight. The TOC content is highest in the topsoil near the surface and decreases rapidly with increasing depth. The TOC content increases slightly moving from the oxidized zone to the reduced zone, reflecting the slower degradation rate associated with reduced conditions (Ernsten *et al.* 1998).

Table A5.5. $CaCO_3$ and total organic carbon (TOC) content of sediment from the test pit and selected wells.

Locality	Depth m b.g.s.	TOC %	$CaCO_3$ %	Sediment
Test pit	0.15	1.38	0	Top soil
Test pit	0.50	0.26	0	Clay till
Test pit	0.95	0.12	0	Clay till
Test pit	1.5	0.06	16	Clay till
Test pit	2.0	0.07	20	Clay till
Test pit	2.5	0.10	20	Clay till
Test pit	3.0	0.08	20	Clay till
Test pit	3.75	0.09	19	Clay till
Test pit	4.1	0.17	3.0	Sand
Test pit	5.0	0.23	21	Clay till

Data from GEUS Sediment Laboratory.

Porosity and permeability

For determination of porosity and permeability 100 cm^3 samples were collected from the test pit horizontally using stainless steel cylinders (Table A5.6).

Table A5.6. Special core analysis data from the test pit.

Depth m b.g.s.	Plug type	Liquid permeability mD	Saturated hydraulic conductivity 10^{-9} m/s	Porosity cm^3/cm^3	Grain density g/cm^3
2	2	0.147	1.42	0.24	2.685
3.5	2	0.059	0.57	0.23	2.679
5	2	0.065	0.63	0.22	2.686

Data from GEUS Core laboratory.

Field vane tests

The field vane tests revealed slightly increasing undisturbed shear strain (Cv) values with increasing depth (Figure A5.10), ranging from 50–90 kN/m^2 at the top of the profile to 10–190 kN/m^2 at the bottom. According to Harremoës *et al.,* (1984), this characterizes the till units as a soft till (<150 kN/m^2) at the top and as a "normal" clay till (>150 kN/m^2) at the bottom.

A5.4 Pedology

Pedological field work

The pedological fieldwork at Faardup was carried out from April 26 to 28 1999. Three soil profiles were excavated and described, two of them in detail (Figure A5.5). Two of these were located beside each of the two groups of suction cups. 24 soil cores were collected to a depth of 120 cm in the buffer zone (Figure A5.5). Inside the test field, 36 samples were collected from the topsoil (0–25 cm).

Profile description

The pedological descriptions of the three profiles are summarized in Table A5.7 to A5.9. The profile horizons are shown in Figure A5.13. The profile laboratory data (grain size, texture, organic matter, nutrients and major cations) are summarized in Table A5.10 and A5.11.

In Table A5.12 the profiles are classified according to both "A Pedological Soil Classification System Based on Danish Soils" (Madsen and Jensen, 1985) and USDA Soil Taxonomy (Soil Survey Staff, 1999).

Table A5.7. Description of profile 1 (Faardrup West).

Soil classification, DK	Degralessive	**Soil classification, USDA**	Haplic Vermudoll
Parent material	Clay till	**Profile depth**	210 cm
UTM	32U UB Easting 648671 Northing 6132852	**Drainage class**	Moderately well drained
Landform	Moraine plain	**Groundwater level**	> 400 cm
Map sheet	1412 I NV	**Vegetation**	None
Elevation	28 m DNN	**Maximum rooting**	110 cm
Topography	Flat	**Authors**	Søren Torp
Slope	1–3°	**Date of description**	26.04.99

Profile description

Ap (0–33 cm)
Clay 5–10%, containing humus, some stones of all sizes, condition and type – lumps of lime, a few small roots, 1–10 wormholes and root channels per dm^2, clear smooth boundary.

BEv (33–60 cm)
Clay content 5–10%, the horizon consists almost solely of humus filled with worm-holes, here between pale eluvial material, some stones of all sizes, condition and type – lumps of lime, thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.

Bvt (60–105 cm)
Clay content 10–15%, still many wormholes filled with humus material, clay skins on aggregate peds, humus poor, some stones of all sizes, condition and type – lumps of lime, a few small roots, clear smooth boundary.

Cc(g) (110–200 cm)
Clay content 15–20% with bands of coarse sand, lots of vertically striped pseudogley (20%) in the upper 70 cm of the horizon, thereafter pseudogley stripes (5%), humus poor, limy (lumps of lime), matrix reacts with 10% hydrochloric acid, a clay-free sand lense is water–bearing.

Remarks	The Bvt horizon: Just beneath the plough layer, the soil contains numerous worm-holes. The wormholes stop at the chalk border.

Table A5.8. Description of profile 2 (3090 Faardrup North).

Soil classification DK	Pseudogleytypilessive	**Soil classification, USDA**	Oxyaquic Hapludoll
Parent material	Clay till	**Profile depth**	180 cm
UTM	32U UB Easting 648678 Northing 6132859	**Drainage class**	Moderately well drained
Landform	Moraine plain	**Groundwater level**	>180 cm
Map sheet	1412 I NV	**Vegetation**	None
Elevation	28 m DNN	**Maximum rooting**	140 cm
Topography	Flat	**Authors**	Søren Torp
Slope	1–2°	**Date of description**	28.04.99

Profile description

Ap (0–31 cm)
Dark brown (10YR 3/2 f) clayey silty sand, containing humus, many stones of all sizes, form, type and degree of weathering, very few fine roots, 1–10 wormholes and root channels per dm^2, moderately coarse subangular structure, weak sticky consistency, clear smooth boundary.

Ap2 (31–43 cm)
Dark greyish brown (10YR 4/2 f) clayey silty sand, containing humus, lots of stones of all sizes, form, type and degree of weathering, a few fine roots, 1–10 wormholes and root channels per dm^2, moderately coarse angular structure, nonsticky consistency, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.

BEv (43–70 cm)
Dark yellowish brown (10YR 4/4 f) with spots of strongly brown (7,5YR 5/6 f) clayey silty sand intermixtured with yellowish brown (10YR 5/4 f) loamy sand, humus poor, many stones of all sizes, form, type and degree of weathering, some fine roots, 1–10 wormholes and root channels per dm^2, moderately coarse subangular structure, weak sticky consistency, mottled moderately thick coating of humus in root channels and on aggregate peds, clear wavy boundary.

Bv (70–140 cm)
Brown (10YR 5/3 f) clayey silty sand with spots of light brownish grey (10YR 6/2 f), humus poor, many stones of all sizes, form, type and degree of weathering, a few small soft rounded nodules of Fe and Mn oxide and hydroxide, a few fine roots, 1–10 wormholes and root channels per dm^2, moderately coarse subangular structure, weak sticky consistency, mottled moderately thick coating of clay minerals and humus in root channels and on aggregate peds, clear irregular boundary.

Cc(g) 140–180 cm)
Yellowish brown (10YR 5/4 f) clay with lots of vertically striped conspicuous big light brownish grey (10YR 6/2 f) spots with diffuse boundary, secondary stain colour yellowish brown (10YR 5/8 f), humus poor, lots of stones of all sizes, form, type and degree of weathering, a few small soft rounded nodules of Fe and Mn oxide and hydroxide, limy mainly as lumps, moderately coarse angular structure, sticky consistency, thin mottled coating of clay minerals on aggregate peds.

Remarks	None

Table A5.9. Description of profile 3 (3089 Faardrup East).

Soil classification, DK	Pseudogleytypilessive	**Soil classification, USDA**	Oxyaquic Argiudoll
Parent material	Clay till	**Profile depth**	200 cm
UTM	32U UB	**Drainage class**	Moderately well drained
Landform	Moraine plain	**Groundwater level**	> 400 cm
Map sheet	1412 I NV	**Vegetation**	None
Elevation	30 m DNN	**Maximum rooting**	110 cm
Topography	Undulating	**Authors**	Søren Torp
Slope	1–3°	**Date of description**	26.04.99

Profile description

Ap (0–33 cm)
Very dark greyish brown (10YR 3/2 f) clay, containing humus, some stones of all sizes, condition and type – lumps of lime, a few small roots, 1–10 wormholes and root channels per dm^2, weak subangular structure, weak sticky consistency, clear smooth boundary.

Bvt (33–70 cm)
Yellowish brown (10YR 5/4 f) clay, humus poor, some stones of all sizes, condition and type – lumps of lime, a few small roots, 1–10 wormholes and root channels per dm^2, moderately coarse angular structure, weak sticky consistency, mottled moderately thick coatings of clay minerals and humus in root channels and on aggregate peds, clear wavy boundary.

Bvt(g) (70–110 cm)
Yellowish brown (10YR 5/4 f) clay, lots of vertical stripes of large clear spots of pale olive (5Y 6/3 f), secondary stain colour light brownish grey (10YR 6/2 f), humus poor, some stones of all sizes, condition and type – lumps of lime, a few small roots, 1–10 wormholes and root channels per dm^2, moderately coarse subangular structure, sticky consistency, mottles moderately thick coatings of clay minerals and humus in root channels and on aggregate peds, clear irregular boundary.

Cc(g) (110–200 cm)
Light yellowish brown (10 YR 6/4 f) sandy heavy clay with bands of coarse sand, lots of vertically striped big clear spots of pale olive (5Y 6/3 f), secondary stain colour yellowish brown (10YR 5/8 f), humus poor, very calcareous, sticky consistency, continuous very little thick coatings of sesquioxides on aggregate peds.

Remarks	The Bv horizon: Just under the plough layer, the soil contains numerous wormholes. C(g) horizon: In the upper 10–15 cm of the horizon there are a few scattered roots. The wormholes stop at the chalk border. The upper 25–30 cm has a moderately thick, horizontal plate structure with aggregates covered with iron oxides.

Table A5.10. Soil texture analysis from the pedological profiles.

Pro. no.	Hor. no.	Horizon	Depth	Soil texture (mm) %							$CaCO_3$ %	OM[1] %
			cm	<0.002	0.002–0.02	0.02–0.63	0.63–0.125	0.125–0.2	0.2–0.5	0.5–2		
2	1	Ap	10–20	14.8	13.2	11.8	21.4	13.4	16.4	6.4	–	2.6
2	2	Ap2	33–42	13.3	11.3	13.0	17.6	15.9	16.1	11.7	–	1
2	3	BEv	48–59	14.5	12.5	10.6	15.4	10.6	12.4	3.6	20.0	0.1
2	4	Bv	90–100	12.6	12.4	13.6	17.6	16.4	15.6	11.4	–	0.4
2	5	Cc(g)	153–163	24.9	16.1	13.0	16.2	12.0	13.2	4.4	–	0.2
3	1	Ap	10–20	15.7	13.3	12.4	21.8	13.4	16.4	4.6		2.4
3	2	Bvt	45–55	23.6	13.4	12.8	16.8	14.0	13.4	5.6		0.4
3	3	Bvt(g)	85–95	17.5	12.5	13.8	19.6	12.4	17.2	6.8		0.2
3	4	Cc(g)	–	12.5	12.0	12.8	13.6	12.8	11.3	3.7	21.0	0.1

1) OM: Organic matter, OM = 1.72 x TOC. Analysed by DIAS.

Table A5.11. Soil chemistry of samples from the pedological profiles.

Pro. no.	Hor. no.	N_{total}	C/N	P_{total}	pH[1]	K	Na	Ca	Mg	Total bases	H^+	CEC	Base sat.	Fe (Ox)	Al (Ox)
		%		mg/kg				cmol/kg					%	mg/kg	
2	1	0.16	9	759	6.39	0.51	0.07	9.91	0.61	11.1	–	10.5	100	2320	700
2	2	0.07	8	424	7.05	0.17	0.11	9.73	0.44	10.5	–	7.6	100	2336	706
2	3	0.03	2	433	7.73	0.1	0.12	19.8	0.42	20.4	–	5.2	100	788	403
2	4	0.05	5	332	6.91	0.11	0.13	5.79	0.4	6.43	–	5.8	100	2500	732
2	5	0.04	3	252	7.06	0.17	0.13	13.4	0.77	14.4	–	11.8	100	1640	1040
3	1	0.16	9	617	6.6	0.58	0.07	10.3	0.72	11.7	–	10.2	100	2324	730
3	2	0.05	5	262	6.91	0.17	0.3	11.9	0.62	13	–	10.8	100	1488	936
3	3	0.03	4	348	7.49	0.12	0.14	11.7	0.51	12.4	–	7.9	100	980	714
3	4	0.02	3	411	7.76	0.1	0.11	19.3	0.4	19.9	–	4.8	100	568	360

1) pH determined in $CaCl_2$ solution. Analysed by DIAS.

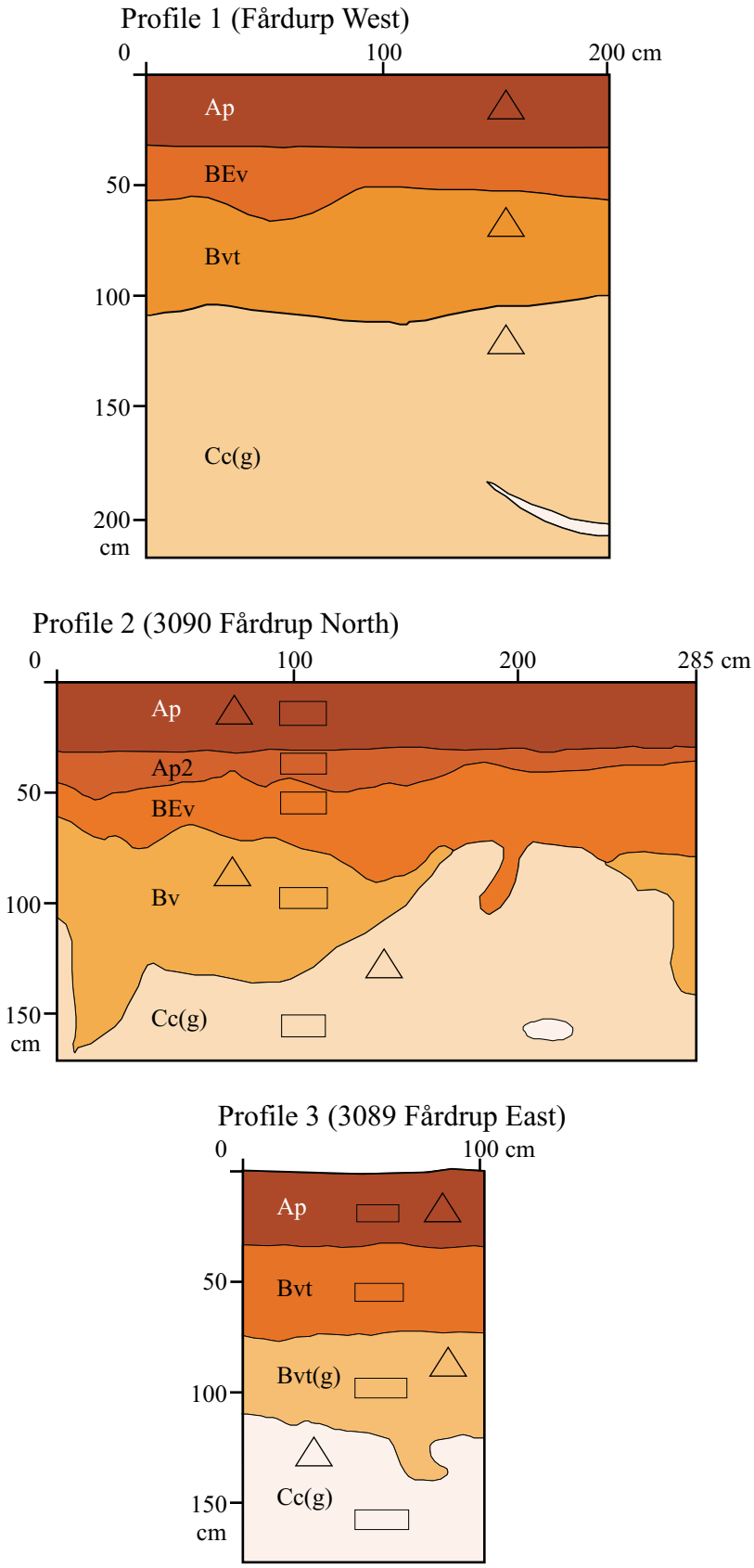


Figure A5.13. Schematic drawings of profiles showing horizon distribution. Rectangular boxes indicate sampling points for soil texture and soil chemistry. Triangular boxes indicate sampling points for hydrological analysis.

Table A5.12. Classification of the profiles.

	Danish Soil Classification	USDA Soil Taxonomy
1 (West)	Has an illuvial Bt horizon, the order is Lessive. The BEv horizon may be described as degraded as it contains eluvial material and thus is **Degralessive**.	The profile has a Mollic epipedon. Because of the numerous wormholes, the BEv horizon is an Agric. The order is Mollisol and the suborder Udolls. Given the numerous wormholes (Agric), the great group is Vermudolls. Because it is a Mollic epipedon, the soil is a **Haplic Vermudoll**.
2 (3090 North)	Because there is an illuvial Bt horizon the order is Lessive. With no further characteristics it is a Typilessive. With pseudogley at a depth of 40–80 cm, the soil is a **Pseudogleytypilessive**.	The profile has a Mollic epipedon. Diagnostic subsurface horizons: The difference in the clay contents is too small to classify the B horizons as Argillic and they are thus Gambic. With a base saturation of 100% until a depth of 125 cm, the soil is a Mollisol. The suborder is Udoll and the great group is Hapludoll. Having periodically saturation, the soil a **Oxyaquic Hapludoll**.
3 (3089East)	Because there is an illuvial Bt horizon the order is Lessive and with no further characteristics a Typilessive. With pseudogley in a depth from 40 to 80 cm, the soils will be **Pseudogleytypilessive**.	The epipedon is Mollic. The subsurface horizon, Bvt, is Argillic with clayskins and a high clay percentage. The order is therefore Mollisols and the suborder Udolls. Because of the Argillic horizon the great group is Argiudolls. The soil is perodically saturated is therefore a **Oxyaquic Argiudoll**.

Total carbon mapping

The total organic carbon content ranges from 1.2 to 1.8% (dry weight), with an average of 1.4% ±0.14%. The concentration is highest in the northwestern part of the test field (Figure A5.14).

