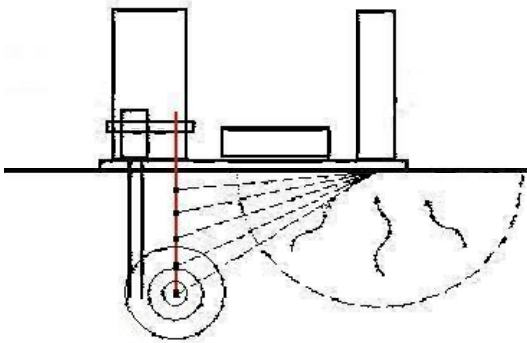


Measuring sediment properties in the field using MEDUSA RhoC



Menno Eelkema

Delft, February 2008

Front cover:

Upper left: “Medusa”. Kazuya Akimoto (2006)

Lower left: sketch Medusa RhoC system. M. Eelkema (2007)

Upper & lower right: photographs Western Scheldt. M. Eelkema (2007)

Measuring sediment properties in the field using MEDUSA RhoC

M.Sc. thesis

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Preface

This Master of Science thesis describes the use of radiometric sedimentology in the field, in particular the use of the MEDUSA RhoC device in the Western Scheldt. This thesis also forms the conclusion to my study Civil Engineering at Delft University of Technology. The research for this thesis was carried out in association with Medusa Explorations and the Netherlands Institute of Ecology (NIOO).

I would like to thank the following people (in non-particular order) for helping me during the last year of my study: First of all at the faculty of Civil Engineering: professor Huib de Vriend, Han Winterwerp, Maarten van der Vegt, professor Guus Stelling, Gerben de Boer, Jirat Laksanalamai, and everyone else at the fluid mechanics lab. I would especially like to thank Walter Jacobs for his frequent comments, feedback, and enthusiasm. I would like to thank Francesc Montserrat, Daphne van der Wal, Peter van Breugel, and everyone else at NIOO-CEME and guesthouse “De Keete” for allowing me to do fieldwork with them and to make unscrupulous use of their facilities. I would also like to thank Han Limburg, Marco Tijs, Ronald Koomans, and everyone else at Medusa Explorations for supplying me with a fantastic device. Finally of course I would like to thank my parents, my brother and his girlfriend, my aunts, and all my friends in Delft and The Hague for all the other stuff.

Menno Eelkema

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Abstract

An important tool to predict the effect of human interferences on the behavior of estuaries is the use of large-scale numerical models. These models require detailed input conditions, for example concerning the composition of sediments bed on tidal flats. Traditionally, obtaining information on the composition and spatial distribution of sediments requires extensive in-situ sample collection and subsequent laboratory analysis, which is usually very costly and time-consuming. However, alternative measuring methods are currently being developed. A promising new method is called MEDUSA RhoC¹. This device measures mud and sand content, sediment density, and water content in the field using Radiometric sedimentology. The aim of this thesis is to investigate the accuracy and applicability of the MEDUSA RhoC system with its new components. This is done by comparing results obtained with the RhoC to results obtained with traditional analyses, both in the lab and the field. Besides this, also the general characteristics of natural sediments are investigated in order to see what other properties can be derived from mud content, sediment density and water content alone.

The radiometric activity of sediment is related to its mud content. The MEDUSA RhoC system determines mud content by measuring the radio-activity of sediment, and translating the activity to mud content. The relation between mud content and activity concentration is called the radiometric fingerprint. Depth averaged sediment density is determined by pushing a radio-active source into the soil, and measuring the attenuation of the activity coming from the source. The water content is determined with a technique known as Time Domain Reflectometry.

To investigate the performance of the RhoC under controlled circumstances, tests are performed in the laboratory. The experimental set-up consists of a box with known dimensions and volume, which is filled with either dry sand, sand saturated with sediment. The aim of these tests is to determine the offset and the random error in the density measurements. The offset seems to be negative for lower densities, and positive for higher densities. The random error has a standard deviation of 15 kg/m³.

The field tests of the RhoC are performed on tidal flats in the Western Scheldt. On several locations the RhoC is used to measure radiometric activity, density profile, and water content. At the same locations, sediment cores are collected. These samples are taken to the laboratory to determine sediment density, water content, grain size distribution, organic matter content, and radiometric activity concentration. This is done using 'ordinary' techniques.

The comparison between the results of the RhoC and the results of the analysis of the cores also reveals an offset. However, this offset is larger than the offset of the laboratory tests, and is always positive. It is not yet clear what causes this offset, although a relation to the degree of saturation occurs. This relation is used to make a correction for the offset.

The fingerprint is generated from the activity concentrations measured in either the laboratory or the field. Both types of fingerprints return results which are comparable in

¹ MEDUSA stands for 'Multi-Detector system for Underwater Sediment Activity'. RhoC stands for density (symbolized by the Greek letter Rho) measured using the number of counted decaying atoms (C).

accuracy. The profile of the density as a function of depth ($\rho(z)$) is calculated from the depth-average densities measured by the RhoC.

The laboratory analyses on the sediment samples taken from the Western Scheldt show several relations between various sediment properties. The RhoC measures only the mud content, bulk density, and water content. From these properties other properties such as the silt content, clay content, porosity, and relative water content are derived. These properties are important for the mechanical behavior (such as erosion) of the sediment.

In general, the MEDUSA RhoC system is able to supply valuable information on the composition, density and water content of sediment. Although these properties are the only things the RhoC measures, the known relations between these properties and other parameters enable the user to derive much more information on the cohesiveness and mechanical behavior of the sediment. Since the RhoC also gives insight into the stratification of the sediment, the MEDUSA RhoC system can generate sediment maps in three dimensions. This makes the MEDUSA RhoC a valuable measuring device for sediment mapping, which can improve the quality of the input parameters for large-scale numerical models.

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List of symbols

Symbol	Description	Unit
A	Radio Activity	Bq
A_{cl}	Activity of clay mineral	-
N	Number of radionuclides	-
N_0	Number of radionuclides at time $t=t_0$	-
C	Activity concentration	Bq/kg
c	Speed of light in vacuum	m/s
d	Grain size	μ
K	Dielectric constant	-
M_{dry}	Mass of dry sample	kg
M_{water}	Mass of water in the sediment	kg
M_{wet}	Mass of wet sample	kg
M_{sed}	Mass of all solids	kg
n	Porosity	%
n_{sasi}	Porosity of sand and silt fractions	%
S	Saturation: volume water / volume pores	%
$T_{1/2}$	Half life time	s
v	Velocity electromagnetic wave	m/s
V_{bulk}	Bulk volume soil	m^3
V_{pores}	Volume of the pores	m^3
V_{water}	Volume of the pore water	m^3
W	Water content: mass of water / mass of dry sediment	%
W_{ll}	Water content at liquid limit	%
W_{pi}	Plasticity index	%
W_{pl}	Water content at plastic limit	%
W_{rel}	Relative water content	%
λ	Decay constant	s^{-1}
μ	Mass attenuation coefficient	m^2/kg
ξ_i	Contents of fraction i : mass of fraction i / mass of dry sediment	%
ξ_{cl}	Clay content: mass of clay / mass of dry sediment	%
$\xi_{cl;0}$	Critical clay content for cohesive behavior	%
$\xi_{o.m.}$	Organic matter content: mass of organic matter / mass of dry sediment	%
ξ_{sa}	Sand content: mass of sand / mass of dry sediment	%
ξ_{si}	Silt content: mass of silt / mass of dry sediment	%
ρ	Density	kg/m^3

List of Symbols

ρ_{bulk}	Bulk density of sediment	kg/m ³
ρ_{dry}	Dry density of sediment	kg/m ³
ρ_{sed}	Specific density of sediment	kg/m ³
ρ_w	Density of water	kg/m ³
σ	Microscopic cross-section for Compton-scattering	m ²
τ	Microscopic cross-section for photo-electric absorption	m ²
ϕ_{cl}	Volumetric concentration of clay	%
ϕ_{sa}	Volumetric concentration of sand	%
ϕ_{si}	Volumetric concentration of silt	%
ϕ_{sed}	Volumetric concentration of sediment	%
ψ_{cl}	Clay fraction: volume clay / total volume sediment	%
ψ_{sa}	Sand fraction: volume sand / total volume sediment	%
ψ_{si}	Silt fraction: volume silt / total volume sediment	%

1 Introduction

1.1 Background

Marine wetlands, as encountered in estuaries and tidal lagoons, belong to the most valuable ecosystems in the world. The use and management of these wetlands are restricted by (inter)national law and regulations. Managing authorities are therefore under strong pressure to compensate for infrastructural and other measures, e.g. the mining of gas in the Wadden Sea or the deepening of the fairway in the Western Scheldt. However, it is difficult to design the required compensating measures at a sufficient level of confidence, as these systems are characterized by complicated interactions between physical, biological and chemical processes. Most of these processes involve the mixed nature of the sediment bed. Natural sediment beds in estuaries are often a mixture of sand, silt, clay and water. The qualities and quantities of these components play a major role in the exchange of sediment between water column and sediment bed. It is therefore important for modelers to obtain information on the composition of these sand-silt-clay mixtures. An important tool to predict the behavior of estuaries is the use of large-scale numerical models. These models require detailed input conditions, for example concerning the composition of the sediment bed of tidal flats. However, no practical measuring method is available yet that can quickly provide this kind of information for relatively large areas.

Traditionally, obtaining information on the composition and spatial distribution of sediments requires extensive in-situ sample collection and subsequent laboratory analysis. This is usually a very costly and time-consuming operation. However, alternative measuring methods are currently being developed. These require far less time and equipment, and thus reduce costs. A promising method is known as Radiometric Sedimentology. A measuring system based on radiometric sedimentology is called MEDUSA, which stands for 'Multi-Detector system for Underwater Sediment Activity'. The system has been developed by a company called MEDUSA Explorations. It operates by measuring gamma-rays emitted by decaying radio-active isotopes bound on the sediment particles. For the translation of radio-activity into sediment composition it is assumed that there is a specific relation between mineral composition and concentration of radio-active material. The typical concentration of radio-active nuclides in a specific type of sediment is called the radiometric 'fingerprint' of that sediment. If two types of sediment have different fingerprints, they can be radiometrically distinguished (Roberti, 2001). The derivation of these fingerprints is the actual calibration of MEDUSA. To derive a fingerprint for a certain area, the radio-active emissions measured by MEDUSA have to be compared to the actual sediment composition, which is established using traditional measuring techniques. When the relation between measured gamma-ray intensities and sediment composition is known, the fingerprint of the soil is derived. This fingerprint is then used to determine bed composition using radiometric measurements alone. However, before the results obtained with this method are used, it is important to qualify and quantify the influence of sediment composition on this fingerprint.

1.2 Literature review of previous studies

Alternative measuring methods for the determination of sediment properties are currently being developed. One of these methods is called remote sensing. Remote sensing operates by using radar to transmit pulses of microwave energy to the ground, which are partly backscattered to the receiver (see Figure 1.1). The radar is housed in either an airplane or a satellite. The amount of backscattering depends among other things on the roughness of the terrain (Eleveld, 1999). By making an assumption on the relation between sediment type and bed roughness, the sediment composition is derived from the amount of backscattering (Van der Wal *et al.*, 2005).

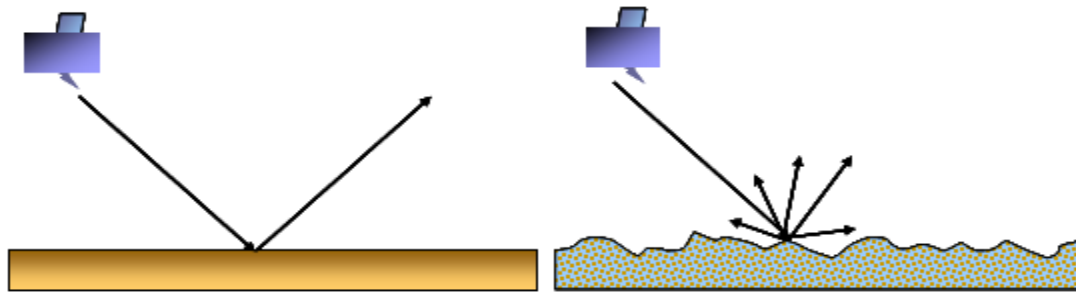


Figure 1.1: Schematic approach of Remote Sensing. Radar backscattering is supposed to be a function of bed roughness (van der Wal & Herman, 2006).

Another promising method is called radiometric sedimentology. In the past, radiometric sedimentology has been used to determine sediment origin and sediment composition. De Meijer (1995) used this method to determine the origin of coastal sand deposits along the Dutch and German Wadden islands. In this research the origin of sediment was identified according to the local ‘fingerprint’. Differences in fingerprints are then coupled to differences in origin. Herman *et al.* (2001) and Goulet *et al.* (2000) used activity concentrations to calculate accretion rates of tidal flats. The accretion rates were actually determined by calculating the age of sediment layers. The activity of isotopes with relatively short half-life times (53 days) were coupled to short-term sedimentation rates. A high activity of these short-lived isotopes would indicate recent accretion. Long-term sedimentation rates were determined in a similar way by measuring on isotopes with longer half-life times (22 years). Koomans (2001) used the MEDUSA system to measure the concentration of heavy minerals such as zircon, monazite and garnet. The spatial distribution of these minerals was examined to gain a better understanding of selective transport processes in front of beaches. Van Wijngaarden *et al.* (2002a; 2002b) used the MEDUSA system to map mud deposits in the Hollandsch Diep and the Haringvliet (see also Roberti, 2001). Both of these surveys consisted of towing a gamma ray detector behind a ship and linking sediment compositions to the activity concentrations using known relations between composition and activity. De Groot *et al.* (2002) used a system very similar to MEDUSA, called PANDORA, to investigate sediment characteristics in salt marshes. The aim of this survey was to find spatial patterns of fingerprints. This would give more insight into the transport processes of sediments in salt marshes.

The surveys described above only looked at results in terms of origin, net accretion rates or grain size distribution, and did not look at other parameters such as water content

or bulk density. However, to be able to link bed characteristics to mechanical behavior (e.g. erosion) more information is required such as structure and cohesiveness.

1.3 Problem definition and objectives

Information on the grain size distribution is not sufficient to get an accurate image of the characteristics of a sediment bed. Knowledge on quantities such as the density and the water content are also required. This is why two new components have been added to the MEDUSA system. These components enable the system to measure not only sediment composition, but also the bulk density and water content of the upper 15 cm of the sediment bed. This new system is the ‘MEDUSA RhoC²’.

An important step in the process of developing a new measuring device is the calibration. The newest version of the MEDUSA system has been calibrated for laboratory conditions (see Tijs, 2007), but not for field conditions. It has to be tested whether the MEDUSA RhoC can yield reliable, accurate results on sediment composition, density and water content from field data alone. Also its practical applicability has to be tested in the field.

The aim of this thesis is to investigate the accuracy and applicability of the MEDUSA RhoC system with its new components. This is done by comparing results obtained with the RhoC to results obtained with traditional analyses, both in the lab and the field. The components that measure water content and soil density are calibrated under controlled circumstances. This calibration in the lab involves the use of the RhoC on artificially generated samples. Besides the testing in the lab, the RhoC is tested and applied in the field. The test locations are several tidal flats in the Western Scheldt. These tidal flats are selected for two reasons; they show a variety in sediment composition, and they have already been studied extensively by the Netherlands Institute of Ecology (NIOO).

1.4 Thesis outline

The first part of this thesis (chapter 2) describes the theories and background information of sediment beds and radiometric sedimentology. The definitions used in sedimentology are discussed, as well as the governing principles behind radiometric sedimentology. Chapter 3 describes the RhoC device and the other methods used for the collection and analysis of the data, both in the field as well as the laboratory. Also the setup for the laboratory calibration tests is presented. Besides this, chapter 3 includes a description of the field site and the measurement procedures. Chapter 4 consists of two parts. The first part gives the data measured in the laboratory calibration tests. The second part presents the general characterization of the sediment according to the samples analyzed in the laboratory. It also presents the data measured by the RhoC in the field. Chapter 5 consists of a comparison of the field- and lab data, and, subsequently, a discussion on the accuracy of the data. This chapter results in the conclusions and recommendations given in chapter 6.

² The name ‘RhoC’ refers to the density (symbolised by the Greek letter Rho) measured using the number of counted decayed particles (C).

2 Theory

2.1 Sedimentology

As this thesis discusses new methods to acquire information on the characteristics of sediments, it is useful to consider the most important properties and definitions of sediments.

2.1.1 Sediment composition

Most sediments in estuaries and tidal lagoons consist of a mixture of minerals, water, organic matter and gas. The mineral part can have a marine or riverine origin. The distribution of different types of sediment over an estuary or tidal lagoon is not only determined by water motion, but also the nature of the sediment. In general fine sediments are mostly found at the landward side of an estuary. Towards the sea the sediment becomes coarser. Considering the large variety of sediment characteristics it is difficult to classify sediments in estuaries. This is the reason why different fields of research use different classifications. In sedimentology a classification based on sizes and mass contents is used, while geotechnics focuses on the mechanical behavior of soils which is related to the structure and volume fractions. For this thesis both classifications are considered.

Water in soil is either located in the pores between the grains (free water), or bonded to clay minerals (bonded water). In general, it is possible that pores are partially or fully filled with gasses such as air or methane. The latter is the result of the decomposition of organic matter.

Mineral composition

With regard to minerals sediments are divided into silicates and non-silicates (Jacobs, 2006). Silicates are further divided into quartz, feldspar, and clay minerals. An important difference between clay on the one hand and quartz and feldspar on the other is that clay particles can possess an electromagnetic charge. This charge enables clay particles to bind positively charged ions (cations) to them. These cations can sometimes be heavy metals such as mercury or lead, making clayey sediment in industrialized coastal zones a transport mode for contaminants. The cations can also be radioactive isotopes, making clayey sediment very weakly radioactive. The electromagnetic charge has another important consequence, which is coupled to the size of the particles: cohesive behavior. The small size of the clay particles enables them to bond together under Van der Waals forces, forming a cohesive structure. This is only possible however, if the negative charge of a clay particle is neutralized by a sufficient concentration of cations in the pore water. The cohesive strength between the clay particles depends on the pore water chemistry, salinity, pH, temperature and type of clay material.

Granular composition

In the classification of soil based on grain size distribution, grain sizes are often divided into mass contents. Content ξ_i [%] is defined as the mass of fraction i in relation to the total dry mass of the sediment:

$$\xi_i = \frac{M_i}{M_{sed}} \quad (2.1)$$

where M_i [g] is the mass of the solids of fraction i and M_{sed} [g] the mass of all the solids together. With regard to grain size three different contents relevant for this thesis are distinguished; the sand-, silt-, and clay contents. The sand content ξ_{sa} ranges between 63 μm and 2 mm, and consists solely of quartz and feldspar. The silt content ξ_{si} is defined as particles between 2 μm and 63 μm , and consists of a mixture of quartz, feldspar and clay minerals. Particles smaller than 2 μm make up the clay content ξ_{cl} . The clay content is mostly made up out of clay minerals, however some quartz and feldspar still remain. The erosion behavior of sediment changes as soon as it starts to show cohesive behavior. Whether or not a mixture of sand, silt, and clay can be classified as cohesive depends partly on the clay content, but also to a large extent on the structure of the soil. Sediment with a clay content of roughly 10 % or higher will show cohesive behavior. In most geotechnical applications the silt and clay contents are simply taken together as the mud content ξ_m , which is defined as all the particles smaller than 63 μm . The clay content often seems to be correlated to the silt content. The precise ratio between silt and clay contents can vary considerably amongst different estuaries (Flemming, 2000).