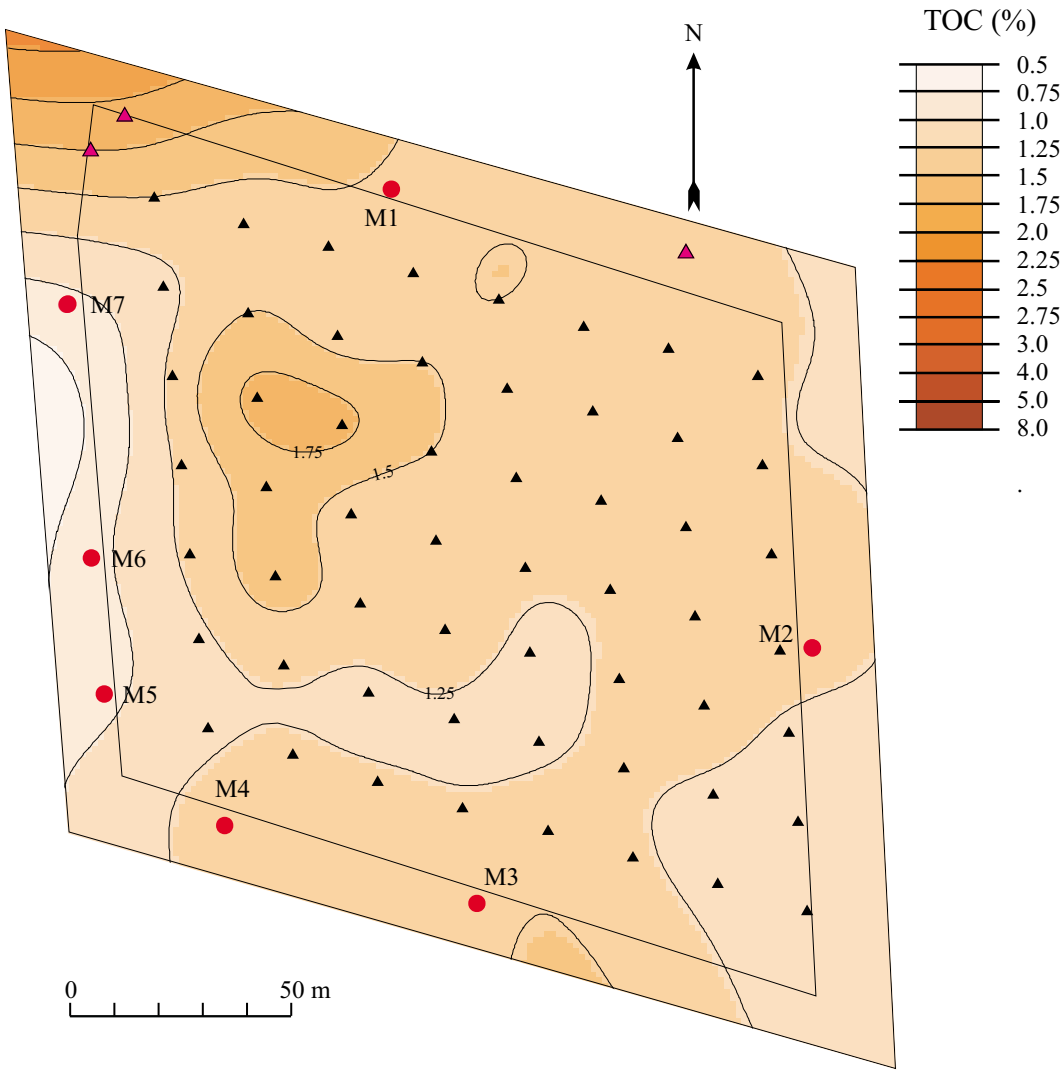


Figure A5.14. Map showing total organic carbon (TOC) content within the test field. Sampling points are indicated by ▲.

Pedological development

The clay content of the plough layer is approx. 15% in all three profiles. The grain size distribution beneath the top soil exhibits considerable spread, with the fine sand fraction being dominant. Compared to the soil cores, the EM-38 measurements indicate that the topsoil varies from sandy areas with approx. 5% clay to areas with approx. 15% clay. At various depths below this there are horizons containing 20–25% clay, e.g. a Bt horizon without chalk or a calcareous C horizon.

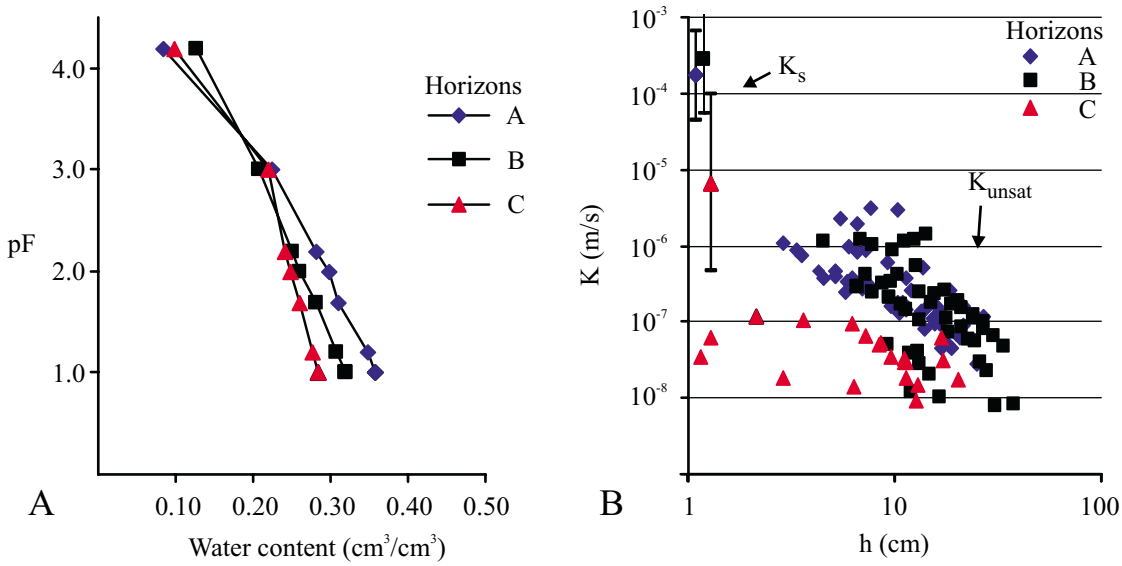


Figure A5.15. A) Retention curve based on values for the soil-water potential determined on the small soil core samples (100 cm^3). The data are the mean values from all three profiles. B) The unsaturated hydraulic conductivity (K_{unsat}) as a function of soil water potential in cm H_2O and the saturated hydraulic conductivity (K_s) determined on the large soil cores (6,280 cm^3).

As mentioned, the $CaCO_3$ has been leached to depths varying from 70–120 cm, and in some places even deeper. The pH is generally around 7 ($CaCl_2$), and a little less in the topsoil. The base saturation is 100%. The C/N ratio indicates good turnover in the soil.

Signs of clay eluviation are present in all of the profiles as thick clay coatings on aggregate surfaces and wormholes. In the texture analysis, this is reflected as an enhanced clay content in the Bt horizon of profile 3, but not in profile 2. The subsurface has a strong and coarse columnar structure. Clear pseudogley stripes are a sign of a temporary water table over the illuvial horizon in moist periods.

Soil hydrology

Soil cores (100 cm^3 and 6,280 cm^3) for the measurement of hydrological properties (soil water characteristics and hydraulic conductivity) were sampled at three levels corresponding to the A, B and C horizons.

The soil water characteristic of the nine small cores (100 cm^3) from each horizon are shown together with bulk density and porosity in Table A5.13 and Figure A5.15.

Table A5.13. Soil water characteristics determined on the small cores. pF = $\log_{10}(-h)$.

Profile	Horizon	Depth cm	Water content at pF values cm^3/cm^3							Bulk density g/cm^3	Porosity[1] cm^3/cm^3
			1.0	1.2	1.7	2.0	2.2	3.0	4.2		
1 (West)	Ap	15	0.37	0.36	0.32	0.30	0.28	0.21	0.08	1.42	0.46
	Bvt	75	0.32	0.31	0.28	0.26	0.25	0.20	0.13	1.60	0.40
	Cc(g)	120	0.27	0.27	0.25	0.23	0.23	0.21	0.10	1.84	0.31
2(3090)	Ap	15	0.32	0.31	0.29	0.28	0.27	0.22	0.09	1.73	0.35
	Bv	80	0.32	0.31	0.29	0.27	0.26	0.22	0.10	1.70	0.36
	Cc(g)	130	0.29	0.28	0.27	0.26	0.25	0.23	0.09	1.78	0.33
3(3089)	Ap	15	0.38	0.37	0.33	0.32	0.30	0.24	0.08	1.52	0.43
	Bvt(g)	80	0.32	0.30	0.27	0.25	0.24	0.20	0.15	1.70	0.36
	Cc(g)	130	0.29	0.28	0.26	0.25	0.24	0.22	0.10	1.83	0.31

1) Assuming a particle density of 2.65 g/cm^3.

The soil water content gradually decreases as a function of pF due to the relatively uniform pore size distribution, which is typical for a clayey/loamy soil. The majority of pores are about 0.6 µm (tube-equivalent diameter) (Figure A5.16). The percentage of pores >12 µm is particularly low in the C horizon.

The saturated and unsaturated hydraulic conductivity determined on the large cores (6,280 cm^3) is shown in Figure A5.15. Unsaturated conductivity was low, especially in the C horizon. The marked difference between near-saturated hydraulic conductivity and saturated hydraulic conductivity indicates a high degree of direct piping (preferential flow) through macropores when the soil is fully saturated.

The measurements of saturated hydraulic conductivity and air permeability made using small (100 cm^3) or large (6,280 cm^3) soil samples differed markedly (Figure A5.17). This difference is probably related to the structure of the soil leading to a high dependence on sample size. With the large soil samples, infiltration takes place through a much larger soil area than is the case with the small soil samples and a greater number of macropores and other soil heterogeneities are therefore included.

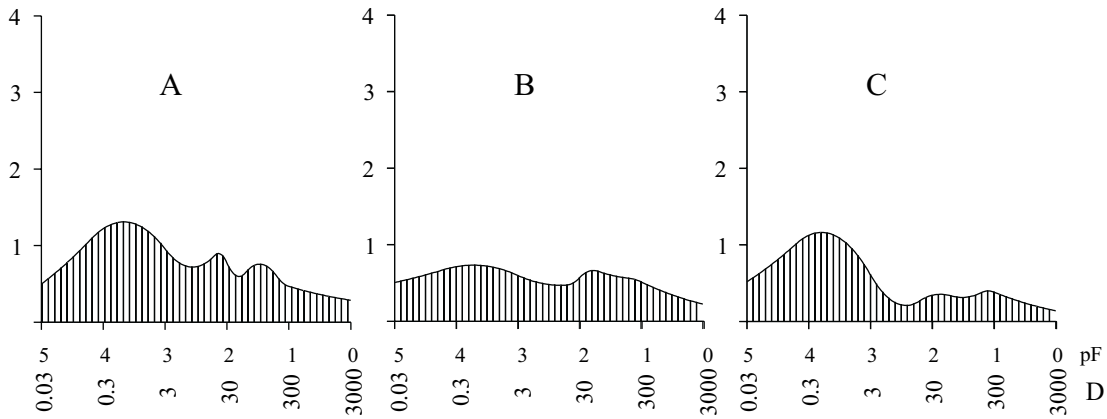


Figure A5.16. Pore size distribution measured (A, B, and C horizon) calculated from water retention data assuming the unity D=3000/10pF (D = pore diameter equivalent diameter, µm). A cubic spline interpolation procedure is used to yield discrete interpolate values on the sum curve obtained from the water retention curves. Abscissa: pF=log10(-h) in which h is the soil water potential in cm H_20. D = pore diameter, µm. Ordinate: percentage of pore volume per 1/10 pF-values, % v/v.

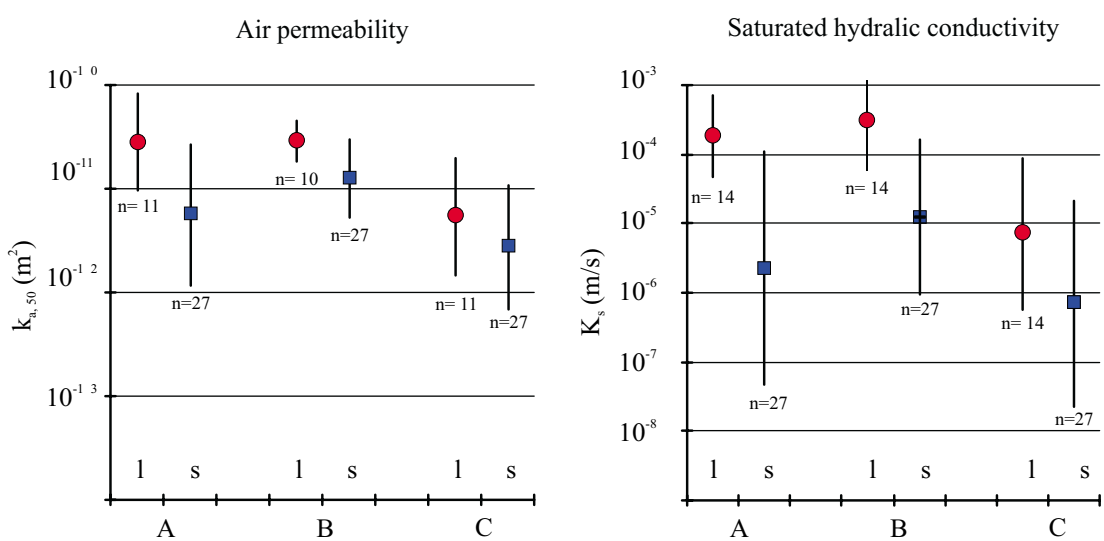


Figure A5.17. Air permeability at a water content of –50 cm H_20 ($k_{a,50}$) and saturated hydraulic conductivity (K_s) measured on large (6,280 cm^3) samples (●) and small (100 cm^3) samples (■).

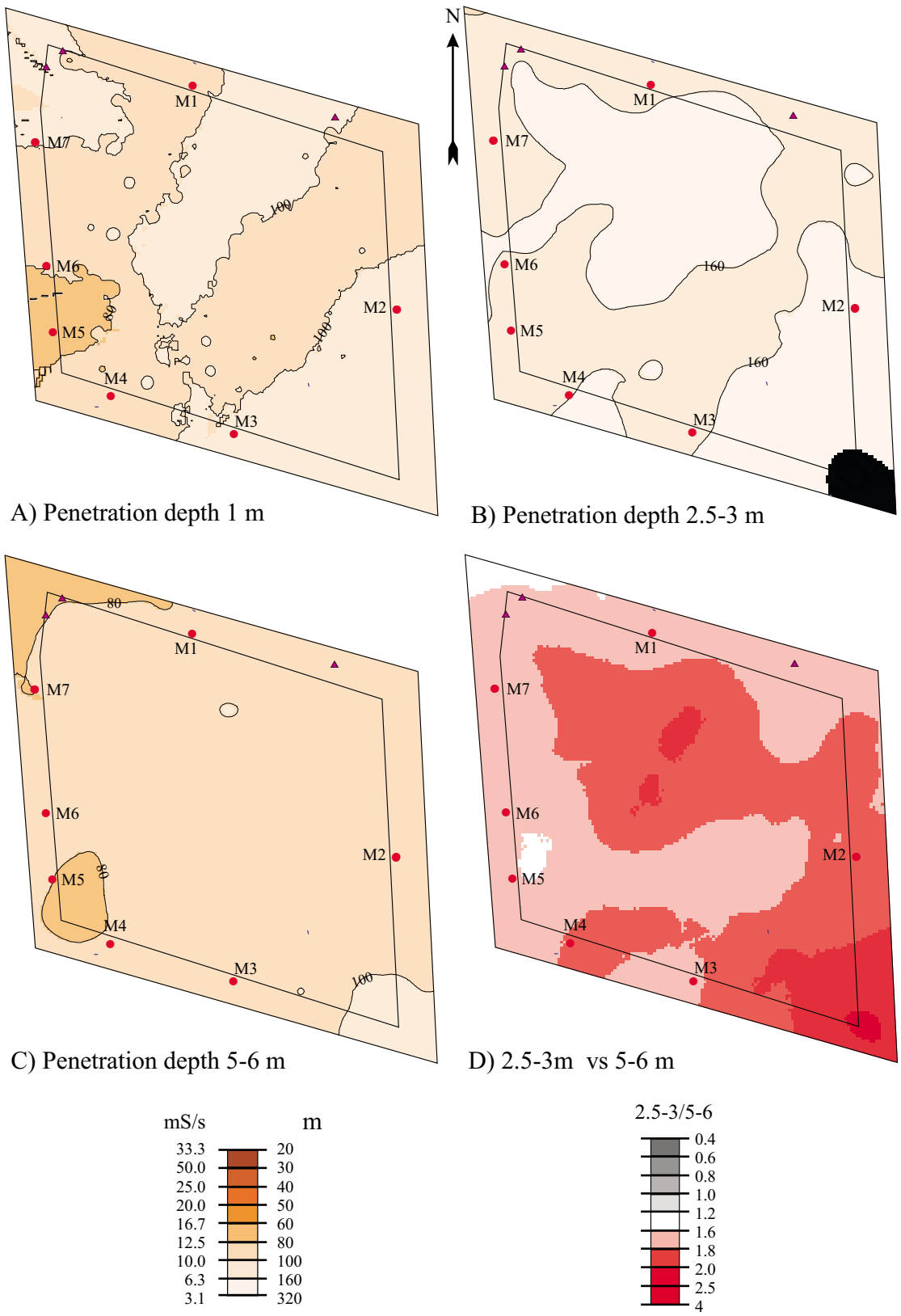


Figure A5.18. Resistivity maps of the area. Map D shows the relative difference between map B and C and provides an idea about the homogeneity of the electrical properties to a depth of approx. 6 m b.g.s.

A5.5 Geophysical mapping

Since destructive mapping methods are not accepted in the test field, it was decided to use EM-38, CM-031 and ground-penetrating radar. The EM-38 measurements were made in spring 1999.

EM-38

The EM-38 map (Figure A5.18A) indicates that the area is rather homogenous and that the resistivity of the upper meter is 60–160 Ωm. Two larger areas of elevated resistivity stand out – the southeastern corner of the test field and an area stretching from just east of well M1 south-southwest towards the southwestern corner. In these areas, the upper meter is interpreted as havning a higher sand content.

CM-031

The CM-031 maps are shown in Figures A5.18B, C and D. The resistivity is high for clay till, but most of the area lies within the range for clay till and sand till (Skov- og Naturstyrelsen, 1987). In some areas, for example the southeastern corner, resistivity exceeds that for sand till, but the pedological, GPR and well data reveal shallow glacio-fluvial sediments that correlate with the resistivity data.

The resistivity ranges from 60 to >320 Ωm. It must be emphasized, though, that the values are relative. The maps show that the area is homogenous with a layer of high resistivity overlying a layer of relatively low resistivity, and that the resistivity decreases as the depth increases (Figure A5.18D).

Ground-penetrating radar (GPR)

In order to map the geological variability of the site, GPR mapping was carried out on 16 April 1999. Cross sections were laid out as shown in Figure A5.19. In areas where the penetration was higher than average, the distance between the cross sections was decreased in order to obtain better resolution. In most of the area mapped, penetration of the radar was poor (less than 1.5 m), as is apparent from the profiles. Based on the well logs and test pit excavation data, the areas with poor penetration are interpreted as areas with a clay till just below the topsoil. According to the penetration map (Figure A5.19), enhanced penetration of up to 2.5 meters is seen in two areas at the site indicating a higher content of coarse-grained material. These areas coincide well with the geoelectrical data. The coarse-grained material is either a more sandy till, or the presence of shallow glaciofluvial clastic sediments. One of the areas stretches in a northeasterly direction from the oval topographic depression (Figure A.5.5), widening from approx. 25 m at its southwestern end to approx. 80 m at the northern edge of the test field. This struc-

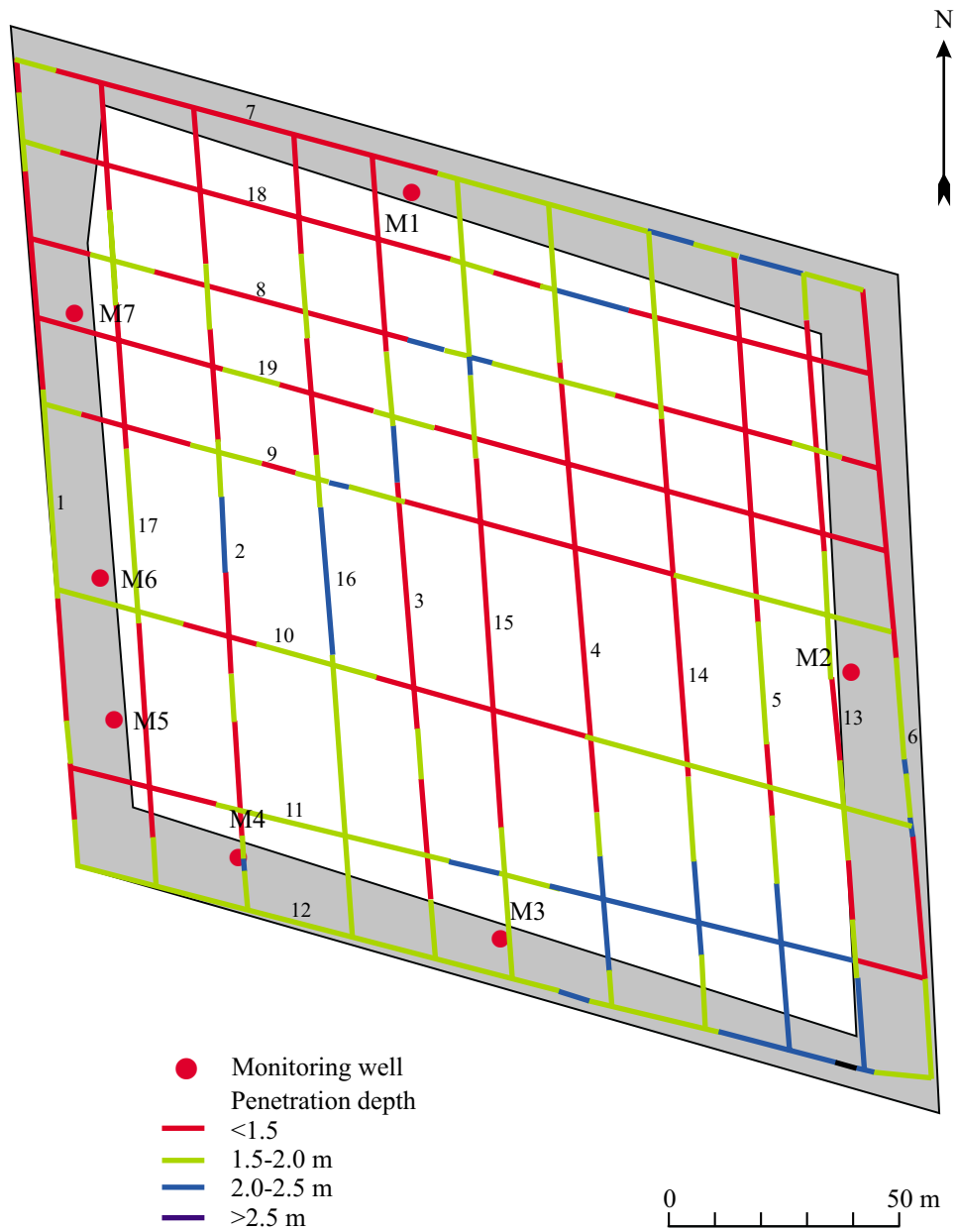


Figure A5.19. Ground penetrating radar profile.

ture could be a channel filled with glaciofluvial sediments draining into the depression.

Another area with increased penetration is located in the southeastern corner and along the southern border of the test field coinciding with distinct bedding and disorderly reflection patterns. Experience from other sites indicates that penetration of up to 8 m can be obtained in glaciofluvial sand and gravel (Annexe 4). There is no reason to believe that the sand bodies mapped at Faardrup reach any deeper than 2–3 m.

Appendix A5.1. Cultivation and pesticide application history at Faardup.

Year	Crop	Date	Pesticide brand	Dose per ha
1995	Winter wheat	01.05.95	DLG-Flux	1.75 l
		20.05.95	Tilt Top	0.3 l
		10.06.95	Tilt Top	0.3 l
1996	Sugar beet	20.04.96	Goltix	1.0 l
		20.04.96	Betanal	1.0 l
		30.04.96	Goltix	1.0 l
		30.04.96	Kemifam	1.0 l
		07.05.96	Betasana Flow	1.5 l
		07.05.96	Ethosan	0.2 l
		20.05.96	Betanal Progress	1.5 l
		20.05.96	Matrigon	0.4 l
1997	Spring barley	20.05.97	Ariane Super	0.75 l
		20.05.97	Manganese sulphate	2.5 kg
		07.06.96	Tilt Top	0.3 l
		07.06.96	Manganese sulphate	2.5 kg
		25.06.97	Tilt Top	0.3 l
		25.06.97	Pirimor G	0.15 kg
1998	Winter wheat	01.05.98	Ariane Super	1.5 l
		01.05.98	Tilt Top	0.25 l
		01.05.98	Manganese sulphate	2.5 kg
		01.06.98	Tilt Top	0.25 l
		20.06.98	Amistar	0.3 l
		20.06.98	Tilt Top	0.3 l
		11.08.99	Roundup 2000	2.0 l.

Site Characterization and Monitoring Design

Annexe 6.

Site 6: Slaeggerup

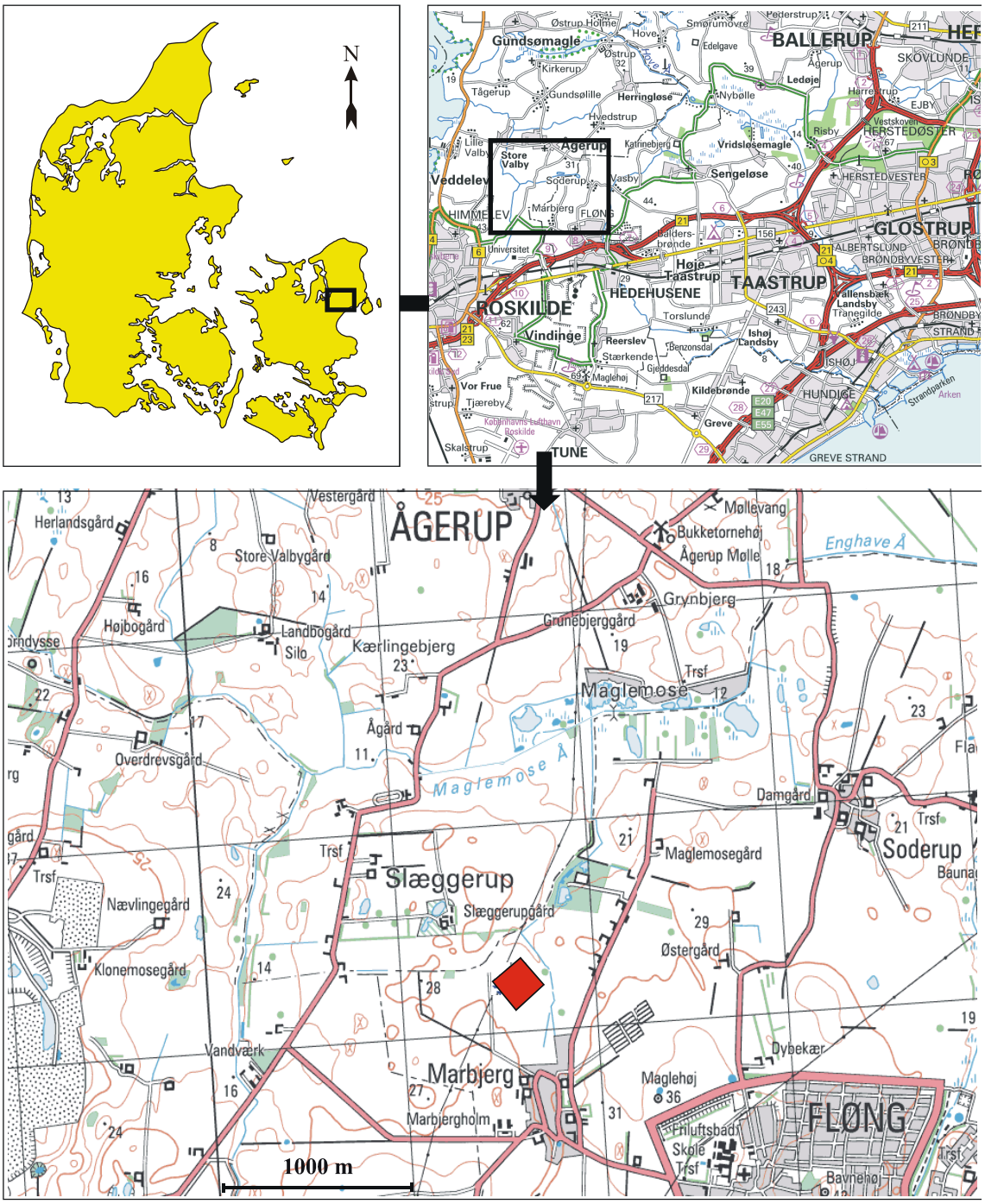


Figure A6.1. Location of the test field.

A6.1 Location, ownership and earlier cultivation and use

The test field is located on Zealand near the village of Slaeggerup NE of the city of Roskilde (Figure A6.1).). It is leased by the Danish Institute of Agricultural Sciences (DIAS). Site characteristics are given in Table A6.1.

Table A6.1. Site characteristics.

Length and width of the test field	156–178 m x 130 m
Total area of the site, incl. buffer zone	3.8 ha
Area of the test field	2.17 ha
Municipality	Gundsø
County	Roskilde
Land registry no.	5e, Marbjerg By, Fløng Sogn
Ownership	Private, leased by DIAS

Earlier use

The area has been used as farmland for at least the past 50 years (Figure A6.2). Cultivation and pesticide application history of the field during the five years prior to the present investigations are summarized in Appendix A6.1.

A6.2 Technical installations

All installations at Slaeggerup are numbered according to the code described in Section 3. In the present description, however, the site-specific code for Slaeggerup, i.e. “6”, has been omitted for the sake of simplicity. The location of all installations were selected on the basis of the drainage system and the groundwater flow pattern (Figures A6.3) and and are shown in Figure A6.4.

Buffer zone

The width of the buffer zone at Slaeggerup is >12 m along the northwestern and northeastern borders and >10 m along the southwestern and southeastern borders.

Suction cups, TDR and Pt-100 sensors

The suction cups, TDR and Pt-100 sensors at Slaeggerup were all installed as described in Section 3.3 except suction cup (1.5) intended to be placed at 2.0 m b.g.s. was installed approx. 1.7 m b.g.s. because it was not possible to penetrate a gravel layer occurring in this level. The suction cups installed 2 m b.g.s. are located in clay till whereas those installed 1 m b.g.s are in glaciofluvial sand, locally containing thin lenses of clay.

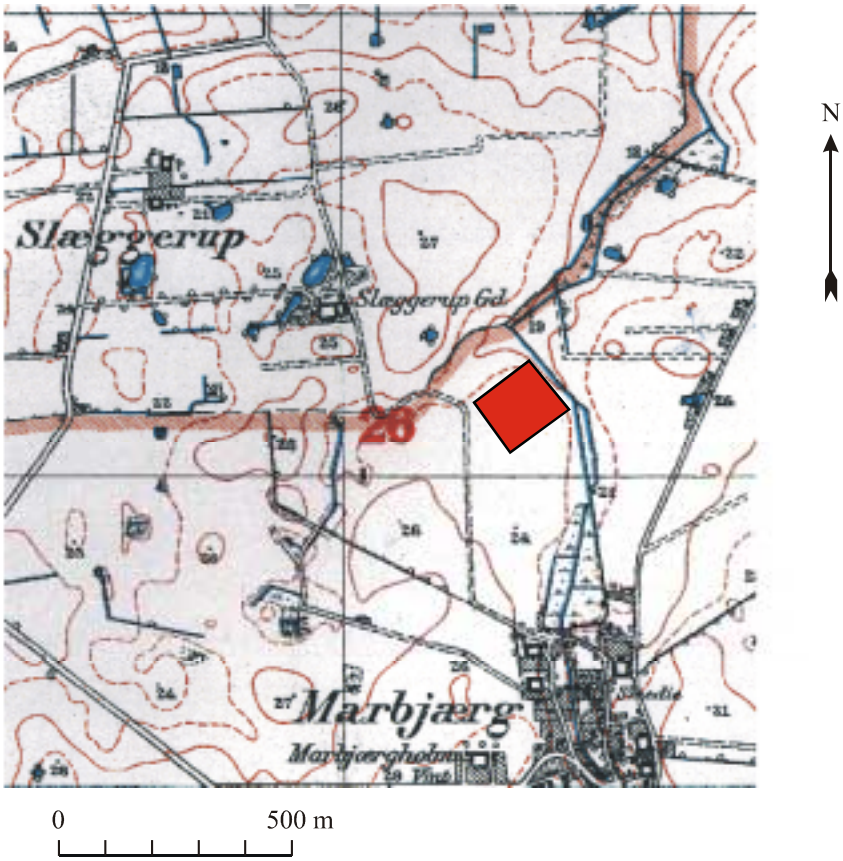


Figure A6.2. Topographic map 1:20.000 from 1939. The test field is marked as a red square.

Wells

Horizontal monitoring wells

Two horizontal monitoring wells each containing three 18 m screen sections separated by 1.0 m bentonite seals were installed on October 18–21 2000. Well H1 that intersects the northern corner of the field was installed as described in Section 3.1.3.

During the process of drilling well H2, upward transport of drillwater was recorded in two places – one located 32 m from the drill rig and 5 m east of the well trajectory and the other located 48 m from the drill rig and 9 m east of the well trajectory. When the PVC liner was drawn out of the well, a far larger force than usual was needed, thus indicating the presence of a gravel/boulder bed with hydraulic contact to the surface in the well path.

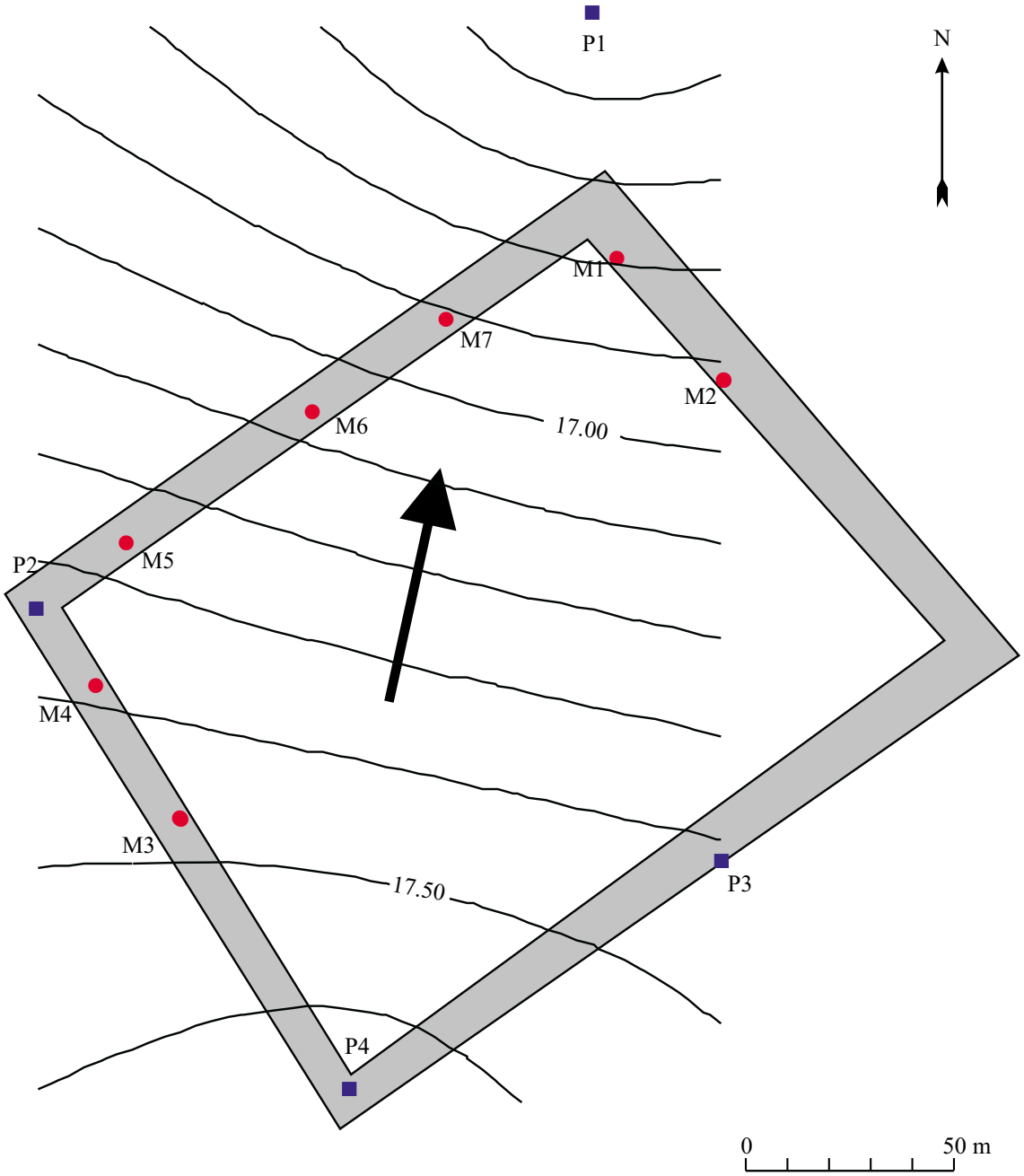


Figure A6.3. Potential head at the site measured in April 2000 and the direction of the ground water flow.

Piezometers

All wells at Slaeggerup were drilled as cased wells with a 6" (152 mm) solid stem auger. Four piezometers were drilled first in order to enable the direction of groundwater flow to be determined. P1 and P3 were drilled in July 1999 while P2 and P4 were drilled in October 1999. The depths of the piezometer screens are summarized in Table A6.2.