Mixtures with differing contents are classified using so-called sand-silt-clay-triangles (see Figure 2.1a for an example). The triangle is divided into different zones, each zone representing a different soil type. There are many ways to define these divisions, one of which is shown in Figure 2.1b. Most of these diagrams show a distinction between pure sand, silt, and clay, and any number of transitional mixtures. However, diagrams like Figure 2.1a and b do not give any insight into the cohesive behavior of the sediment. An improvement on these diagrams is the sand-silt-clay triangle as proposed by Van Ledden (2004), see Figure 2.2. The division between the sediment types in this triangle is based on both the occurrence of cohesion as well as the dominant network structure. The diagram in Figure 2.2 also includes data on the sediment composition of the Western Scheldt. It seems that for this estuary the ratio between clay- and silt-contents is more or less constant.

Organic composition

Organic matter in the soil can exist in many forms such as organic polymers, macro-organisms and micro-organisms. Organic content is created either by organisms living either in or on top of the sediment, or organisms living elsewhere. Micro-organisms such as algae or diatoms and macro-organisms such as plants can trap fine sediment and increase erosion resistance. Besides that, organic polymers can bond to clay particles through Van der Waals forces. This ability can enhance cohesive behavior, and can also increase erosion resistance. The same kind of triangular diagram used in the previous figures can be made for sand, clay and organic matter content instead of sand, silt, and clay (see Figure 2.3). Due to the correlation between mud and organic matter, samples from a single estuary form more or less a straight line, much like the clay-silt ratio for the Western Scheldt sediments in Figure 2.2. This sand-silt-clay-organic matter triangle also has different zones corresponding to different soil types. However, the main distinction here is between peat and other material such as sand, silt, or clay. In most estuaries peat is not present, and the organic matter content is less than 10 percent.

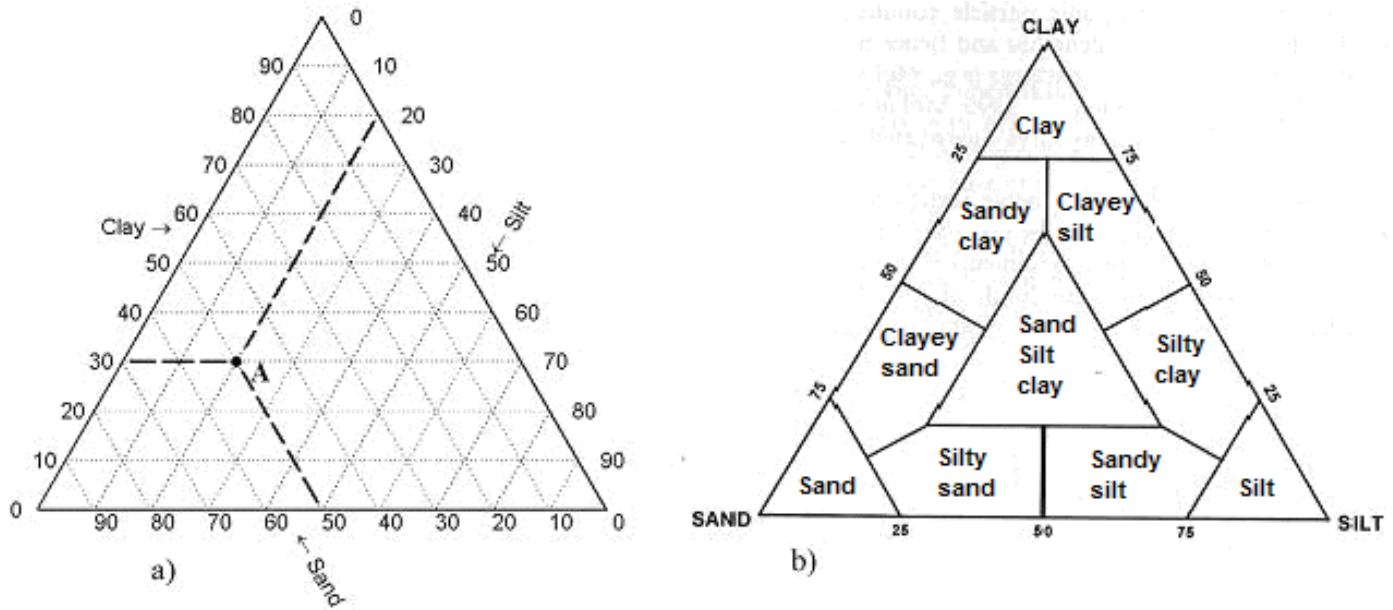


Figure 2.1: Examples of sand-silt-clay triangles: (a) In this triangle sediment in point A has a clay content of 30%, a silt content of 20%, and a sand content of 50%. (b) This triangle is used for sediment classification (Flemming, 2000).

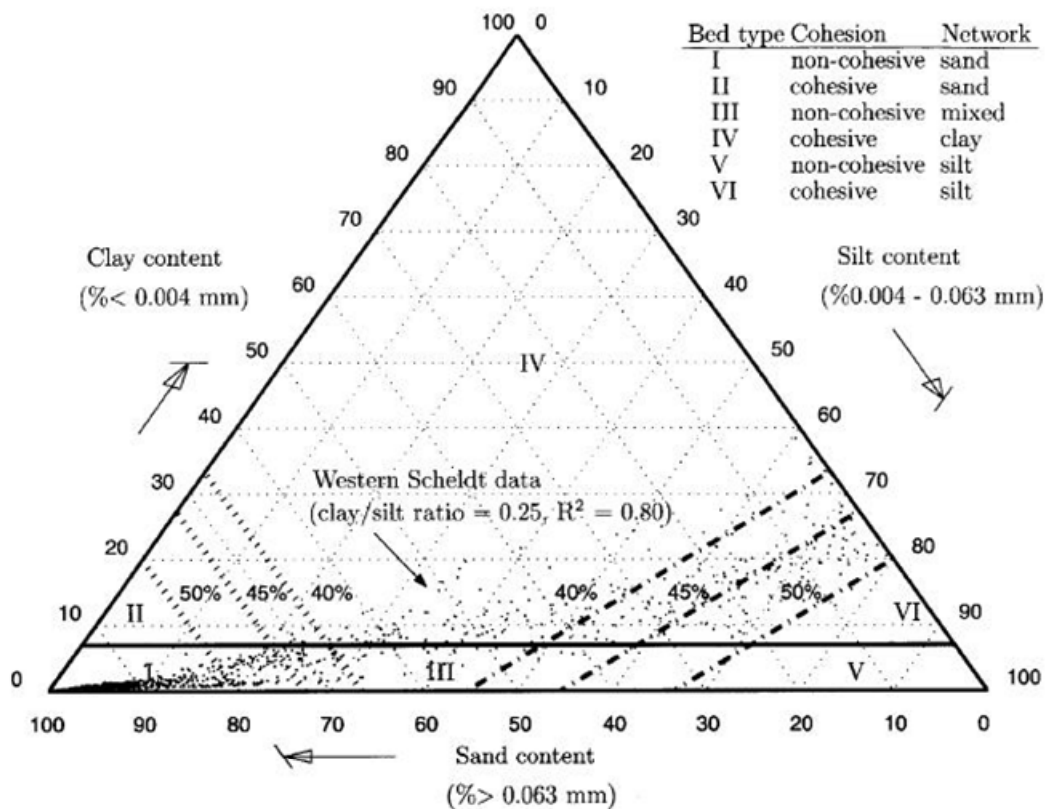


Figure 2.2: Sand-silt-clay triangle used for classification of sediment based on cohesion and network structure (Van Ledden, 2003). The dotted lines indicate the transition of network structure depending on water content.

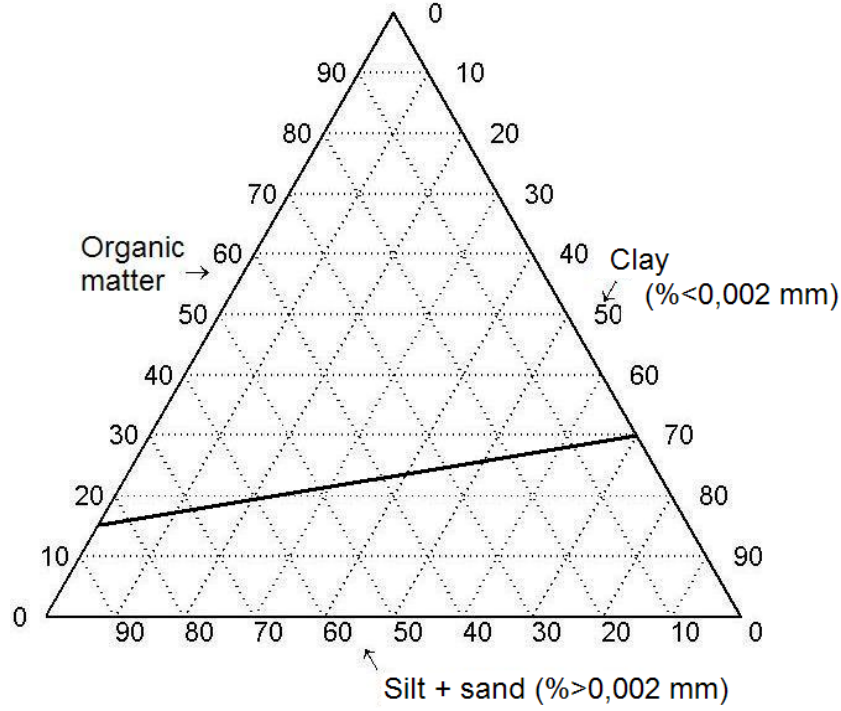


Figure 2.3: Sand-clay-organic matter triangle. The area above the black line is considered peat. The area below the black line can be better classified according to Figure 2.2. (NEN 5104, 1989)