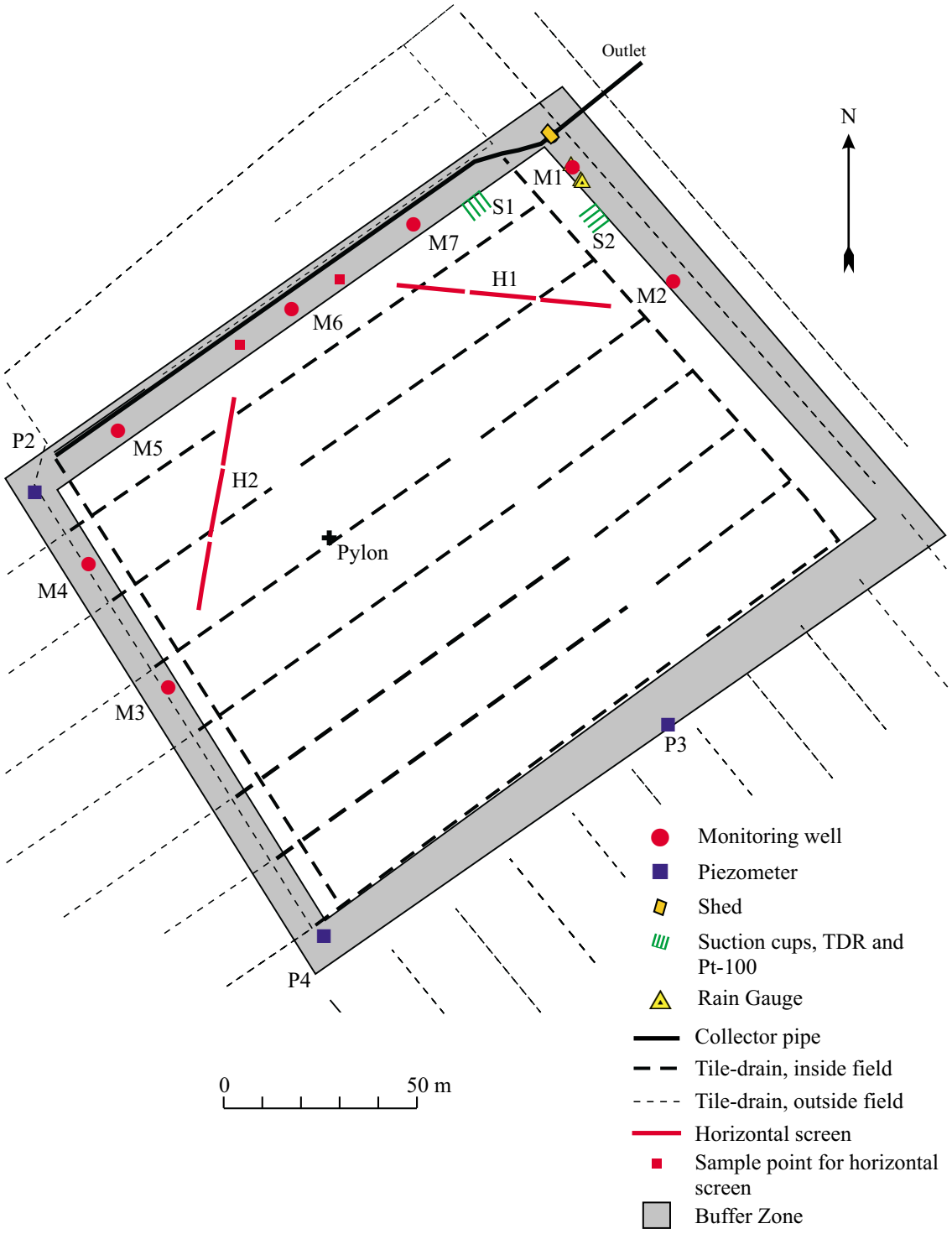


Figure A6.4. Sketch of the field showing the test and buffer zones and location of installations.

Table A6.2. Depth of the piezometer screens.

Well no.	DGU no.	Upper screen m b.g.s	Upper Middle screen m b.g.s	Lower Middle screen m b.g.s	Lower screen m b.g.s
P1	199.1168	5.1–5.6	7.8–8.3	Not installed	11.0–12.0
P2	199.1169	2.0–2.5	3.8–4.3	6.7–7.2	10.6–11.8
P3	199.1170	2.5–3.0	5.5–6.0	9.2–9.7	12.5–13.5
P4	199.1171	6.5–7.0	8.8–9.3	Not installed	11.8–12.8

Monitoring wells

A total of seven monitoring well clusters (M1–M7) each consisting of four individual wells were installed at Slaeggerup on October 6–13 1999. The technical specifications are described in Section 3.

The monitoring well screens of all seven clusters are located at the following depths:

Mx.1: 1.7–2.7 m b.g.s.
Mx.2: 2.7–3.7 m b.g.s.
Mx.3: 3.7–4.7 m b.g.s.
Mx.4: 4.7–5.7 m b.g.s.

Drainage system

The drainage system was planned by the Agricultural Extension Service in Roskilde. The exact year is unknown, but the system is shown on a 1963 map of several other drainage systems. The systems all exit to a ditch running 30–40 m from the eastern boundary of the test field. The drainpipes used are traditional clayware. The laterals are 5.5 cm i.d. while the main drains are 8 cm and 10 cm i.d.

The field is systematically drained. The spacing between the laterals is 20 m. Since the field has a hilltop in the middle, the field drains are connected to the main drains on either side of the hill. A preliminary investigation revealed that the western of the two main drains was located somewhat differently than indicated on the map. Apart from that, the drains were in good condition and located as indicated on the map.

New collector pipes and measuring chamber

The Ø 125 cm measuring chamber with a 30° Thompson notch was placed in the northern corner of the test field. The outlet runs to the ditch via a 36 m long Ø 160 mm o.d. PVC pipe.

On the upstream side a new PE tube, welded in situ, connects the two main drains to the measuring chamber. The pipe runs along the northwestern border of the test field. The stretch upstream from the measuring chamber to the first of the two main drains consists of a 13 m long Ø 160 mm pipe while the stretch from there to the second main drain consists of a 145 m long Ø 110 mm pipe. The slope of the long stretch is 5‰, with greater slope at each end.

Cut-off drains

The main pipe on the southwestern side of the hill has side drains attached from both sides. Eight drains approaching from the west were cut off along the western border of the test field by a new main drain placed 8 m away from and parallel to the old main. A standard corrugated and perforated tube covered with filter cloth was used. The remains of the eight pipes, attached to the old main pipe, were plugged at their distal ends.

Dimensions of the outlet

The outlet from the measuring chamber has sufficient capacity to carry the drainage water from the approx. 2.4 ha of the test field. The risk thus exists that water could pond in the measuring chamber under conditions of high water level in the ditch as the crest of the notch is just 50 cm above the bottom of the ditch. Although no information is available concerning peak water level in the ditch, it appears to be regularly maintained and such conditions should not arise.

The work was carried out during October 1999.

A6.3 Geology

Regional geology

The test field is situated in a weakly to moderately undulating moraine landscape intersected by small valleys with local pitting due to dead ice formation. The ground surface is generally 20–30 m a.s.l., but hills may reach heights of about 40 m a.s.l. The hills commonly have a NNE-SSW orientation (Jacobsen, 1984). The Quaternary deposits are 10–40 m thick. In the eastern part of the area they rest on Danian limestone. Towards the west they rest on Selandian marl, clay, sand and limestone with a characteristic green colour due to the presence of glauconite. The lithostratigraphic difference in the pre-Quaternary surface is due to differentiated subsidence along a mainly N-S orientated fault occurring east of Roskilde (Jacobsen, 1984). A schematic regional profile made by Jacobsen (1984) based on information from water wells and observations from gravel

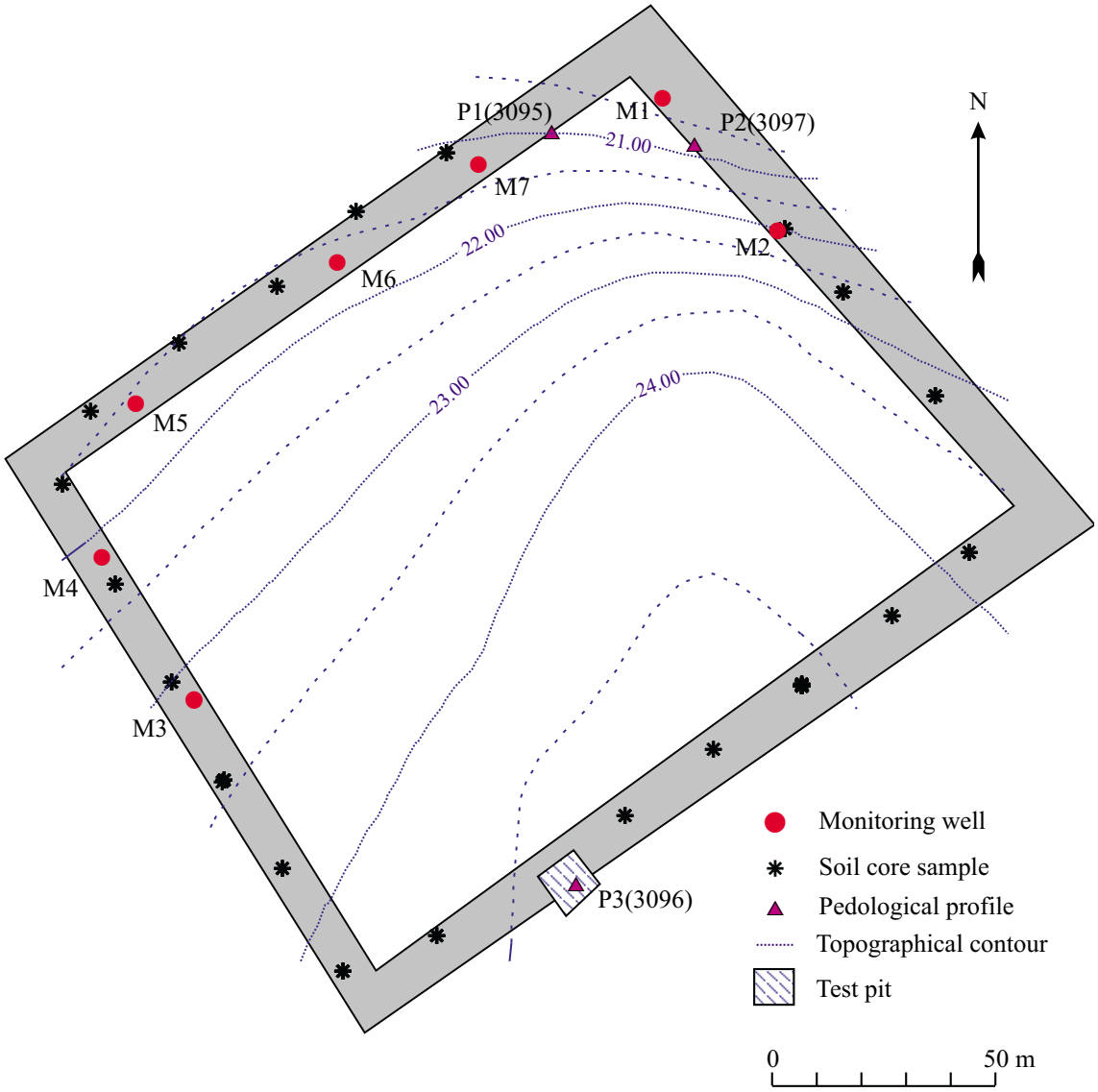


Figure A6.5. Topography at the site and location of soil cores, test pit and monitoring wells.

pits describes the regional geology. The oldest Quaternary deposits consist of thin meltwater deposits and clay till formed during the Saalian time or earlier. These are overlain by the Himmelev Formation, a up to 17 m thick layer consisting of alternating beds of meltwater sand and gravel interpreted as formed in connection with the Norwegian ice advance in Weichselian time. This in turn is overlain by the Hedeland Formation, a 6–25 m thick layer consisting of a lower and upper part of alternating beds of meltwater sand and gravel separated by clay till. The two formations comprise a source of raw materials and are extensively commercially mined. This formation is also interpreted as having been formed in connection with the Norwegian ice advance. Above the Hedeland Formation, there are deposits from two Young Baltic ice advances and their deglacia-

tion. During each of the ice advances a thin clay till was deposited, followed by a period of deglaciation and dead ice formation where fine-grained sand, silt, clay and occasionally gravel was deposited in ice lakes. The geology of the abstraction wells nearest to the site (DGU no. 199.14; 778; 82; 83 and 85) reveals approx. 15–20 m of Quaternary clay till resting on Danian limestone.

Geomorphology

The test field is located on a moraine surface limited by the Maglemose Å river system towards west, north and east. Within the test field the ground surface slopes slightly towards NE, the difference in altitude between the lowest and highest levels being about 4.5 m (Figure A6.5).

The test field is shown superimposed on the map of Quaternary sediments in Denmark (Hermansen and Jacobsen, 1998), the Soil Classification map and a 1999 aerial orthophotograph in Figure A6.6. As is apparent, the field is located on a loamy soil (JB7). This is in good agreement with the fact that the map of the Quaternary sediments in Denmark places the field in an area of clay till. The freshwater sediments marked on the map of Quaternary sediments are not present in the test field, and are an inaccuracy on the map. Based on the orthophotograph, the field appears homogenous.

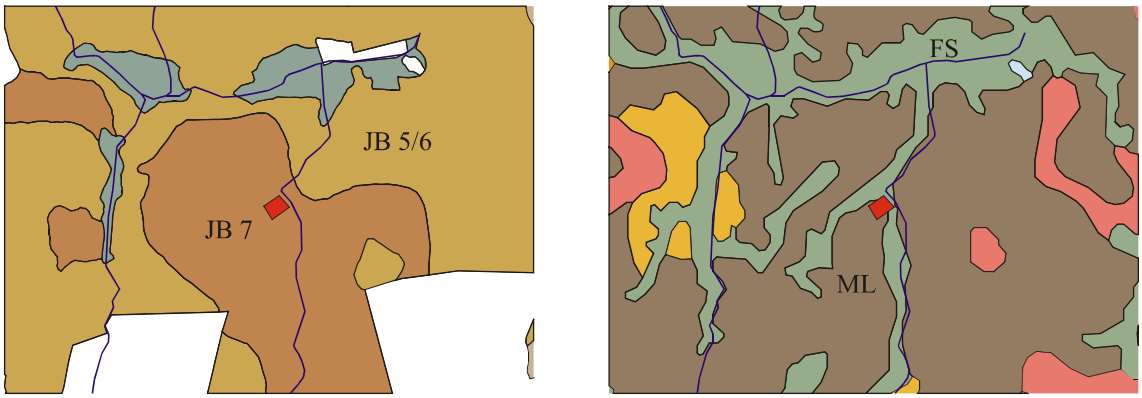
Geology of the monitoring wells and piezometer wells

The geological layers were described during the drilling of piezometers P1–P4 and monitoring wells M1–M7. The location of the wells is indicated in Figure A6.4. The penetrated sediments are subdivided into three informal lithological units described below. The units are shown on cross sections based on wells in the test field in Figures A6.7 and A6.8.

Upper unit (0–2.5 m b.g.s.)

The unit is up to 2.5 m thick and reaches the ground surface in all the wells except P3. It develops upwards from gravely meltwater sand or sandy meltwater gravel in the lower part to meltwater clay in the upper part. In a few wells it consists of meltwater clay alone (P4 in Figure A6.7) or meltwater sand (M1 and M2 in Figure A6.8).

The basal meltwater sand and gravel is up to 1.8 m thick and erosively overlies the deposits of the middle unit. Locally it is bedded and contains thin clay lenses. The colour is light yellow brown or yellow brown indicating oxic conditions.



A B

C

Figure A6.6. Location of the test field (red square) superimposed on: A) The soil type map. JB 5/6: Sandy loam soil, JB 7: Loamy soil. B) Map of Quaternary sediments in Denmark, ML: Clay till, FS: Postglacial freshwater sand. C) An aerial orthophotograph, (Kampsax Geoplan, DDO1999).

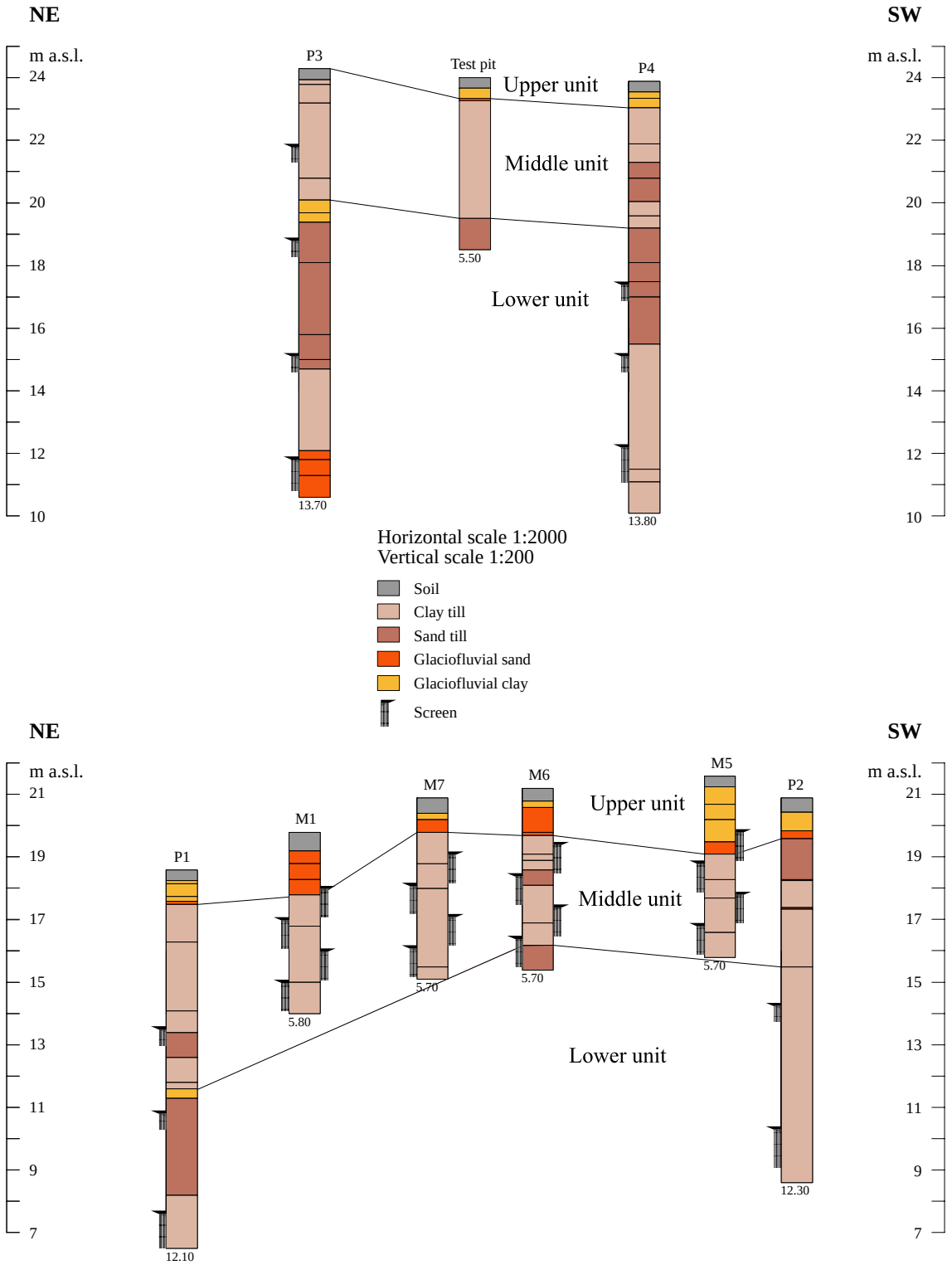


Figure A6.7. NE-SW cross sections based on wells at the site. The location of the wells is shown in Figure A6.4.