2.1.2 Sediment structure

For the mechanical behavior of soils (e.g. erosion) also structure and cohesiveness are important. As mentioned in the previous paragraph, the transition from non-cohesive to cohesive behavior depends on both the clay content and the structure of the soil. Therefore, it is important to be able to describe the transitions between different types of possible structures. An important discriminator in this description is the porosity n [%], which is defined as the ratio between pore volume V_{pores} [m³] and the total wet volume V_{bulk} [m³]:

$$n = \frac{V_{pores}}{V_{bulk}} = 1 - \phi_{sed} \quad (2.2)$$

where ϕ_{sed} [%] is the volumetric concentration of the solids. The relation with the dry density and bulk density ρ_{dry} [kg/m³] and ρ_{bulk} [kg/m³] is as follows:

$$\rho_{dry} = (1 - n) \rho_{sed} \quad (2.3)$$

$$\rho_{bulk} = n \rho_w + (1 - n) \rho_{sed} = \rho_w + \left(\frac{\rho_{sed} - \rho_w}{\rho_{sed}} \right) \rho_{dry} \quad (2.4)$$

where ρ_w [kg/m³] is the density of the pore water (1000 kg/m³ for fresh water and 1030 kg/m³ for seawater), ρ_{sed} [kg/m³] is the specific density of the solids (about 2600 kg/m³),

and ρ_{dry} [kg/m³] is the density of the dry sediment. Equation 2.4 is only valid if total saturation is assumed. If the saturation term is included, Equation 2.4 becomes:

$$\rho_{bulk} = S n \rho_w + (1 - n) \rho_{sed} \quad \text{with } S = \frac{V_{water}}{V_{pores}} \quad (2.5)$$

where S [%] is the saturation of the soil. In general three types of structures are distinguished: sand-dominated skeletons, silt-dominated skeletons, and clay-water matrices. The first two structures are granular skeletons, with grains in mutual contact. The porosity of these skeletons is determined by their sorting and their packing. There are however minimum and maximum porosities. The theoretical minimum of about 25 % is obtained with the densest packing possible (see Figure 2.4a). A lower porosity would result in sedimentary rock, which is out of the scope of this thesis. Maximum porosity is obtained with the loosest packing possible (Figure 2.4b). This packing yields a porosity of about 50 %. The actual limits of these extremes as well as the question whether the skeleton is sand- or silt-dominated depends on the fraction sizes ψ_{sa} and ψ_{si} , where fraction ψ_i [%] is defined as the ratio of the volume concentration of fraction i (ϕ_i) to the total solids volume concentration (ϕ_{sed}):

$$\psi_i = \frac{\phi_i}{\phi_{sed}} \quad \psi_{sa} = \frac{\phi_{sa}}{\phi_{sa} + \phi_{si}} \approx \frac{\xi_{sa}}{\xi_{sa} + \xi_{si}} \quad (2.6)$$

The right hand term of the second part of Equation 2.6 is only valid if the specific densities of the fractions are equal. The development of the maximum and minimum porosities as a function of sand- and silt- fractions is given in Figure 2.5. One has to keep in mind the porosity in this graph only relates to the space between the granular material, and gives no insight into whether the pores are filled with clay or water. Higher porosities than the maximum in Figure 2.5 means that the granular particles are no longer in mutual contact (Figure 2.4c). In this case the particles are either suspended in water (quicksand), or trapped in a clay-water matrix. For this region the sand-silt porosity is determined according to Equation 2.7.

$$n_{sasi} = n + \xi_{cl} (1 - n) \quad (2.7)$$

As in Equation 2.6, this equation is only valid if the specific densities of all the fractions are equal, and the clay fraction is equal to the clay content ($\xi_{cl} = \psi_{cl}$).

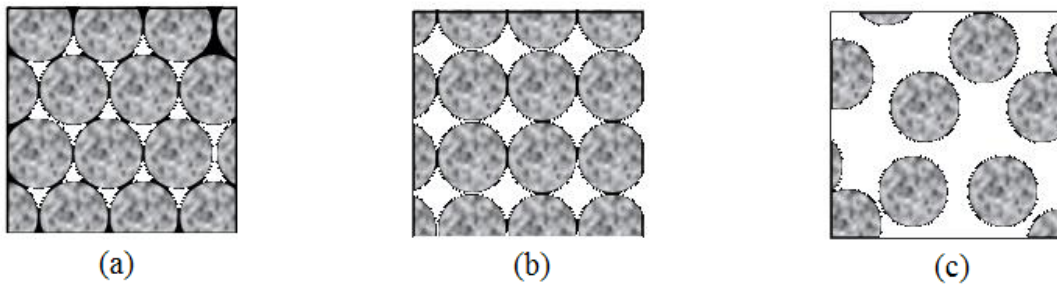


Figure 2.4: Different network structures for granular material. (a) Most dense packing. (b) Least dense packing. (c) No contact between particles.

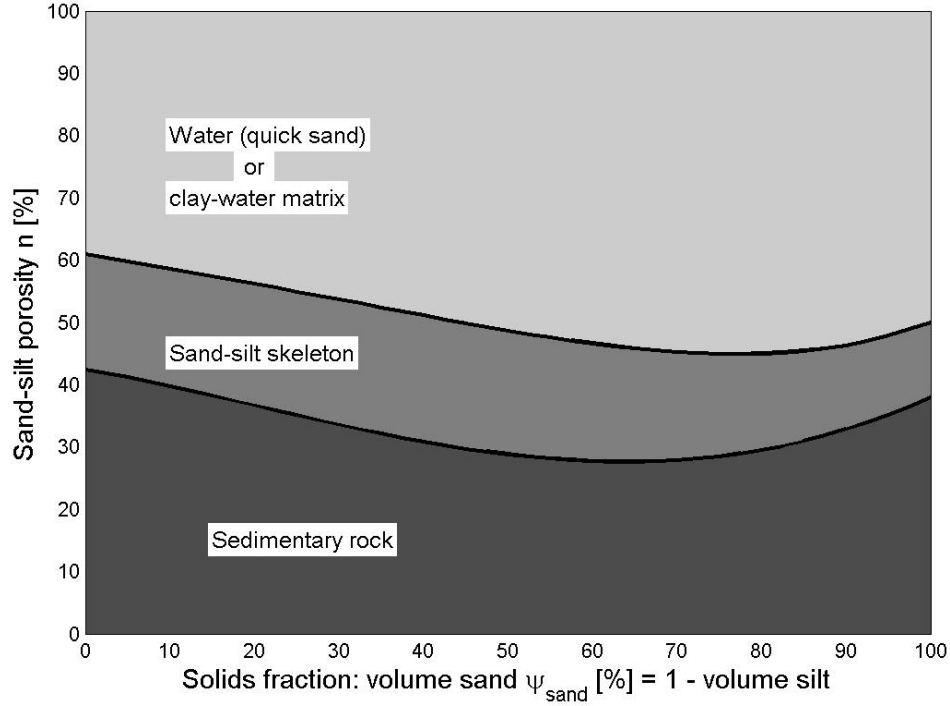


Figure 2.5: Minimum and maximum porosity of sand-silt mixtures. The continuous lines separating the different types of network structures (marked in shades of grey) indicate the measured minimum and maximum porosities for granular skeletons.

2.1.3 Geotechnical properties

Geotechnical classifications are based more on the mechanical behavior of the soil. This behavior determines for example the resistance of the soil against erosion. As mentioned in the previous paragraph, the cohesiveness of a sand-silt-clay mixture does not solely depend on the content sizes. It also depends on water content, which is defined in the following way:

$$W = \frac{M_{water}}{M_{sed}} \quad (2.8)$$

$$W = S \frac{n}{1-n} \frac{\rho_w}{\rho_{sed}} \quad (2.9)$$

where M_{water} [g] is the mass of the water in the soil, which includes both the water in the pores as well as the water bonded to the clay particles. The water content has a strong influence on the geotechnical behavior of the soil. There are three types of behavior: solid, plastic, and liquid behavior. The water contents that mark the transitions between these types are called the Atterberg or plasticity limits (see Figure 2.6). The plastic limit W_{PL} [%] is the transition between solid and plastic behavior. The liquid limit W_{LL} [%] is the transition between plastic and liquid behavior. The difference between these two limits is called the plasticity index W_{PI} [%]:

$$W_{PI} = W_{LL} - W_{PL} \quad (2.10)$$

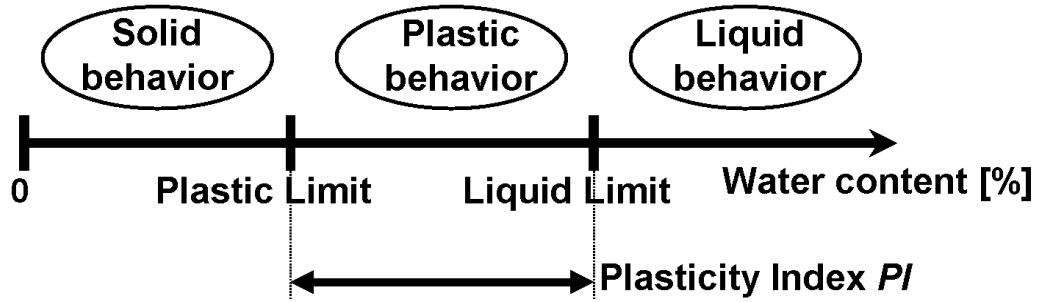


Figure 2.6: Atterberg or plasticity limits.