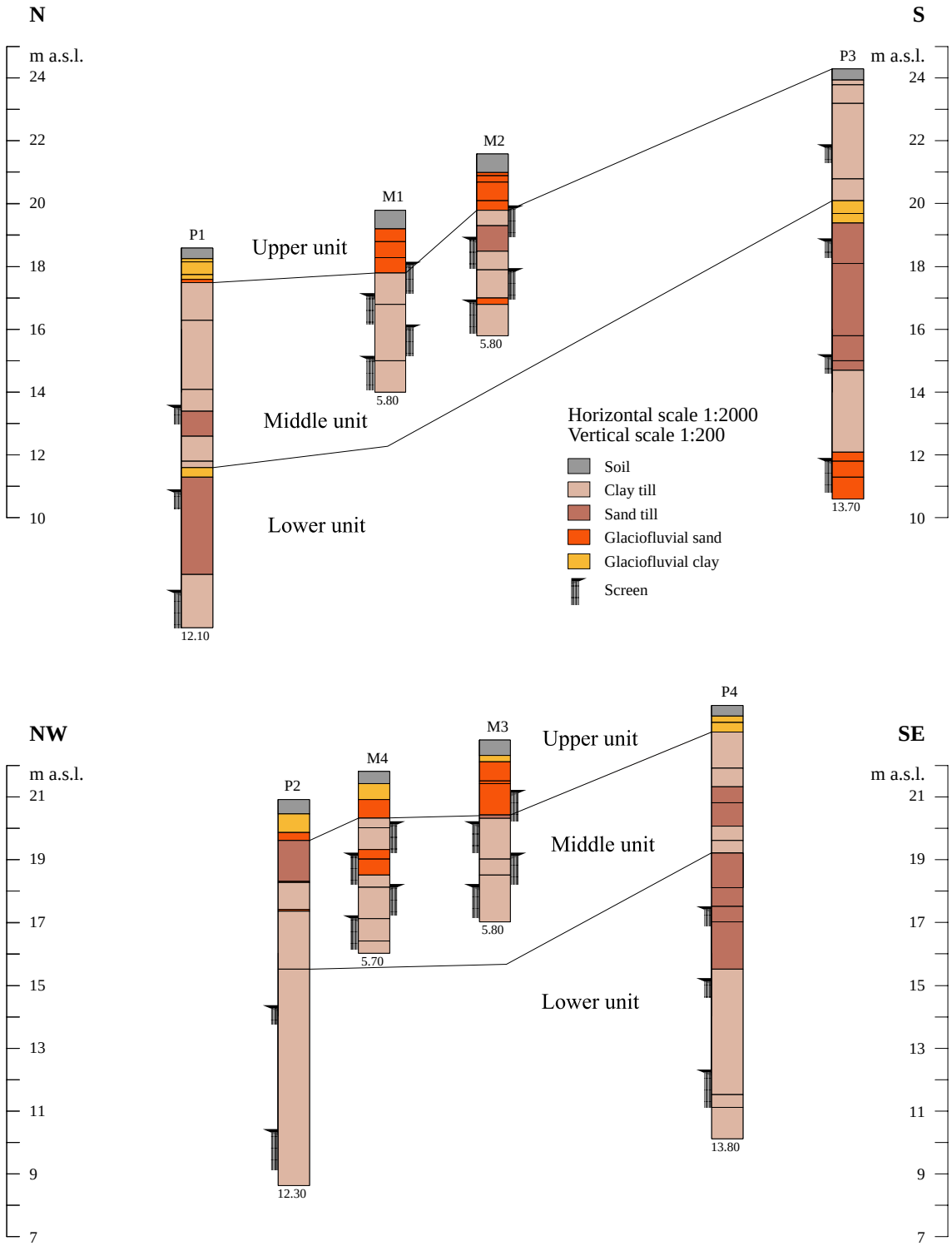


Figure A6.8. Cross sections based on wells along the eastern and western ends of the test field. The location of the wells is shown in Figure A6.4.

The overlying meltwater clay is up to 1.8 m thick. Sand laminae may occur in the lower part of the clay, giving a gradual transition from the underlying meltwater sand. The clay is commonly laminated and becoming increasingly finer towards the surface as evidenced by the fact that it is sandy and strongly silty in its lower part, but weakly sandy and silty in its upper part. Generally the colour of the clay changes upwards from grey below 1.5 m b.g.s. to light olive grey from about 1.5–1 m b.g.s. From about 1–0.5 m b.g.s. it is mainly light grey, light olive or light olive brown. Below the topsoil layer, the colour is commonly yellow brown indicating that oxic conditions only occur within the clay down to approx. 0.5 m b.g.s.

The depth to which calciumcarbonate has been dissolved within the upper unit generally ranges from 0.45 to 0.9 m b.g.s., although a maximum depth of 1.5 m was recorded in well M1, where the unit consists entirely of meltwater sand.

Middle unit (0–7 m b.g.s.)

This unit is 3.5–6 m thick and its upper boundary occurs 0–2.7 m b.g.s. It consists of clay till, locally with lenses of sand till and meltwater sand, up to 1.3 m thick. The clay till only reaches the ground surface in P3, where it is developed as a dark grey brown topsoil layer, approx. 0.35 m thick. The clay till is generally silty, sandy and gravely with scattered stones. The lower part may be strongly sandy and gravely, however. Thin sand lenses occur in places. The clay till is calcareous except in P3, where it occurs close to the ground surface and is noncalcareous down to 0.5 m b.g.s.

The colour of the till depends on the distance below the ground surface and the topography. Below 3 m b.g.s. it is light olive grey or grey. Between 3 and 1.5 m b.g.s. it is light brown grey or olive grey and between 1 and 1.5 m b.g.s. it is light grey brown or light yellow brown. Below the topsoil layer, the colour is grey brown. The overall colour change reflects a downwards change from oxidized conditions close to the ground surface to reduced conditions in the deeper parts. In piezometers P3 and P4, however, which are situated on the topographically highest level within the test field, the downwards colour changes of the clay till show that oxidizing conditions are present to deeper levels than in the other wells (down to 4.7 m b.g.s.). Moreover, where thick lenses of sand till and meltwater sand occur in the reduced zone of the clay till, these have a light yellow brown or yellow brown colour indicating local areas of oxidized conditions.

Lower unit (5–13.7 m b.g.s.)

The unit is at least 8.5 m thick with the upper boundary located about 5 m b.g.s. It consists of clay till overlain by sand till locally topped by meltwater clay. Well P3 was

stopped by stones 13.7 m b.g.s. This could reflect either the top of the Danian limestone or the top of the meltwater deposits of the Hedeland Formation.

The clay till which forms the lowest part of the middle unit is strongly sandy, silty and gravely, in places with thin sand laminae. The clay till has a grey or olive grey colour, indicating reduced conditions.

The sand till consists mainly of fine-grained sand. The lower part of the till is clayey or strongly clayey, silty and weakly gravely, while the upper part is weakly clayey and weakly gravely, locally containing stones and clay lenses. The sand till is calcareous with a grey colouration indicating reduced conditions. The boundary between the clay and sand tills is gradual, making it difficult to distinguish the tills around the boundary. The only deep drill hole in which the sand till has not been found is P2. This is probably because the sand till lateral to this place has changed into the clay till (Figure A6.7 and A6.8).

The meltwater clay forming the upper part of the lower unit is 0.3–0.7 m thick. It only occurs in the wells P1 and P3 (Figure A6.7). The clay is weakly sandy and weakly silty or silty. It has a grey colouration indicating reduced conditions.

Geology of the test pit and drainage ditch excavations

A test pit was excavated to 5.3 m b.g.s. using a back hoe in the buffer zone of the southern part of the test field for lithological description, fracture description and characterization, fabric analysis and field vane tests. Samples were taken for grain size analysis, $CaCO_3$ and total organic carbon content (TOC), clay mineral analysis, exotic stone counts and porosity/permeability analysis.

Lithological description

The depths in the following descriptions (Table A6.3) are average depths from the test pit, and correspond to the log in Figures A6.9–A6.11. A lithological description following Larsen *et al*. (1998) is given in Table A6.3. The sediments in the test pit can be grouped into three units corresponding to the geological units described in the well data. The units are described briefly below:

Upper unit (0–1.8 m b.g.s.)

The unit is 0.75–1.8 m thick and coarsens towards the surface from gravely sand with scattered stones overlying the lower boundary followed by alternating beds of sand, silt

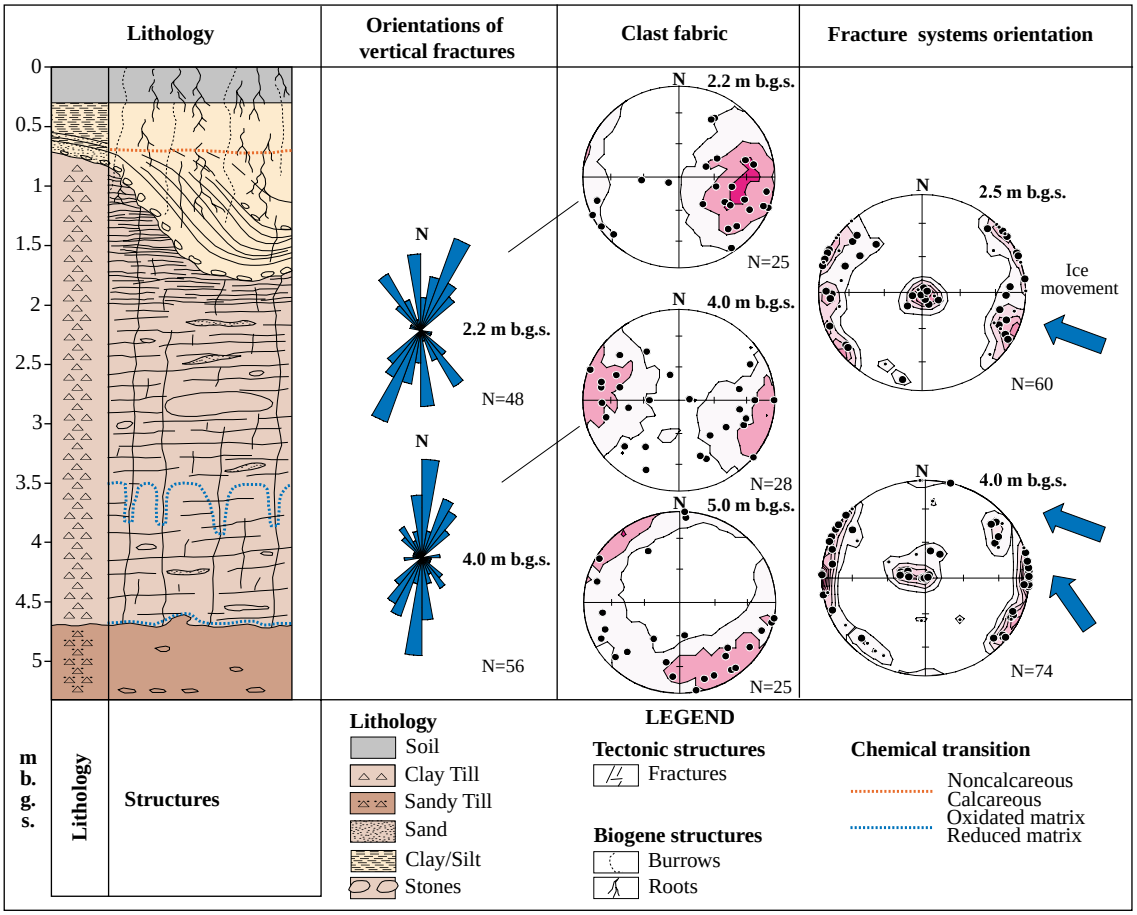


Figure A6.9. Lithology, fracture orientation, clast fabric data and interpreted ice movement direction.

and clay and finally clay in the upper part. The lower boundary is erosional and generally occurs around 0.75 m b.g.s. In the SW corner of the excavation, however, it cuts down to a level of 1.8 m b.g.s. Here the unit seems to form a channel fill deposit with a NE-SW orientation. Macropores made by roots and burrowing organisms occur down to 1.3 m b.g.s. The generally yellow brown and light yellow colours of the unit indicate oxic conditions. Below 0.65 m b.g.s., however, reduced conditions occur locally as evidenced by the grey colour of some of the clay beds.

Middle unit (0.6–4.7 m b.g.s.)

The unit consists of a clay till, up to 4 m thick, which is sandy to strongly sandy, weakly silty and gravely. The boundary to the underlying sand till of the lower unit is a sharp undulating surface. Stones and a few boulders up to 80 cm in size occur scattered in the clay till. Slightly deformed silt and sand lenses up to 2 m long are common from

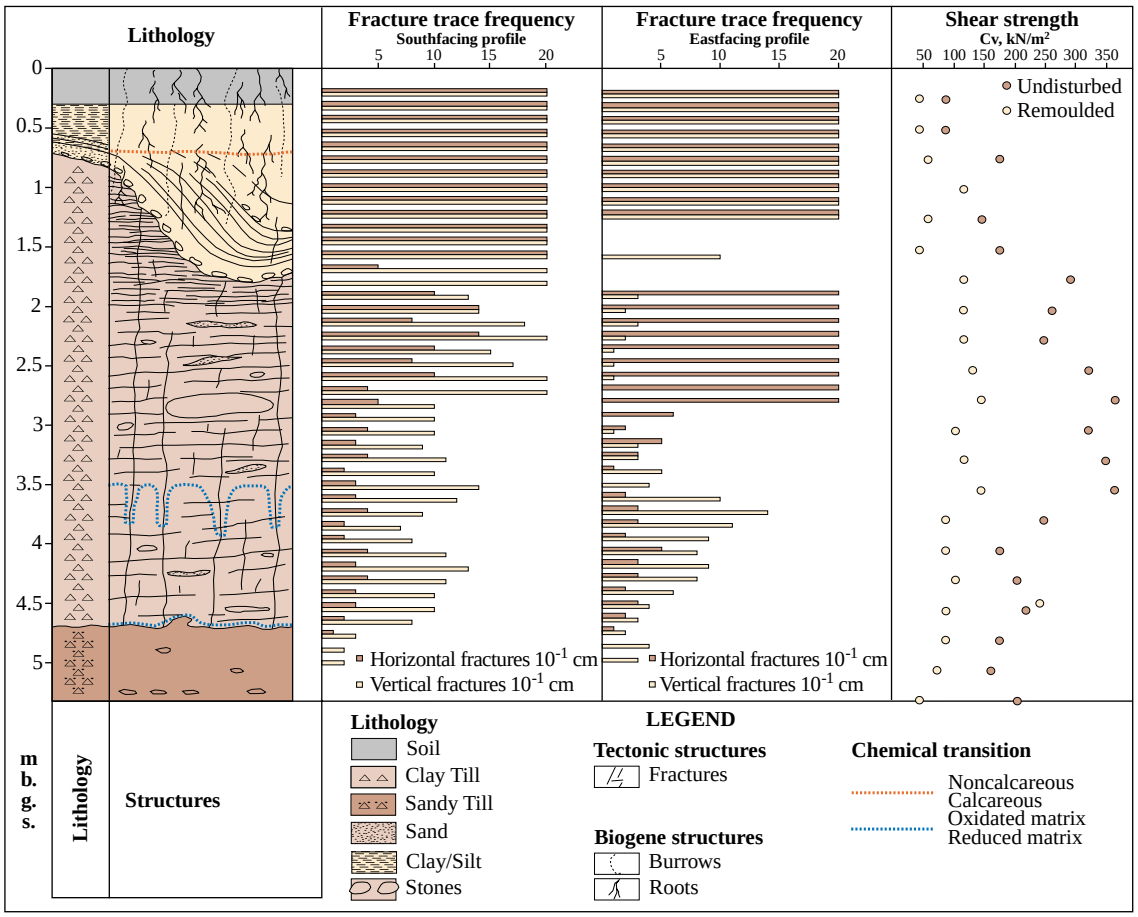


Figure A6.10. Lithology, fracture trace frequency and shear strength in the test pit.

2 m b.g.s. down to the lower boundary, approx. 4.7 m b.g.s. The clay till has a light yellow brown colour down to around 3.5 m b.g.s. where it gradually changes into a light brown grey colour. In the vicinity of major vertical fractures the light yellow brown colour commonly extends deeper, however, down to about 3.8 m b.g.s. The colour changes mark a downward change in the chemical environment from oxidized to reduced conditions.

Lower unit (4.7–5.3 m b.g.s.)

Only the uppermost 0.6 m of the lower unit is exposed in the excavation. It consists of sand till equivalent to that in the upper unit in most of the wells. The till is dominated by fine-grained sand which is clayey, silty, weakly gravely to gravely and contains scattered stones. The sand till has a light yellowish brown colour indicating oxidized conditions. This indicates a return to oxidized conditions over the clay till-sand till boundary, i.e. a reversed geochemical profile.

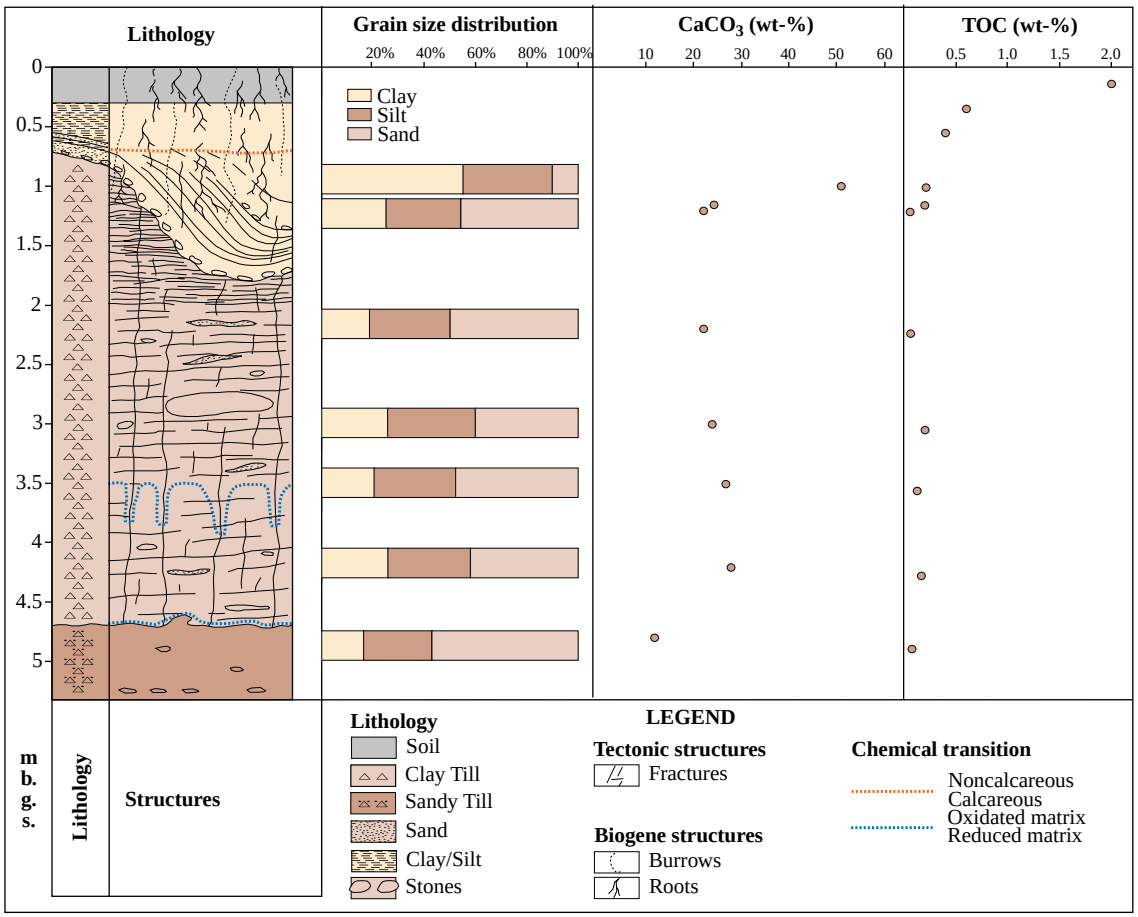


Figure A6.11. Lihology, grain size distribution and $CaCO_3$ and total organic carbon (TOC) content in the test pit. Grain size fractions larger than 2.0 mm are not included in the grain size analysis.

Fracture description

In order to develop a conceptual model of the fracture systems and macropores at the test field, fracture orientation at various depths and fracture position and frequency were measured in the test pit for calculation of fracture parameters. The data are presented in Figure A6.9 and A6.10 and the fracture systems described according to Klintand Gravesen (1999). The fracture analysis was supplemented by till fabric measurements in order to clarify the stratigraphic relationships in the test pit. Down to about 2 m b.g.s., the systematic fracture systems have been obscured by agricultural processes, bioturbation and desiccation cracks. At 0.3 m b.g.s. there were an estimated 1900 biopores/m^2.

Vertical and horizontal fractures are abundant in the clay till of the middle unit. In the southwestern corner of the pit, however, vertical fractures are less common below the upper unit and down to approx. 3 m b.g.s. (east-facing profile in Figure A6.9*)* compared

to the remainder of the pit where the clay till is exposed. This is probably because the upper unit is thickest in the southwestern corner of the pit and because the sand and gravel in the unit has attenuated the formation of fractures by desiccation and freeze/ thaw processes into the underlying clay till. The largest vertical fractures intersect the whole clay till, stopping at the boundary of the underlying sand till of the lower unit.

Table A6.3. Lithological descriptions from the test pit at Slaeggerup.

Depth m b.g.s.	Description	Unit
0.0–0.3	Topsoil, clayey, brown, numerous biopores, noncalcareous	Upper Unit
0.3–0.65	Clay, sandy, weakly silty, locally thin silt lenses, abundant desiccation fractures and biopores, small roots on fracture surfaces and in biopores, yellow brown and brown, noncalcareous.	
0.65–1.8	Sand, silt, clay and occasionally gravel, alternating beds, the sand is commonly cross-laminated whereas the clay and silt is horizontally laminated. Small vertical and horizontal fractures are abundant in the clay and silt. The clay has a light grey, white or light yellow colour whereas the silt and sand is olive yellow in colour and strongly calcareous.	
1.8–3.5	Clay till, sandy to strongly sandy, weakly silty, gravely, stones, lenses of silt and sand are common, fractures, light yellow brown, calcareous.	Middle Unit
3.5–4.7	Clay till, sandy to strongly sandy, weakly silty, gravely to strongly gravely, stones, lenses of silt and sand are common, fractures, light brown grey, calcareous.	
4.7–5.4	Sand till, mainly fine, weakly gravely to gravely, few stones, light yellow brown, calcareous.	Lower Unit

It is possible to subdivide the fractures of the clay till into two fracture systems:

- System 1. These fractures consist of vertical/subvertical fractures that can be subdivided into 1st and 2nd order fractures. The 1st order fractures extend from the lower boundary of the clay till (approx. 4.7 m b.g.s.) and up to approx. 2 m b.g.s. The 2nd order fractures are cut by the 1st order fractures or by horizontal fractures of system 2 fractures and consequently have a smaller extent than the 1st order fractures. The system 1 fractures are mainly oriented N-S or NE-SW (Figure A6.9). They are attributable to glaciotectonic forces in connection with an ice advance from the southeast or west.
- System 2. These fractures consist of subhorizontal/horizontal fractures. In the lower part of the clay till some of the fractures dip slightly towards east or south. The system 2 fractures are attributed to a horizontal stress component of the ice advance that formed the system 1 fractures.

No fractures were recognized in the sand till of the lower unit.

Fracture geochemistry

Five depth-dependent types of coatings could be observed on the fracture surfaces in the test pit. There was generally less precipitate on the fracture surfaces in the southwestern corner of the pit, where the overlying upper unit is thickest, than on fracture surfaces exposed elsewhere in the clay till.

I. 0–2 m b.g.s. The surfaces of the fractures are generally light grey in colour, probably reflecting locally reduced conditions in an otherwise oxidized chemical environment. The reduced conditions are probably caused by oxygen depletion due to decomposition of organic matter.

II. 2–2.3 m b.g.s. The surfaces of the fractures are either slightly rust-coloured or light yellow brown corresponding to the colour of the matrix.

III. 2.3–3.7 m b.g.s. The surfaces of the fractures are rust-coloured and commonly have black areas due to manganese precipitation. The matrix has a light yellowish brown colour down to around 3.5 m b.g.s., whereafter it gradually changes into a light brownish grey colour indicating a downward change from oxidized to suboxic conditions.

IV. 3.7–4 m b.g.s. Similar coating to the fractures as from 2.3–3.7 m b.g.s. except that there is less manganese precipitate.

V. 4–4.7 m b.g.s. The surfaces of the fractures are mainly rust-coloured.

Clast fabric analysis

Two clast fabric analyses were performed on the clay till of the middle unit, 2.5 and 4.7 m b.g.s. A further analysis was performed on the sand till of the lower unit, 4.75 m b.g.s. The clast fabric analysis of the clay till revealed an average clast fabric orientation of 110° while that of the sand till was 145° (Figure A6.9), thus indicating that the tills were formed by an ice advance from an easterly-southeasterly direction.

Field vane tests

Field vane tests were performed in the test pit at 25 cm intervals from top to bottom (Figure A6.10). Down to a depth of 1 m b.g.s. the undisturbed shear strength (Cv) increases from approx. 90 to approx. 290 kN/m^2. At depths from 1 to 2.5 m b.g.s. the shear strength is generally 250–280 kN/m^2 while from 2.5 to 3.5 m b.g.s. it is 320–370 kN/m^2 and from 3.5 to 5.25 m b.g.s. it is 160–250 kN/m^2.

Laboratory analysis

Grain size analysis

Grain size analysis has been carried out on 15 samples from the site (Table A6.4 and Figure A6.11). The analyses show that the meltwater clay within the upper unit has a clay content of 40–55% while that of the clay till of the middle unit is 13–26%. Two grain size analyses of the sand till of the lower unit revealed a clay content of 12–16%,

Table A6.4. Texture analysis of sediment from the test pit and from selected wells.

	Grain size in mm, %							
Depth and location m b.g.s.	<0.002	0.002–0.020	0.02–0.63	0.63–0.125	0.125–0.200	0.20–0.5	0.5–2.0	Sediment
Test pit								
1.0	55.1	33.0	1.9	7.4	1.9	0.5	0.2	Meltwater clay (upper unit), oxidized
1.2	25.1	24.6	4.6	14.6	12.3	13.4	5.5	Clay till (middle unit), oxidized
2.2	18.5	21.7	9.7	14.8	12.7	14.5	8.2	Clay till (middle unit), oxidized
3.0	25.4	23.8	11.0	12.3	10.4	11.1	6.0	Clay till (middle unit), oxidized
3.5	20.3	22.6	9.7	13.6	11.9	14.0	7.9	Clay till (middle unit), suboxic
4.2	25.8	22.6	9.6	12.9	11.2	11.7	6.3	Clay till (middle unit), reduced
4.8	16.3	17.5	9.2	19.6	14.1	16.5	6.8	Sand till (lower unit), oxidized
Wells								
P4(2.8)	13.4	14.4	9.0	20.6	17.3	16.8	8.4	Clay till (middle unit)
P4(10.0)	13.2	22.0	5.9	20.0	14.8	16.9	7.2	Clay till (lower unit)
P4(13.8)	18.2	24.6	14.4	16.1	10.2	10.6	5.9	Clay till (lower unit)
P2(4.5)	26.4	44.3	11.9	7.2	3.9	4.1	2.2	Clay till (middle unit)
P2(7.0)	13.1	14.5	13.1	24.5	14.5	15.0	5.3	Clay till (lower unit)
P1(7.1)	43.7	44.1	4.8	3.8	1.8	1.3	0.5	Meltwater clay (lower unit)
P1(8.5)	11.6	13.5	12.0	22.8	16.5	17.4	6.2	Sand till (lower unit)
Ditch								
0.7	41.1	44.7	11.3	2.6	0.1	0.1	0.1	Meltwater clay (upper unit)

Data from GEUS Sediment Laboratory. Some of the fractions were determined by linear interpolation.

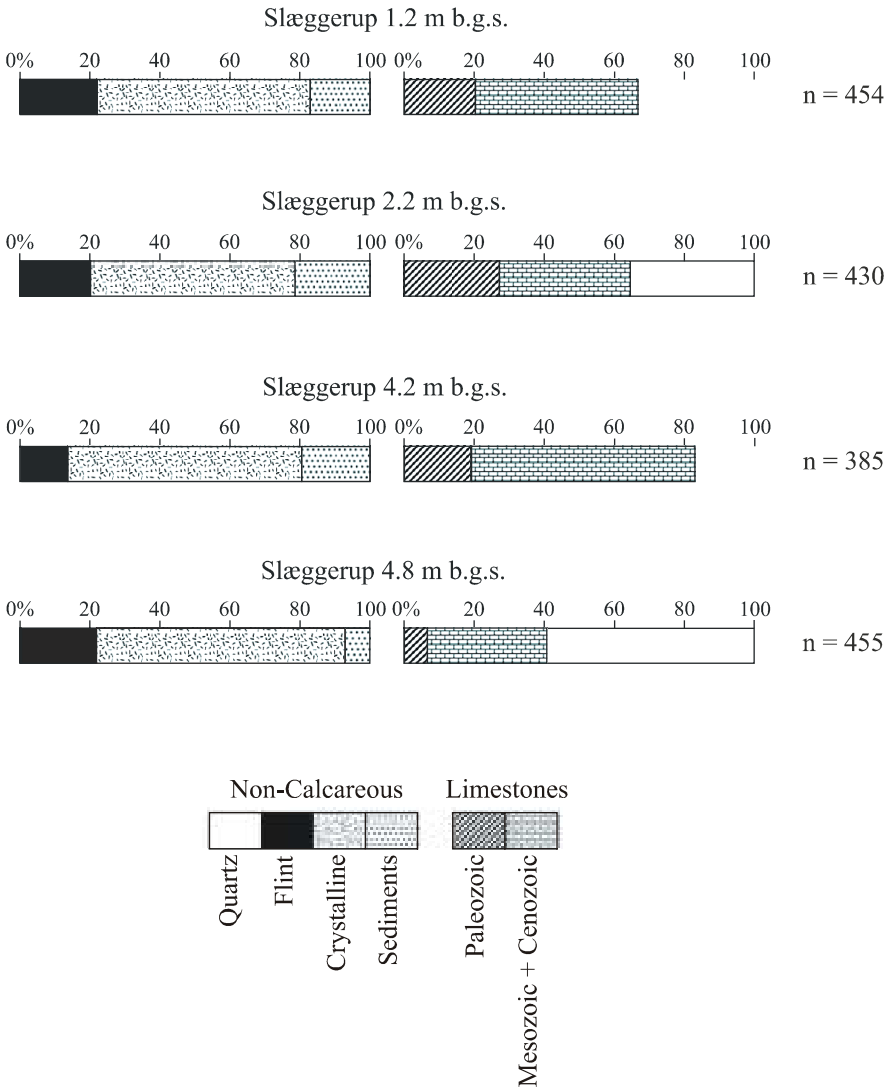


Figure A6.12. Fine gravel analysis from four levels in the test pit. n is the number of grains counted.

although the latter value is not representative for the matrix of the sand till, as the sample was taken close to the upper boundary of the till where clasts and lenses of silt and clay are abundant. The clay content of the clay till in the lower unit is 13–19% (Table A6.4: P4 (10.0 m b.g.s.) and P4 (13.8 m b.g.s.)).

Clay mineral analysis

Two samples of the clay till of the middle unit collected 1.3 and 4.0 m b.g.s. reveal that the clay fraction (<2 µm) is dominated by smectite. Other minerals present are vermiculite, illite, kaolinite and quartz.

Fine gravel analysis

Exotic stone counts were performed on four samples from the test pit. As shown in Figure A6.12, the content of sediment and Palaeozoic limestone grains is slightly lower in the sand till of the lower unit (sample from 4.8 m b.g.s.) than in the clay till of the middle unit.

Total organic carbon (TOC) and $CaCO_3$ content

The TOC and $CaCO_3$ data are shown in Figure A6.11 and Table A6.5. The $CaCO_3$ content of the clay till at Slaeggerup is 21–28% by weight, while that of the meltwater clay is somewhat higher at 51%.

The TOC values from the test pit range from 0.06 to 0.21%, the highest values generally occurring in the reduced zones of the sediments.

Porosity and permeability

Three samples were collected for determination of the hydrogeological characteristics of the sediments. In the clay bed of the upper unit the porosity was 46% and the saturated hydraulic conductivity was 7.3×10^{-7} m/s. These values are relatively high compared to the porosity and saturated hydraulic conductivity of the underlying clay and sand till (Table A6.6), probably due to the presence of horizontal sand lamina and fractures in the clay. Analysis of two samples of the clay till of the middle unit revealed a porosity of about 28% and a saturated hydraulic conductivity of 7.3×10^{-9} m/s and 3.9×10^{-8} m/s, respectively. In the sand till of the lower unit the porosity was 26% and the saturated hydraulic conductivity was 3.7×10^{-8} m/s. The samples were collected horizontally.

Table A6.5. Sediment $CaCO_3$ and total organic carbon (TOC) content in the test pit and selected wells.

Locality	Depth m b.g.s.	TOC %	$CaCO_3$ %	Sediment
Test pit	1.0	0.21	51	Meltwater clay (upper unit)
Test pit	1.2	0.06	22	Clay till (middle unit)
Test pit	2.2	0.06	22	Clay till (do.)
Test pit	3.0	0.21	24	Clay till (do.)
Test pit	3.5	0.13	27	Clay till (do.)
Test pit	4.2	0.17	28	Clay till (do.)
Test pit	4.8	0.08	12	Sand till (lower unit)
P4	2.8	0.04	19	Clay till (middle unit)
P4	10.0	0.12	11	Clay till (lower unit)
P4	13.8	0.12	26	Clay till (lower unit)
P2	4.5	0.57	33	Clay till (middle unit)
P2	7.0	0.11	11	Clay till (lower unit)
P1	7.1	0.33	33	Meltwater clay (lower unit)
P1	8.5	0.13	7	Sand till (lower unit)
Ditch (close to P2).	0.7	0.17	29	Meltwater clay (upper unit)

Data from GEUS Sediment Laboratory.

Table A6.6. Special core analysis data from the test pit.

Plug no.	Depth m b.g.s.	Plug type	Liquid permeability mD	Saturated hydraulic conductivtiy 10^{-9} m/s	Porosity cm^3/cm^3	Grain density g/cm^3
1	1.0	2	75.543	729.7	0.46	2.680
2	1.5	2	0.754	7.290	0.29	2.703
3	4.25	2	4.035	38.98	0.28	2.672
4	4.75	2	3.851	37.20	0.26	2.667

Data from GEUS Core Laboratory.

A6.4 Pedology

The pedological field work at Slaeggerup was carried out from September 27 to September 30 1999. Three soil profiles were excavated and described (Figure A6.5). Two were located beside the suction cups and one beside the test pit. In the buffer zone, 20 soil cores were collected to a depth of 120 cm (Figure A6.5). Inside the field 47 soil samples were collected from the topsoil (0–25 cm).

Profile description

The pedological descriptions of the three profiles are summarized in Tables A6.7, A6.8 and A6.9. The profile horizons are shown in Figure A6.13, while the laboratory data (grain size, texture, organic matter, nutrients and major cations) are summarized in Tables A6.10 and A6.11.

In Table A6.12 the profiles are classified according to "A Pedological Soil Classification System Based on Danish Soils" (Madsen and Jensen, 1985) and USDA Soil Taxonomy (Soil Survey Staff, 1999).

Table A6.12. Classification of the profiles.

Profile no	Danish Soil Classification	USDA Soil Taxonomy
1 (3095 North)	Because of the Bt horizon the profile is a Lessive soil. Having no special characteristics, it is a Typilessive. Because of the Bv horizons on top of the Bt horizons, the soil is a **Brunjordstypilessive**.	With a high base saturation throughout the profile and a median content of organic matter, the soil is a Mollisol. The suborder is Udolls. Because there is an Argillic horizon, the great group is Argiudolls. The soil is a **Typic Argiudolls** a the great group level.
2 (3097 East)	ditto.	ditto.
3 (3096 South)	ditto.	ditto.

Table A6.7. Description of profile 1 (3095 Slaeggerup North).

Soil classification, DK	Brunjordstypilessive	**Soil classification, USDA**	Typic Argiudoll
Parent material	Clay till	**Profile depth**	260 cm
UTM	32U PG Easting 698904 Northing 61743307	**Drainage class**	Moderately well drained
Landform	Hilly Moraine	**Groundwater level**	400 cm
Map sheet	1113 IV SØ	**Vegetation**	Wheat stubble
Elevation	21 m DNN	**Maximum rooting**	70 cm
Topography	On the middle of slope	**Authors**	Søren Torp
Slope	1–3°	**Date of description**	28.09.99

Profile description

Ap (0–27 cm)
Very dark greyish brown (10YR 3/2 f) clay, containing humus, a few small stones of mixed form, type and condition, a few small roots, 1–10 pores per dm^2, strong very coarse angular structure, fast consistency, clear smooth boundary.

Bv (27–34 cm)
Brown (10YR 4/3 f) clay, humus poor, a few small stones of mixed form, type and condition, some small roots, 1–10 pores per dm^2, moderately coarse angular structure, brittle consistency, continuous thin coatings of clay minerals and humus in root channels + aggregate peds, gradual wavy boundary.

Bvt (34–48 cm)
Yellowish brown (10YR 5/4 f) sandy clay, humus poor, a few small stones of mixed form, type and condition, a few small soft rounded Fe and Mn oxide and hydroxide nodules, some small roots, 1–10 pores per dm^2, moderately coarse prismatic structure, very brittle consistency, continuous thin coatings of clay minerals and humus in root channels + aggregate peds, clear, wavy boundary.

Bv2 (48–62 cm)
Brown (10YR 4/3 f) clayey sand, humus poor, a few small stones of mixed form, type and condition, frequent small roots, moderately thin angular structure, brittle consistency, gradual smooth boundary.

2Cc (62–150 cm)
Light yellowish brown (10YR 6/4 f) clayey, silty sand with bands of silty clay, many big clear very pale brown (10YR 8/2) horizontally striped spots, secondary spots of light grey (5Y 7/2 f), horizontally striped gley character, humus poor, a few small stones of mixed form, type and condition plus lumps of lime, a few small soft rounded Fe oxide and hydroxide concretions, structureless, loose consistency, gradual, wavy boundary.

3Cc(g) (150–260 cm)
Brown (10YR 5/3 f) clay, spots of grey (5Y 6/1 f) reducing environment, humus poor, a few small stones of mixed form, type and condition plus lumps of lime, a few small soft and hard rounded Fe oxide and hydroxide concretions, strong very coarse angular structure, very brittle consistency.

Remarks	Horizon 2C: Alternating layers of water-sedimented material, fine and sandy.

Table A6.8. Description of profile 2 (3097 Slaeggerup East).