The plasticity index is a measure of the capacity of the soil to bind water, and depends on the type of clay mineral (Winterwerp and Van Kesteren, 2004). It is in fact a measure for the cohesiveness. When the clay content ξ_{cl} is put out against W_{PI} in a so-called activity plot, it shows a clear linear relationship (see Figure 2.7). The slope of this relationship is called the activity A_{cl} [-], and is a measure of the capacity of a specific clay mineral to bind water to it:

$$W_{PI} = A_{cl} (\xi_{cl} - \xi_{cl,0}) \quad (2.11)$$

The ratio between bonded and free water is reflected in the relative water content W_{rel} [%]:

$$W_{rel} = \frac{W}{W_{PI}} = \frac{W}{A_{cl} (\xi_{cl} - \xi_{cl,0})} \quad (2.12)$$

where $\xi_{cl,0}$ is the critical clay content for cohesive behavior. The relative water content is a practical parameter, because it is independent of forcing conditions and is easy to derive using simple tests.

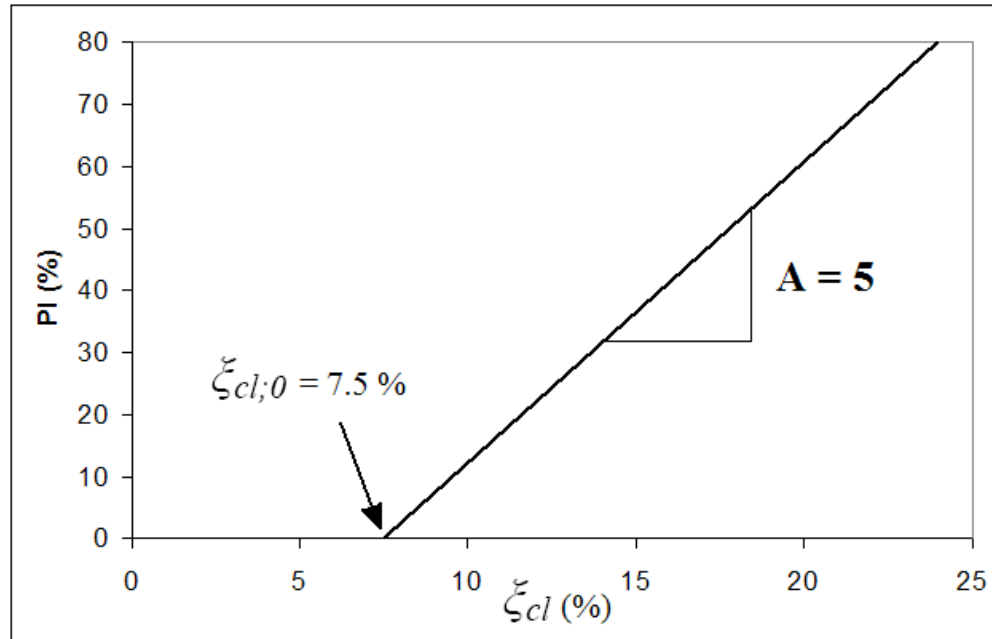


Figure 2.7: Activity plot showing the relation between clay content and plasticity index. In the example in this plot the critical clay content $\xi_{cl,0}$ is 7.5%, and the activity A_{cl} is 5.

2.2 Radiometric sedimentology

One of the techniques used to measure sediment composition in the field is through measurement of natural gamma radiation. The governing principles regarding this technique are explained in this paragraph.

2.2.1 Radioactivity

Cores of atoms can occur in multiple forms. Each individual form is called a nuclide, which can differ from other nuclides in both the number of protons and the number of neutrons. The distinction between chemical elements is made according to the atom number, which is the number of protons in the nucleus. Nuclides with the same atom number but with different atomic masses are called isotopes. The difference in mass is caused by a difference in the number of neutrons and therefore the structure of the nucleus. This structure can make some isotopes unstable, making them able to break up into smaller, lighter atoms. This process is called atomic decay. When atomic decay occurs, it is accompanied by the emission of radiation. Some radioactive isotopes (also called radionuclides) decay into other isotopes which are in turn unstable and decay even further under emission of radiation.

Radioactive decay or radioactivity A is measured in units of Becquerel [Bq]. One Bq indicates 1 decaying nucleus per second. The decay of any atom is an entirely random event, and is therefore described by Poisson statistics. Each atom of a certain isotope is equally likely to decay at any time. Therefore, the number of radionuclides N in a material diminishes in time according to an exponential function:

$$N(t) = N_0 e^{-\lambda t} \quad (2.13)$$

where $N(t)$ is the number of nuclides at time t , N_0 is the number of nuclides at $t=t_0$, and λ [s^{-1}] is the decay constant, which is specific for each isotope. The activity at any given time becomes:

$$A(t) = \lambda N \quad (2.14)$$

Another important quantity is the so-called half life time $T_{1/2}$ [s], which is the time it takes for an amount of isotopes to decay to half its initial activity. The relation with the decay constant is as follows:

$$T_{1/2} = \frac{\ln 2}{\lambda} \quad (2.15)$$

When atoms decay they will emit radiation. Radiation can occur in different forms. Some important forms are alpha, beta, and gamma radiation. Alpha radiation consists of Helium-nuclei, and has a very low penetrative power, in the order of only a few cm in air and even less in more dense material. Beta radiation consists of free electrons or their anti-particles, which are called positrons. It has more penetrative power than alpha-particles, but is still absorbed by mere cm's of material. Finally, gamma radiation is part of the electromagnetic spectrum, and consists of photons with an energy level above 100 keV. The high energy makes the wavelength very small (10^{-11} to 10^{-14} m). Because of this small wavelength and the fact that, unlike alpha- and beta-particles, gamma photons are

not charged, their penetrative power is very high. High intensity gamma radiation can only be attenuated by thick layers of dense material such as lead or concrete.

Gamma radiation is usually released after a nucleus decays under emission of beta radiation, leaving the nucleus in an excited state (Hussein, 2003a). The gamma ray emission carries the energy difference between the excited and stable state of the nucleus. This energy difference is always set, and therefore the energy of the emitted gamma ray is also fixed. The amount of energy differs for each type of isotope. Therefore, different isotopes can be recognized by measuring the energy of their gamma radiation.

2.2.2 Interaction between matter and gamma radiation

When gamma radiation penetrates a medium, it can interact with the atoms in the medium in several ways (Koomans, 2001). The three most important processes are pair production, Compton scattering, and photo-electric absorption. All these types of interactions have a certain probability of occurrence. This probability of interaction of radiation with an atom is expressed in a quantity called the microscopic cross-section (Hussein, 2003a).

With pair production, part of the energy of a photon is converted into an electron-positron pair. The energy threshold for pair production is 1.022 MeV, and becomes dominant above 4 MeV. Since the maximum energy of natural gamma radiation is 2.6 MeV, pair production is not of great importance for the research described in this thesis.

Photo-electric absorption is what happens when the full energy of a photon is absorbed by an atomic electron. This electron is then ejected from the atom. This so-called photo-electric effect is only dominant over the other forms of interaction when the energy of the gamma ray is low (<0.5 MeV), or when the atomic number Z of the atom is high (see Figure 2.8). The cross-section τ [m²] for photo-electric absorption therefore depends on the atomic number Z and the energy of the incident photon.

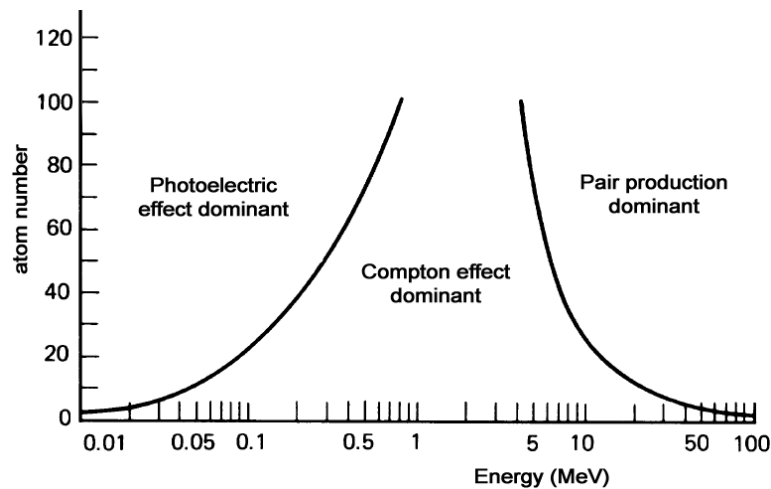


Figure 2.8: Relative importance of interaction processes (Hendriks, 2003)

Compton scattering occurs when a photon collides with an atomic electron and transfers only a part of its energy to the electron. This electron is then ejected. The remainder of the energy of the incoming photon is carried away by a secondary photon. The direction of this outgoing photon is usually different from that of the incoming

photon (see Figure 2.9). The Compton scattering process is dominant over medium range energies ($\sim 0.5\text{-}5\text{ MeV}$). The cross-section $\sigma\text{ [m}^2\text{]}$ for Compton scattering depends only on the energy of the incoming photon.

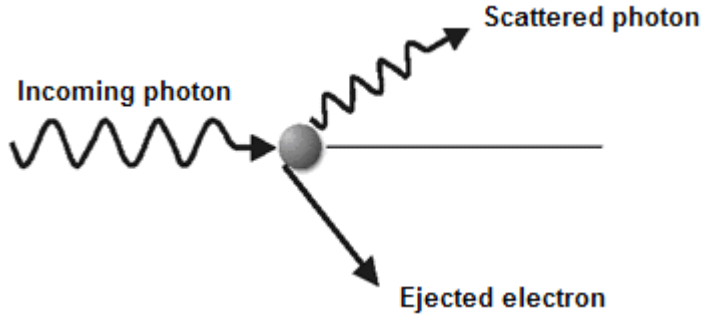


Figure 2.9: Schematisation of Compton scattering (Tijs, 2007).