Soil classification, DK	Brunjordstypilessive	**Soil classification, USDA**	Typic Argiudoll
Parent material	Clay till	**Profile depth**	260 cm
UTM	32U PG Easting 698936 Northing 6,174,304,21	**Drainage class**	Moderately well drained
Landform	Hilly moraine	**Groundwater level**	400 cm
Map sheet	1513 IV SØ	**Vegetation**	Wheat stubble
Elevation	21 m DNN	**Maximum rooting**	70 cm
Topography	Undulating	**Authors**	Søren Torp
Slope	2–4°	**Date of description**	28.09.99

Profile description

Ap (0–25 cm)
Very dark greyish brown (10YR 3/2 f) clay, containing humus, a few small stones of varying shape and type especially unweathered, some small roots, 1–10 wormholes and root channels per dm^2, moderately coarse angular structure, brittle consistency, clear, smooth boundary.

Bv1 (25–50 cm)
Very dark greyish brown (10YR 3/2 f) clay containing humus, a few small stones of varying shape and type especially unweathered, a few small roots, 1–10 wormholes and root channels per dm^2, moderately coarse angular structure, loose consistency, mottled thick coatings of clay minerals and humus in root channels + aggregate peds, gradual, wavy boundary.

Bv2 (50–76 cm)
Light yellowish brown (2.5Y 6/4 f) clayey, silty sand with many vertical stripes of medium clear spots of yellowish brown (10YR 5/6 f), humus poor, a few small stones of varying shape and type, especially unweathered, some small roots, 1–10 wormholes and root channels per dm^2, very weak medium subangular structure, loose consistency, very little spotted moderately thick coatings of clay minerals and humus in root channels, gradual, smooth boundary.

Bt (76–101 cm)
Yellowish brown (10YR 5/4 f) sandy clay with many vertically striped big clear spots of strong brown (7.5YR 5/6 f), humus poor, a few small stones of varying shape and type especially unweathered, a few small soft irregular Fe and Mn oxide and hydroxide nodules, a few small roots, 1–10 wormholes and root channels per dm^2, moderately coarse angular structure, brittle consistency, spotted moderately thick coatings of clay minerals and humus in root channels and on aggregate peds, gradual, wavy boundary.

BC (101–140 cm)
Dark yellowish brown (10YR 4/6 f) clayey sand with many vertically striped big marked clear spots of pale olive (5Y 6/3 f) and secondary spots of dark yellowish brown (10YR 4/6 f), humus poor, a few small stones of varying shape and type, especially unweathered, a few small soft irregular Fe and Mn oxide and hydroxide nodules, a few small roots, moderately coarse subangular structure, loose consistency, clear smooth boundary.

2Cc (140–155 cm)
Light yellowish brown (2.5Y 6/4 f) light clayey sand, humus poor, a few small stones of varying shape and type especially unweathered, weak medium angular structure, loose consistency.

Remarks	The profile is characterized by dizzy lithology, i.e. disorder of shifting layers of sandy pebbles and clay horizons.

Table A6.9. Description of profile 3 (3096 Slaeggerup South).

Soil classification, DK	Brunjordstypilessive	**Soil classification, USDA**	Typic Argiudoll
Parent material	Clay till	**Profile depth**	150 cm
UTM	32U PG Easting 698909 Northing 6174136	**Drainage class**	Well drained
Landform	Hilly Moraine	**Groundwater level**	
Map sheet	1113 IV SØ	**Vegetation**	Wheat stubble
Elevation	24 m DNN	**Maximum rooting**	80 cm
Topography	Undulating	**Authors**	Søren Torp
Slope	0–1°	**Date of description**	29.09.99

Profile description

Ap (0–25 cm)
Very dark greyish brown (10YR 3/2 f) clay, containing humus, a few small stones of mixed form, type and condition, some small roots, 1–10 wormholes and root channels per dm^2, moderately coarse subangular structure, brittle consistency, abrupt smooth boundary.

Bv (25–42 cm)
Brown (10YR 4/3 f) clay with many vertically striped medium clear spots of very dark greyish brown (10YR 3/2 f) with clear boundary, humus poor, a few small stones of mixed form, type and condition, some small roots, 1–10 wormholes and root channels per dm^2, weak medium subangular structure, very brittle consistency, mottled moderately thick coatings of clay minerals and humus in root channels, gradual, smooth boundary.

Bvt (42–78 cm)
Dark yellowish brown (10YR 4/4 f) sandy clay with many horizontally striped big clear spots of strongly brown (7.5YR 4/6 f) and secondary spots of light olive brown (2.5Y 5/4 f), humus poor, a few small stones of mixed form, type and condition, some small roots, 1–10 wormholes and root channels per dm^2, weak thin subangular structure, very brittle consistency, strongly discontinuous plate structure fragipan, mottled thin coatings of clay minerals and humus in root channels and on aggregate peds, diffuse, smooth boundary.

Cc (78–150 cm)
Pale yellow (2.5Y 8/2 f) clay with lots of vertical big clear spots of light olive brown (2.5Y 5/4 f) and secondary spots of light grey (2.5Y 7/1 f), humus poor, a few small stones of mixed form, type and condition + lumps of chalk, a few small soft and hard rounded Fe oxide and hydroxide concretions, calcareous, mainly as lumps, strong, very coarse plate structure, brittle consistency.

Remarks	The Bvt horizon: Has a strongly discontinuous fragipan. The C horizon: In the upper 15 cm there is a horizontal stripe of fine chalk bands. The horizon has a secondary fine horizontal structure of 3–5 cm thick plates.

Table A6.10 Soil texture analysis from the pedological profiles.

Pro. no.	Hor. no.	Horizon	Depth cm	Soil texture (mm) %							$CaCO_3$ %	OM[1] %
				<0.002	0.002–0.02	0.02–0.63	0.63–0.125	0.125–0.2	0.2–0.5	0.5–2		
1	1	Ap	10–20	20.1	19.9	12.6	17.8	13.0	11.2	3.0	–	2.4
1	2	Bv	28–38	18.7	16.3	12.3	24.2	19.6	6.0	2.2	–	0.7
1	3	Bvt	50–60	22.3	5.7	8.5	26.2	29.4	6.4	1.2	–	0.3
1	4	Bv2	53–63	12.7	4.3	3.9	7.7	9.1	32.3	29.7	–	0.3
1	5	2Cc	107–117	11.5	10.0	11.6	14.2	7.8	18.8	12.0	13.9	0.2
1	6	3Ccg	200–210	15.5	10.5	7.1	12.0	12.6	12.6	6.0	23.3	0.3
2	1	Ap	10–20	19.0	16.0	9.0	16.4	17.2	17.4	3.2	–	1.8
2	2	Bv1	28–38	18.0	19.0	10.0	15.8	19.2	13.2	3.4	–	1.4
2	3	Bv2	56–66	12.5	6.2	5.5	22.3	28.1	20.4	4.8	–	0.2
2	4	Bt	80–90	21.3	6.7	4.6	18.8	24.8	16.2	7.4	–	0.2
2	5	BC	105–115	11.1	2.4	4.0	24.4	25.1	27.4	5.4	–	0.2
2	6	2Cc	136–146	7.6	4.9	8.6	21.4	21.6	15.6	6.8	13.3	0.2
3	1	Ap	8–18	24.0	19.0	14.0	18.8	9.8	8.6	3.8	–	2
3	2	Bv	30–40	17.8	10.2	11.4	13.7	13.3	22.4	10.5	–	0.6
3	3	Bvt	53–63	25.3	6.7	8.0	17.0	17.4	17.4	7.8	–	0.4
3	4	Cc	112–123	15.4	9.6	7.3	13.6	11.2	13.4	5.2	24.2	0.2

1) OM: Organic matter. OM = 1.72 x TOC. Analysed by DIAS.

Table A6.11. Soil chemistry of samples from the pedological profiles.

Pro. no.	Hor. no.	N_{total}	C/N	P_{total}	pH[1]	K	Na	Ca	Mg	Total bases	H+	CEC	Base sat.	Fe (Ox)	Al (Ox)
		%		mg/kg					cmol/kg				%	mg/kg	
1	1	0.14	10	400	5.96	0.26	0.07	13.7	0.41	14.4	2.39	16.8	86	2482	1020
1	2	0.06	7	130	6.09	0.12	0.11	10.3	0.41	10.9	2.98	13.9	79	1262	814
1	3	0.04	4	101	7.07	0.2	0.13	12.3	0.79	13.4	2.63	16	84	704	932
1	4	0.04	4	263	6.96	0.1	0.17	7.55	0.48	8.3	4.4	12.7	65	1360	780
1	5	0.03	4	358	7.72	0.12	0.17	19.1	0.41	19.8	–	8.2	100	786	396
1	6	0.03	6	364	7.74	0.18	0.13	20	0.85	21.2	–	9.4	100	638	291
2	1	0.12	9	421	5.97	0.28	0.06	9.53	0.21	10.1	6.62	16.7	60	3388	966
2	2	0.09	9	237	5.74	0.09	0.06	8.43	0.16	8.74	4.26	13	67	2920	1026
2	3	0.03	4	118	6.63	0.08	0.07	5.73	0.35	6.23	6.87	13.1	48	872	528
2	4	0.03	4	140	7.35	0.16	0.1	18.7	0.91	19.9	–	15.5	100	724	646
2	5	0.03	4	209	6.45	0.12	0.05	6.85	0.51	7.53	5.57	13.1	57	1266	559
2	6	0.02	6	321	7.91	0.07	0.06	17.4	0.28	17.8	–	9.9	100	544	270
3	1	0.13	9	483	6.26	0.37	0.16	14.1	0.82	15.4	2.57	18	86	2888	910
3	2	0.05	7	347	6.41	0.13	0.09	8.32	0.29	8.83	7.27	16.1	55	2704	730
3	3	0.05	5	448	6.89	0.24	0.17	15.3	0.98	16.7	1.19	17.9	93	3784	531
3	4	0.02	6	429	7.88	0.12	0.15	20.2	0.51	21	–	9.1	100	742	386

1) pH determined in $CaCl_2$ solution. Analysed by DIAS.

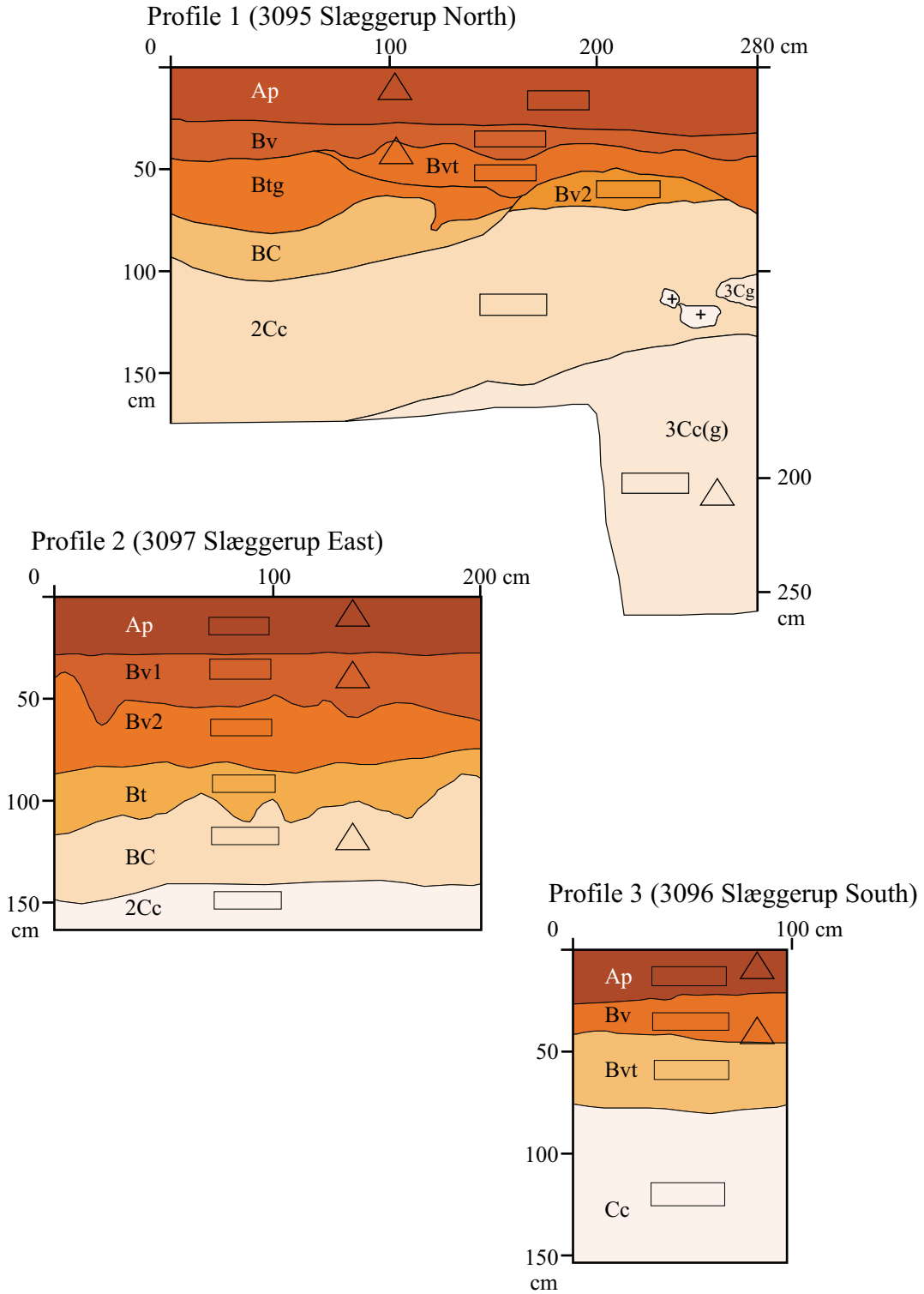


Figure A6.13. Schematic drawings of profiles showing horizon distribution. Rectangular boxes indicate sampling points for soil texture and soil chemistry. Triangular boxes indicate sampling points for hydrological analysis. White areas with + symbolise stones.

Total carbon mapping

The total organic carbon content throughout the field ranges from 1.0 to 1.7% (dry weight), with a mean of 1.37% ±0.22%. The concentration is highest in the southwestern and eastern part of the field and lowest in the northern part of the field (Figure A6.14).

Pedological development

In the plough layer of the three profiles the clay content is 20–24% while the other particle classes are more or less evenly distributed. The total organic carbon content ranges from 1.0 to 1.7%.

Beneath the plough layer there are horizons eluviated in clay, the Bv from 27–34 cm (Profile 1, Slaeggerup North) and 50–76 cm (Profile 2, Slaeggerup East). The degree of eluviation is moderate, and thin to moderate clay coatings are observed in the underlying horizons. The laboratory analysis reveals a difference in clay content of approx. 2–7% compared with the overlying horizon.

The soils in the area all include a clay-enriched illuvial Bt horizon containing 21–25% clay. This horizon lies in a depth of 40 to 80 cm. Clay skins on peds were found in all three profiles. A temporary water table seems to develop during moist periods in some of the area since pseudogley was found in nine of the soil cores as well as in soil profiles 1 and 3. Because the pseudogley is attributable to texture and structure in the soil here, there is no connection to topography.

From the phosphorus content it can be seen that the soil has been used for agricultural purposes, probably for decades. The base saturation in the profiles ranges from 49 to 93% where the soil is lime-free, and increases with increasing depth. The pH generally increases down through the profiles from approx. 6 in the topsoil to 7 just above the chalk border. In the chalk zone, pH is around 7.7.

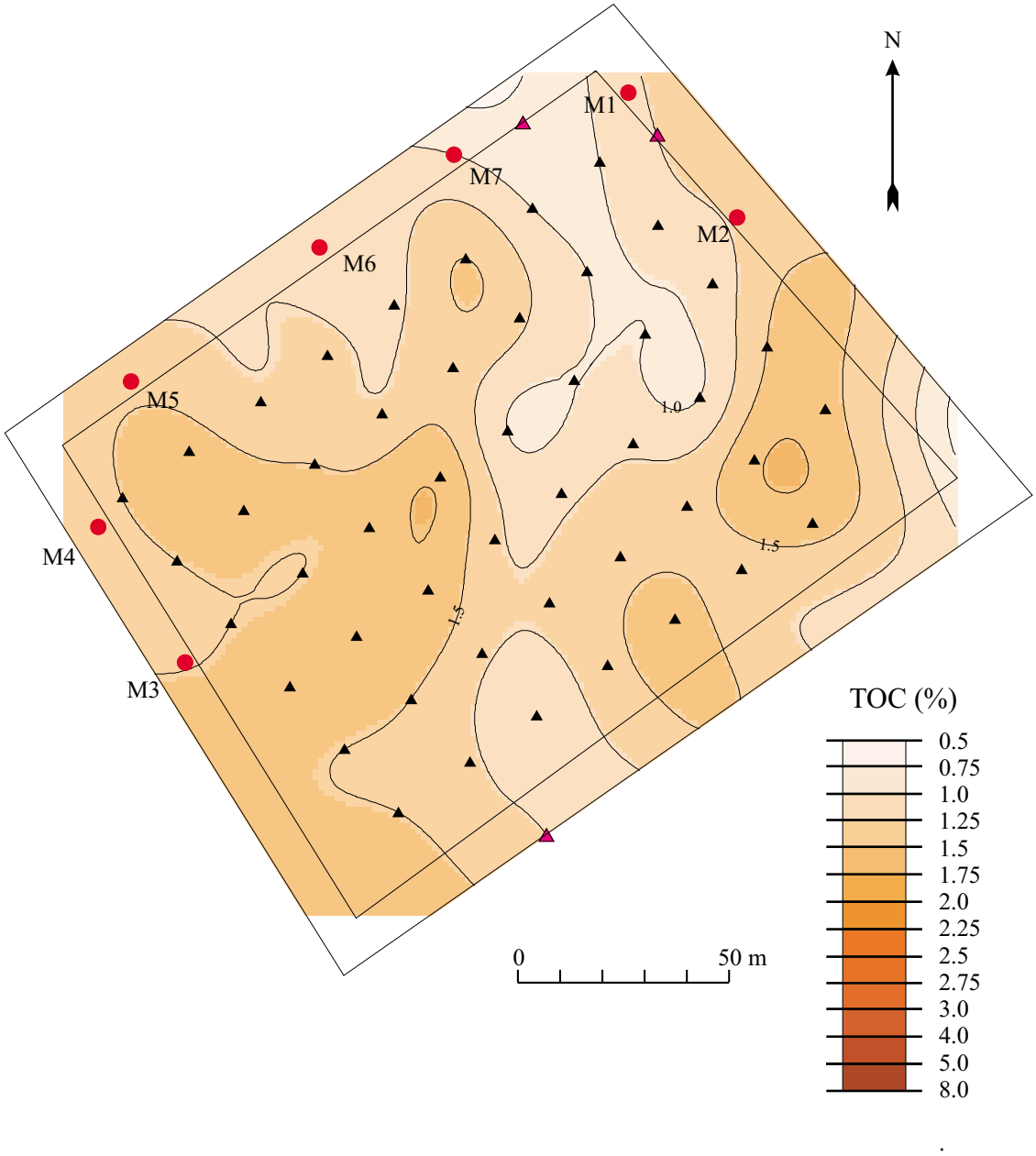


Figure A6.14. Map showing total organic carbon TOC content within the test field. Sampling points are indicated by ▲.

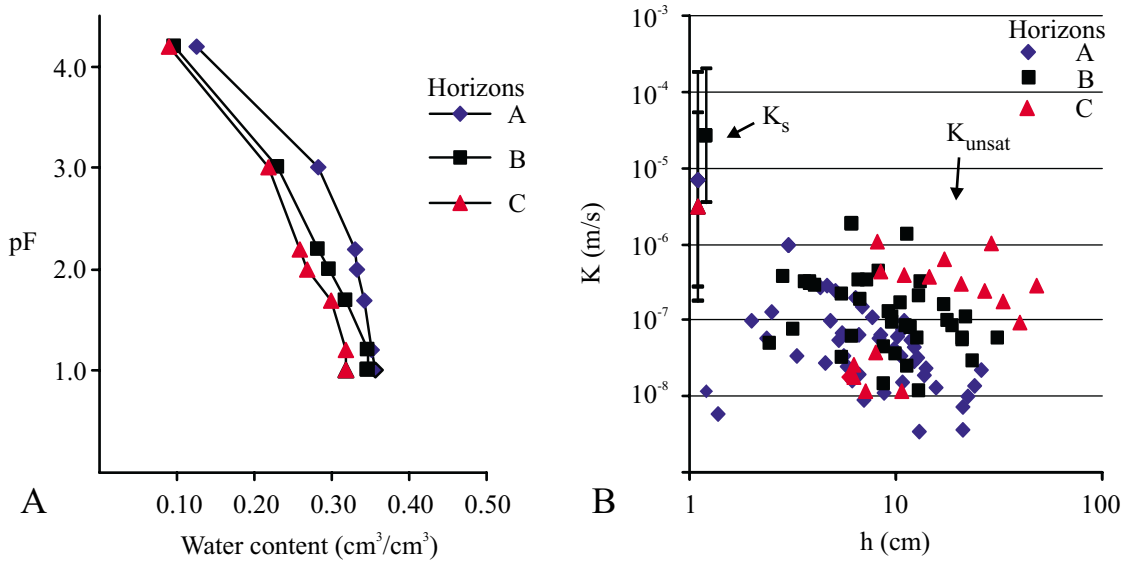


Figure A6.15. A) Retention curve based on values for the soil-water potential determined on the small soil core samples (100 cm^3). The data are the mean values from all three profiles. B) The unsaturated hydraulic conductivity (K_{unsat}) as a function of soil water potential in cm H_2O and the saturated hydraulic conductivity (K_s) determined on the large soil cores (6,280 cm^3).

The texture distribution found at Slaeggerup is typical for a clayey, moderately eluviated east Danish moraine till. In the two profiles to the north, the texture changes because of a change in lithology from till to fluvial deposits. Profile 1 (Slaeggerup North) is unique with different parent materials and following discontinued horizons.

Table A6.13. Soil water characteristics determined on small soil cores, pF = $\log_{10}(-h)$.

Profile no.	Horizon	Depth cm	Water content at pF values cm^3/cm^3							Bulk density g/cm^3	Porosity[1] cm^3/cm^3
			1.0	1.2	1.7	2.0	2.2	3.0	4.2		
1 (3095)	Ap	15	0.34	0.34	0.33	0.32	0.3	0.27	0.13	1.64	0.38
	Bv/Bvt	40	0.33	0.33	0.31	0.27	0.25	0.19	0.10	1.71	0.35
	3Cc(g)	210	0.27	0.27	0.27	0.26	0.25	0.24	0.12	2.01	0.24
2 (3097)	Ap	15	0.35	0.35	0.33	0.32	0.32	0.27	0.11	1.67	0.37
	Bv1	40	0.32	0.32	0.28	0.26	0.25	0.20	0.10	1.70	0.36
	BC	120	0.37	0.37	0.33	0.28	0.27	0.20	0.06	1.70	0.36
3 (3096)	Ap	15	0.38	0.37	0.37	0.36	0.36	0.31	0.14	1.68	0.37
	Bv	40	0.39	0.39	0.37	0.36	0.35	0.30	0.09	1.60	0.39
	C	–	2)	2)	2)	2)	2)	2)	2)	2)	2)

1) Assuming a particle density of 2.65 g/cm^3.

2) Sampling not possible.

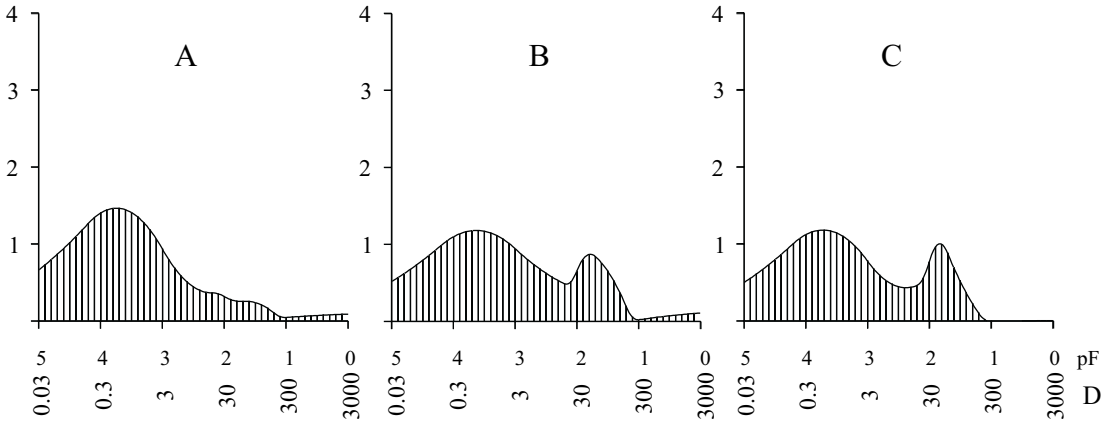


Figure A6.16. Pore size distribution measured (A, B, and C horizon) calculated from water retention data assuming the unity D=3000/10pF (D = pore diameter equivalent diameter, µm). A cubic spline interpolation procedure is used to yield discrete interpolate values on the sum curve obtained from the water retention curves. Abscissa: pF=log10(-h) in which h is the soil water potential in cm H_20. D = pore diameter, µm. Ordinate: percentage of pore volume per 1/10 pF-values, % v/v.

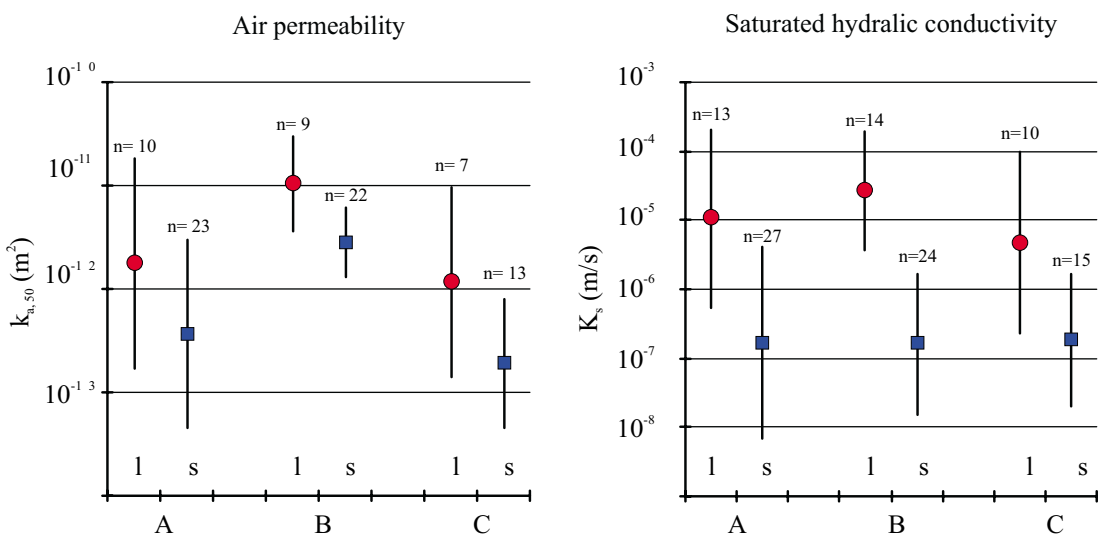


Figure A6.17. Air permeability at a water content of –50 cm H_20 ($k_{a,50}$) and saturated hydraulic conductivity (K_s) measured on large (6,280 cm^3) samples (●) and small (100 cm^3) samples (■).

Soil hydrology

Soil cores (100 cm^3 and 6,280 cm^3) for the measurement of hydrological properties (soil water characteristics and hydraulic conductivity) were sampled at three levels corresponding to the A, B, and C horizon.

The soil water characteristics of the nine small cores (100 cm^3) from each horizon are shown together with bulk density and porosity in Table A6.13 and in Figure A6.15. The soil in the A and B horizons gradually decreases in water content as a function of the relatively uniform pore size distribution, which is typical for a clayey/loamy soil. The C horizon has a high water-holding capacity until pF 3 (-1,000 cm H_2O).

The majority of the pores are about 0.7 µm (tube-equivalent diameter). The B horizons and the C horizons exhibit marked bimodal pore size distribution with a second peak at about 50 µm. The percentage of pores >300 µm is particularly low in the C horizon, thus reflecting the high water-holding capacity of the horizon (Figure A6.16).

The saturated and unsaturated hydraulic conductivity data for the large cores (6,280 cm^3) are shown in Figure A6.15. Unsaturated conductivity was low in all three horizons and highly variable, especially in the B and C horizons. Due to the high inter-measurement variability and lack of data, it is difficult to establish a unique relationship between soil water potential (h) and hydraulic conductivity (k) in the C horizon. The marked difference between near-saturated hydraulic conductivity and saturated hydraulic conductivity indicates a high degree of preferential flow through macropores when the soil is fully saturated.

The measurements of saturated hydraulic conductivity and air permeability made using small (100 cm^3) or large (6,280 cm^3) soil samples differed markedly (Figure A6.17). This difference is probably related to the structure of the soil leading to a high dependence on sample size. With the large soil samples, infiltration takes place through a much larger soil area than is the case with the small soil samples and a greater number of macropores and other soil heterogeneities are therefore included.

A6.5 Geophysical mapping

Since destructive mapping methods are not accepted in the test field, it was decided to use EM-38, CM-031 and ground-penetrating radar.

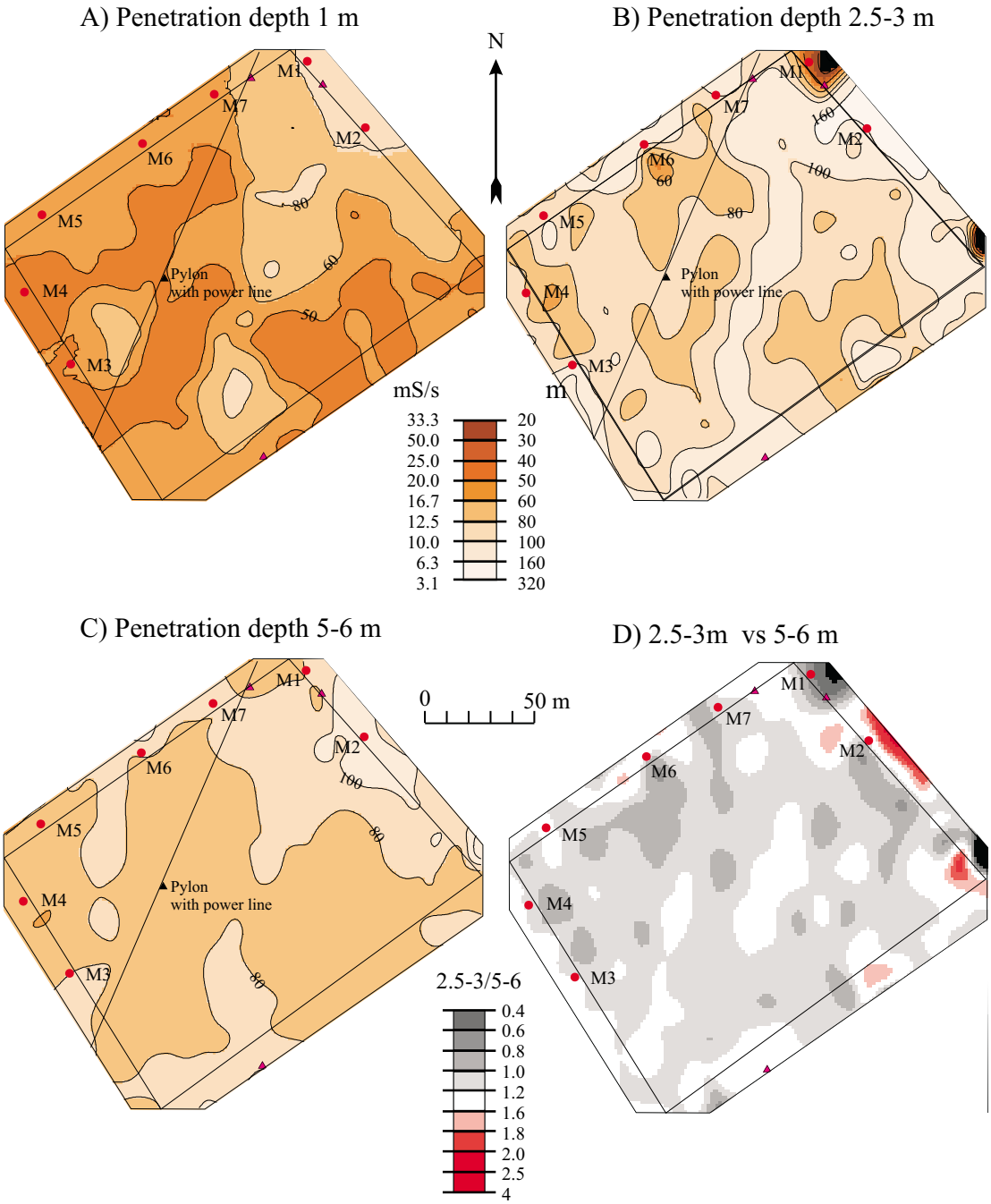


Figure A6.18. Resistivity maps of the area. Map D shows the relative difference between map B and C and provides an idea about the homogeneity of the electrical properties to a depth of approx. 6 m b.g.s.

The EM-38 map shown in Figure A6.18A reveals that the relative resistivity at the site measured in the upper meter ranges from 36 to 100 Ω m. In map A6.18B (the shallow CM 031 map), a distinct area of high resistivity, i.e. 100–160 Ω m, is observed from the northern corner to the southern corner. This anomaly can actually be seen in all

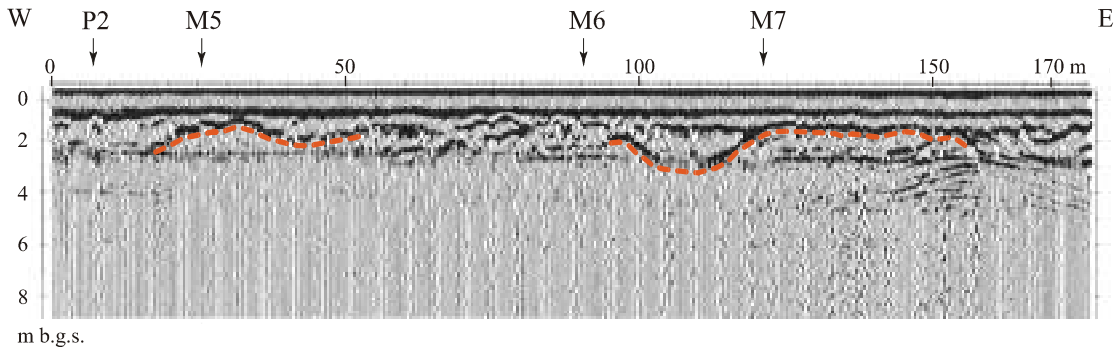


Figure A6.19. Ground-penetrating radar profile from the northern border of the test field.

three maps (A6.18A, B and C). The areas of high resistivity probably indicate meltwater gravel and sand of the upper unit occurring near the surface.

Another anomaly is seen close to and parallel to the well path of the horizontal well H2. This is less pronounced with relatively low resistivity (Figure A6.18B and C). This anomaly provides a good explanation for the upward transport of drilling fluid described above when interpreted as a sand or gravel bed.

Figure A6.18D shows the relative difference between the two CM-031 maps. It must be read with caution since Slaeggerup is basically a three-layer model whereas the map in question interprets the data as a two-layer model. Nevertheless, it does highlight some of the areas where differences in the resistivity occurs with increasing depth.

Ground-penetrating radar (GPR)

The ground-penetrating radar mapping was carried out along a 20 x 20 m grid. The penetration depth is generally 2–3 m b.g.s. Several of the GPR cross sections are characterized by continuos horizontal reflections indicating a homogeneous clayey sediment. With the remaining cross sections the reflection pattern is more uneven, indicating a higher content of sand and gravel. Reflectors are also present, indicating cross-bedding or basin structures. On some of the GPR cross sections the boundary between the clay till of the middle unit and the overlying meltwater gravel and sand of the upper unit is apparent as a very distinct erosive surface (Figure A6.19).

Appendix A6.1. Cultivation and pesticide application history at Slaeggerup.

Year	Crop	Date	Pesticide brand	Dose per ha
1996	Winter wheat	09.10.95	Stomp SC	1.09 l
		09.10.95	DLG IPU	1.09 l
		22.05.95	Corbel	0.32 l
		22.05.95	Manganese sulphate	1.07 kg
		22.05.95	CCC extra	0.43 l
		05.06.96	Tilt Top	0.35 l
		05.06.96	Manganese sulphate	1.00 kg
		28.06.96	Tilt Top	0.35 l
		28.06.96	Pirimor G	0.10 kg
1997	Winter wheat	10.06.96	Stomp SC	1.0 l
		10.06.96	DLG IPU	1.0 l
		12.05.97	Corbel	0.2 l
		12.05.97	Manganese chelate	1.00 l
		12.05.97	Herbanix MPD 400	1.00 l
		12.05.97	Express	0.0019
		22.05.97	Puma Super	1.00 l
		22.05.97	Isobette	0.25 l
		28.05.97	Tilt Top	0.15 l
		28.05.97	Manganese chelate	1.00 l
		28.05.97	Express	0.0038 kg
		28.05.97	Oxitril	0.5 l
		09.06.97	Express	0.0019 kg
		09.06.97	Tilt Top	0.2 l
		09.06.97	Manganese sulphate	1.5 kg
		02.07.97	Tilt Top	0.3 l
1998	Field peas	09.05.98	Decis (eastern part)	0.25 l
	Field divided	09.05.98	Stomp SC (eastern part)	0.75 l
	through experimental area W 45% E 55%	09.05.98	Basagran 480 (eastern part)	0.5 l
		13.05.98	Stomp SC (eastern part)	0.75 l
		13.05.98	Basagran 480 (eastern part)	0.5 l
		18.05.98	Fervin	0.75 l
		08.07.98	DLG Maneb Fl	1.2 l
		08.07.98	Pirimor G	0.15 l

Year	Crop	Date	Pesticide brand	Dose per ha
1998	Spring rape	24.04.98	Roundup (western part)	1.8 l
1999	Winter wheat	24.10.98	Stomp SC	1.0 l
		24.10.98	DLG IPU	1.0 l
		05.05.99	Puma Super	3.0 l
		05.05.99	Isobette	0.2 l
		18.05.99	Mentor	0.2 l
		18.05.99	Express	0.0038 kg
		18.05.99	Mantrac 500	0.5 l
		18.05.99	Starane 180	0.05 l
		14.06.99	Mavrik 2F	0.05 l
		14.06.99	Amistar	0.4 l
		14.06.99	Corbel	0.05 l