When a gamma photon travels through a medium, the probability of the photon either being absorbed or scattered depends on the number of atoms per unit volume, the cross-section for absorption, and the length of the path traveled through the medium:

$$P(n, \sigma, l) = e^{-n\sigma l} \quad (2.16)$$

where $n\text{ [m}^{-3}\text{]}$ is the number of atoms per m^3 , $\sigma\text{ [m}^2\text{]}$ the cross-section for absorption, and $l\text{ [m]}$ the distance traveled through the medium. The cross-section for absorption σ depends on the atomic number Z of the material. For Compton scattering σ is proportional to Z . The product of n and σ can also be expressed as the product of the bulk density ρ and the mass attenuation coefficient $\mu\text{ [m}^2\text{/kg]}$:

$$P(d, \rho) = e^{-\mu \int \rho(l) dl} \quad (2.17)$$

If the thickness of a material is known, the attenuation of gamma radiation is only dependant on bulk density. However, this is only valid if the mass-attenuation coefficient remains constant. The mass attenuation coefficient is simply the sum of the cross-sections from each type of interaction per unit mass. The coefficient is independent on the material as long as the energy range is considered where predominantly Compton scattering occurs. In this case the radiation only interacts with the atomic electrons. The density of this “sea” of electrons is directly proportional to the mass-density (Hussein, 2003b). This makes gamma radiation with medium range energies suitable for the determination of densities of materials with unknown composition.

2.2.3 Gamma ray energy spectrum

A detector receiving gamma photons with a single energy will record an energy distribution composed of roughly two regions: the photopeak and the Compton-continuum, shown in Figure 2.10.

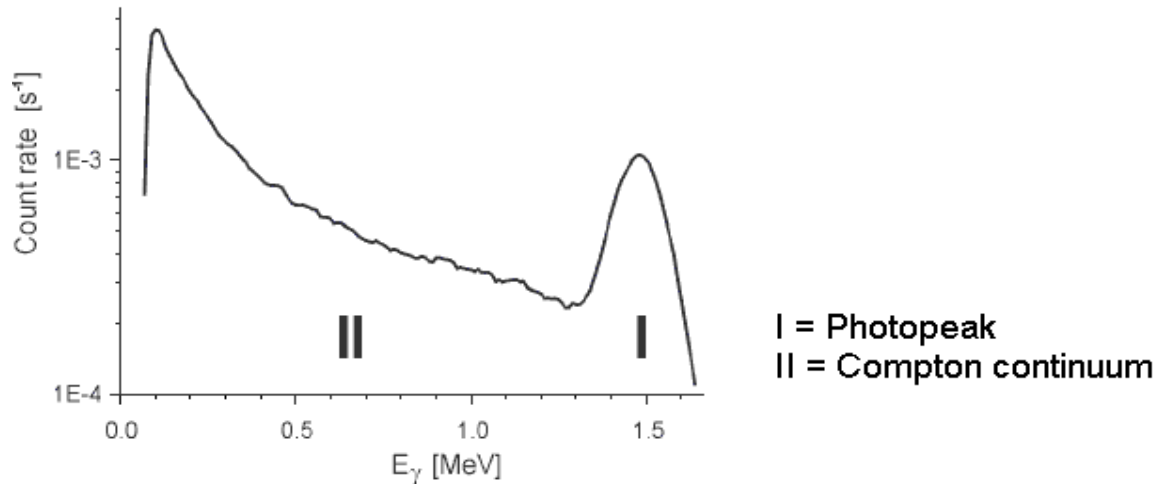


Figure 2.10: Gamma ray spectrum of ^{40}K . The horizontal axis of this histogram represents the measured energy of the photons. The vertical axis represents the number of photons with a certain energy. Area I represents the photopeak, area II the Compton-continuum.

The photopeak is the result of photons transferring all their energy to an electron through photo-electric absorption. While the energy of the photons is discrete, the photopeak has a Gaussian shape due to the inaccuracy in the detecting process. The second part of the spectrum is the Compton-continuum, and represents the photons that interact with the detector through Compton scattering. The energy that is transferred from the incident photon to the electron and secondary photon is not set, and the secondary photon can interact again by either photo-electric absorption or Compton scattering. This leads to the continuum shown in Figure 2.10.

2.2.4 Natural radioactivity

Natural sediments contain trace amounts of four radioactive isotopes: ^{40}K (Potassium), ^{232}Th (Thorium), ^{238}U (Uranium), and ^{137}Cs (Caesium) (Van der Graaf *et al.*, 2007). These amounts vary with the composition of the sediment, as explained in Paragraph 2.1.1. These isotopes are heavy metal ions, and adhere more easily to the charged surfaces of clay particles than to sand particles. They can also be incorporated into the crystalline structure of the sediment (e.g. K-feldspar). This makes the amount of radioactive materials an indicator for the composition of the sediment bed.

To determine the sediment composition three radionuclides are relevant: ^{40}K , ^{232}Th , and ^{238}U . All these isotopes were created in the formation of the earth, and have half-life times longer than or comparable to the earth's age, meaning their amounts do not change significantly over several years. ^{137}Cs nuclides were created in either nuclear weapon tests or the Chernobyl accident. This difference in origin means ^{137}Cs concentrations are generally very low, and its presence is restricted to the top layers. For these reasons ^{137}Cs is not used for the determination of sediment composition.

2.2.5 Fingerprinting

As mentioned in the previous subparagraph naturally occurring radio-active isotopes in sediments are used to determine sediment composition. This is done by measuring the intensity of the gamma radiation coming from ^{40}K , ^{232}Th , and ^{238}U . The intensity is

converted into the activity concentration C [Bq/kg], which is the activity per unit mass for each nuclide. Here the mass is only the mass of the solids, because water is not radioactive, and only dilutes the concentration. The activity concentration is then translated into sediment fraction sizes with a translation key. This translation key is a sediment property, and is called the fingerprint of the sediment. The fingerprint of a specific sediment describes the typical concentration of radio-active nuclides. If two types of sediment have different fingerprints, they are radiometrically distinguishable (Roberti, 2001).

The use of radiometric fingerprints for fraction analysis is based on the assumption that the total activity concentration of a specific nuclide in a sediment is the sum of the activity concentrations from each sediment fraction (see van Wijngaarden *et al.*, 2002a; Tijs, 2007):

$$\sum (\xi_{fraction_i} * C_{fraction_i}(Th)) = C^{tot}(Th) \quad (2.18)$$

where $\xi_{fraction_i}$ equals the content of fraction i , $C_{fraction_i}(Th)$ [Bq/kg] equals the activity concentration for ^{232}Th per fraction, and $C^{tot}(Th)$ [Bq/kg] equals the total activity concentration for the solids for ^{232}Th . In Equation 2.18 the activity concentrations for ^{232}Th ($C_{fraction_i}(Th)$) per fraction represent the actual fingerprint. These values have to be determined beforehand by means of radiometric analysis on samples with known fraction contents. If these values are known, the activity concentration of ^{232}Th measured in the field ($C^{tot}(Th)$ in Equation 2.19) is converted into a fraction content according to the following equation:

$$\xi_{fraction2} = \frac{C^{tot}(Th) - C_{fraction1}(Th)}{C_{fraction2}(Th) - C_{fraction1}(Th)} \quad (2.19)$$

It is also possible to use the activity concentrations and fingerprints for ^{40}K or ^{238}U to compute the contents. However, the correlation between fraction content and Thorium concentrations is generally stronger than the correlation between fraction content and Potassium or Uranium concentrations. This means that using ^{232}Th in Equation 2.19 generally returns better results.

3 Methods

3.1 The MEDUSA RhoC device

The MEDUSA RhoC system is a new instrument designed to measure several quantities in situ; mud content, soil density, and water content. In this paragraph all the system's components are named and explained.

The RhoC roughly consists of five components (see Figure 3.1): a gamma ray detector, a gamma ray source, a TDR (Time Domain Reflectometry) device, a GPS, a logger system and a power supply.

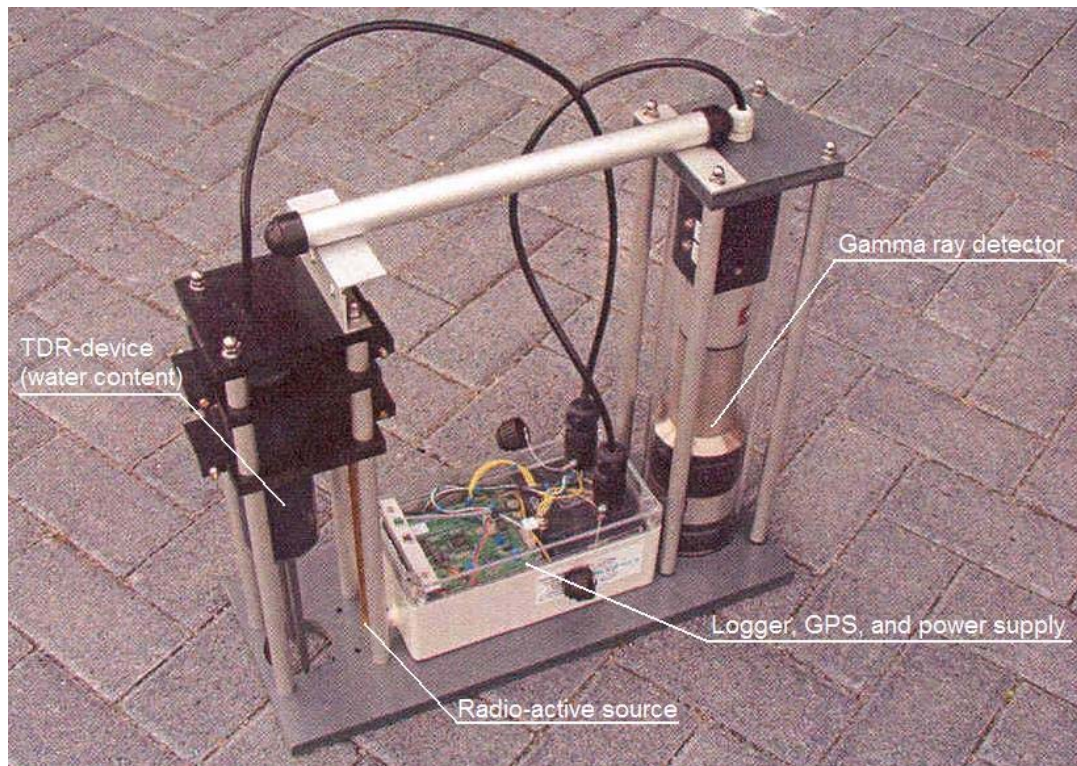


Figure 3.1: Overview RhoC device.

The entire system is 20 cm wide, 50 cm long, 50 cm high, and weighs roughly 8 kg. The device is operated by means of a portable field computer which controls the operation of the RhoC through a wireless connection. The entire system is transported either by carrying it by hand with a handle, or by carrying it in a custom made backpack.

3.1.1 General description

The logger system consists of two parts: a portable tablet computer and a multi-channel analyzer (MCA) housed in the central system box on the RhoC. The MCA is connected to the detector, the TDR-device and the GPS, and relays the data coming from these components towards the tablet computer through a wireless Bluetooth connection. This wireless connection limits the maximum distance between the RhoC and the logger tablet to about 5 meters. The tablet computer carries with it its own power supply. The software

on this computer automatically stores the data coming from the MCA. The data coming from the gamma ray detector is stored both in the form of a gamma ray spectrum as well as quantities derived from that spectrum such as soil density and soil composition. In this way the user can directly read out these quantities, while the raw data is still preserved for possible afterward analysis.

The power supply of the RhoC consists of a 12V lead-acid battery, which can supply power to the RhoC for about 8 to 10 hours of non-stop use. The battery is recharged with a standard charger. In case the battery starts to become depleted, the system will warn the user through a message on the logger tablet.

The RhoC is equipped with a GPS to supply the logger with exact geographical coordinates. The GPS is powered by the same battery which powers the rest of the system, and is incorporated into the system box along with the MCA and the power supply.

3.1.2 Gamma ray detector

The gamma ray detector is used for the radiometric determination of soil composition, as well as the density measurement. The detector comprises a CsI (Caesium Iodine) scintillation crystal and a photomultiplier. When a gamma photon enters the crystal, it interacts with the material of the crystal either by photo-electric absorption or Compton scattering. The process of pair production can also occur, but does not play an important role. In the processes of photo-electric absorption and Compton scattering the energy from the gamma photons is transferred to free electrons, which in turn interact with atomic electrons. In a scintillation crystal this interaction between electrons results in the form of light generation. The intensity of this very faint pulse of light is proportional to the energy of the gamma photon. The number of gamma photons entering the detector is slightly higher than the number of pulses entering the photomultiplier, because it is possible a photon passes through the detector without interacting with the crystal. The photomultiplier converts the light pulses into an electric signal and amplifies it. However, the amplification increases with increasing temperature, resulting in a higher recorded energy. This means an energy spectrum recorded by this kind of detector is slightly scaled linearly towards the higher energies under the influence of the temperature. The exact intensity of the light pulses and the amplification of the electric signal do not only depend on the temperature, but also on the crystal itself. Therefore, every detector has to be calibrated individually.

3.1.3 Gamma ray source

The gamma ray source is used for the density measurement. The source consists of a small ^{22}Na source. It is placed on the outer end of a brass rod, which is extended over 15 cm into the soil. When the rod is pushed into the soil, some of the gamma radiation emitted by this source enters the same gamma-ray detector used to determine soil composition. By measuring the attenuation of the radiation from the source, the density of the soil between the source and the detector is determined. As the source is pulled up, the density is measured over different pathways (see Figure 3.2). For the determination of the depth of the rod, a steel cable is attached between the top of the rod and a winch inside the box that houses the logger system. The depth is determined by measuring how far the cable is extracted from the winch.

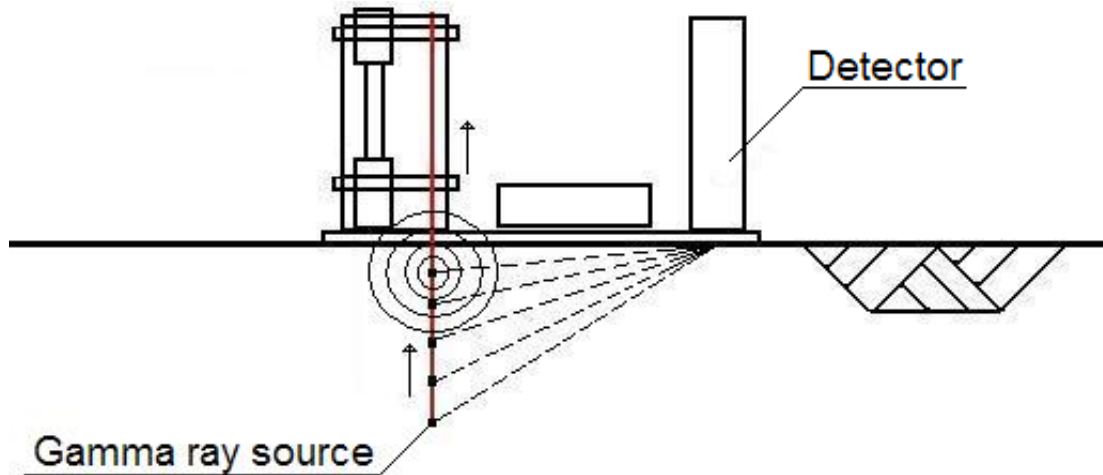


Figure 3.2: Placement of the gamma ray source for density measurements.

The choice for the ^{22}Na source is based on four criteria; the activity of the source, its half life time, its natural absence in sediments, and the shape of the emitted energy spectrum. The activity of the source is strong enough to make density measurements possible with sufficient accuracy. However, it is still weak enough to allow measurements to take place without the need for protection against radiation³. The half life time is 2.6 years, giving the source a constant activity over the course of a measurement. ^{22}Na is not present in natural soils in noticeable quantities (Tijs, 2007). The shape of the energy spectrum emitted by ^{22}Na has a shape that makes it more easily distinguishable from other nuclides.

3.1.4 Energy spectrum analysis

A gamma ray detector placed on top of sediment receives radiation coming from the decaying radionuclides present in the soil as well as other sources such as cosmic radiation. Radiation from these other sources is called the background radiation. The spectrum of the background radiation and the radiation coming from the nuclides in the sediment picked up by the detector is scaled horizontally due to the influence of temperature on the detector. To determine the activity concentration per nuclide, the spectrum of the radiation is broken down into the spectra of the nuclides present in the soil with a technique known as full spectrum analysis. With this technique, standard spectra of ^{40}K , ^{232}Th , and ^{238}U (the red, green and blue lines respectively in Figure 3.3) are scaled and added together to make a fit using a least-squares method upon the spectrum measured by the detector (the dots in Figure 3.3). From this fit the activity concentration for each nuclide is derived. The process of scaling the spectra is known as stabilization. The activity concentration calculated with this method is still a concentration over the bulk of the sediment including the water content. To get the true activity concentration in the dry solids, the concentration measured by the RhoC has to be corrected for the water content (see Equation 4.1).

³ The strength of the source makes MEDUSA RhoC different from other available systems that use radiation for density measurement. In contrast to the RhoC, the other systems have to use a much more powerful source, making radiation protection necessary.

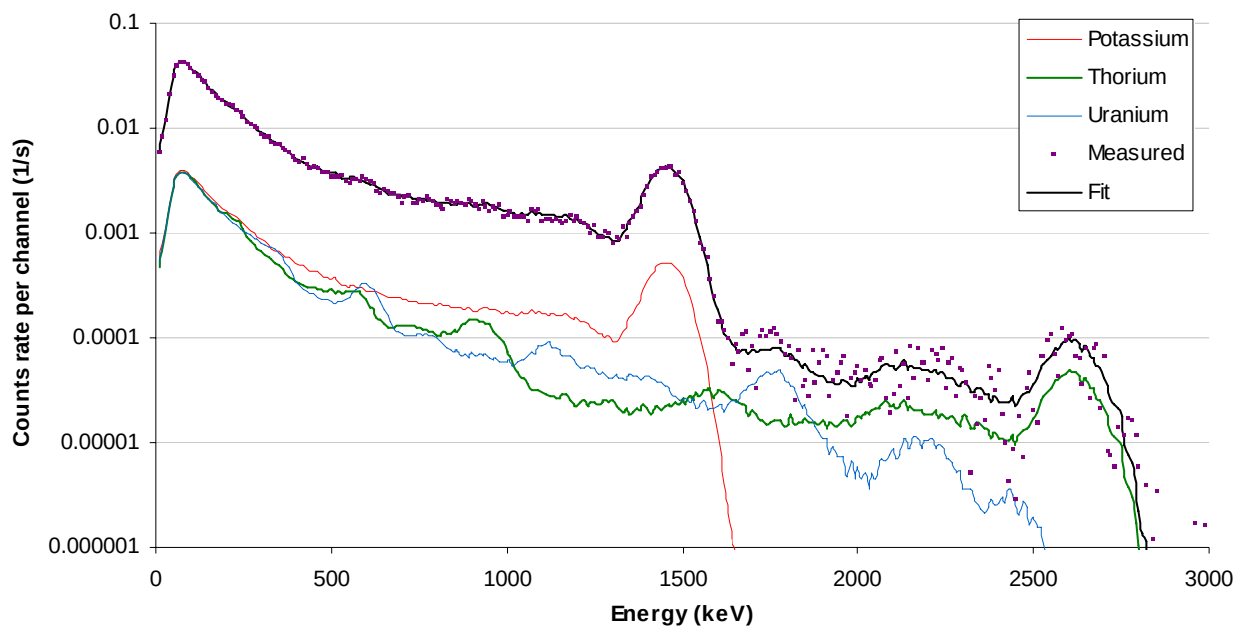


Figure 3.3: Total spectrum and spectrum per nuclide (Tij, 2007).

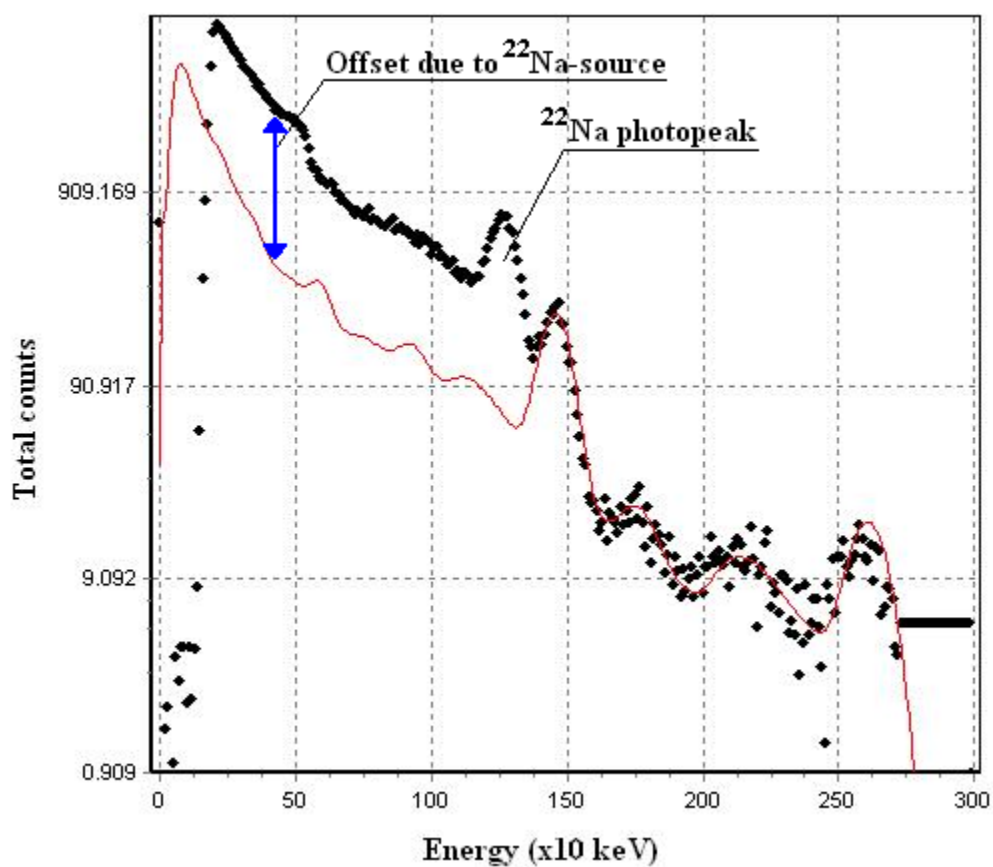


Figure 3.4: Measured energy spectrum with ^{22}Na source. The continuous line is the calculated background spectrum. The dots represent the measured spectrum.

Because of the ^{22}Na source, part of the number of photons picked up by the detector will not belong to the background but instead come from the source. This causes two things: the measured spectrum has an extra photopeak at roughly 1275 keV, and the spectrum below this energy is elevated relative to the background spectrum (see Figure 3.4). This makes full spectrum analysis more complicated, because the shape of the standard spectrum of ^{22}Na changes with changing soil density or when the location of the source is altered (see Figure 3.5). In this figure it is visible that for higher densities the detector does not just receive less photons from the source. The normalized spectra show the spectrum is not just scaled vertically, it also changes shape. This means using just one standard spectrum for ^{22}Na results in inaccuracies in both sediment composition and density measurements. The standard spectra of ^{40}K , ^{232}Th , and ^{238}U do not change for different sediment densities. This is because the sediment can be regarded as a half-infinite source of gamma radiation, where the attenuation of the radiation coming from ^{40}K , ^{232}Th , and ^{238}U is based on mass, and not on volume. Therefore, different densities do not affect the standard spectra of the ^{40}K -, ^{232}Th -, and ^{238}U nuclides in de sediment.

To determine activity concentrations for the nuclides in the sediments as well as the density of the soil, the full spectrum analysis technique can still be applied. The influence of the source is included by the addition of a standard spectrum for ^{22}Na . However, since the shape of this spectrum depends on both the location of the source and the density of the soil, different standard spectra for different depths have to be used. Also, since the soil density is not exactly known beforehand, a standard spectrum has to be chosen based on an estimation of the density. This causes inaccuracies in both the determination of the background spectrum as well as the density. Therefore, a different method is applied.

To determine activity concentrations for the nuclides in the sediments as well as the density of the soil, a technique called partial spectrum analysis is applied. This technique, just like full spectrum analysis, uses standard spectra of ^{40}K , ^{232}Th , ^{238}U , as well as ^{22}Na to make a best fit upon the measured spectrum. The only difference is that for the determination of the activity concentrations of ^{40}K , ^{232}Th , and ^{238}U only the part of the spectrum is considered, which is not affected by the radiation coming from the source. The reason why ^{22}Na is used to calculate the fit but not the activity concentrations, is that the peaks in the standard spectrum of ^{22}Na do not move, but only change shape when the density or source position is altered. Therefore, a standard spectrum for ^{22}Na is not usable for full spectrum analysis, but it is used to determine the stabilisation.

Since the spectrum of ^{22}Na cuts off at about 1400 keV, only the measured spectrum above this energy is used for determination of the activity concentrations. This means partial spectrum analysis incorporates fewer counts per time unit than full spectrum analysis. Since the statistical accuracy of this method depends on the number of counts, partial spectrum analysis needs a longer measurement time. The difference in intensity between the fit (the continuous line in Figure 3.4) and the measured spectrum is caused by the source, and is used to calculate the density.

The density is calculated by using the measured count rate C' (counts per second) coming from the ^{22}Na source as input into the following equation:

$$\rho(C') = -\frac{1}{\alpha_0} \ln(C') + \frac{1}{\alpha_0} \ln(\beta_0) \quad (3.1)$$

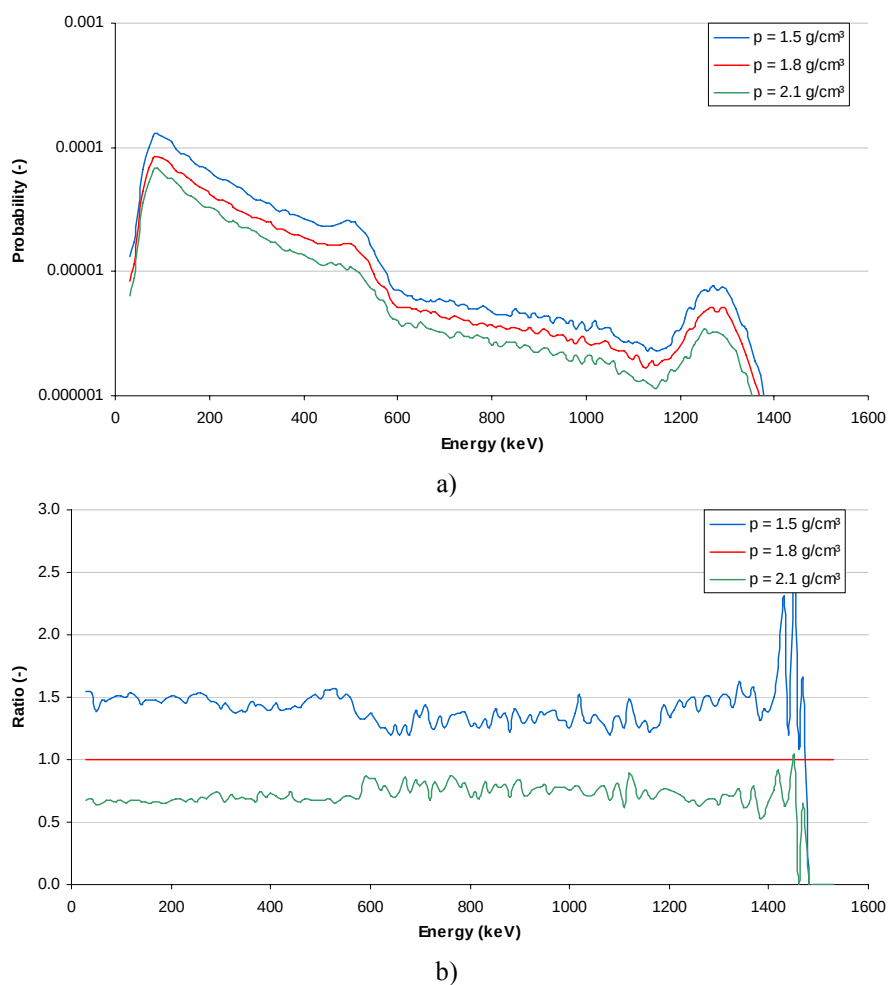


Figure 3.5: a): Three ^{22}Na spectra for different densities. The blue line corresponds to a density of 1.5 g/cm^3 , the red line to a density of 1.8 g/cm^3 and the green line belongs to a density of 2.1 g/cm^3 . In b) these spectra are normalized on the spectrum for 1.8 g/cm^3

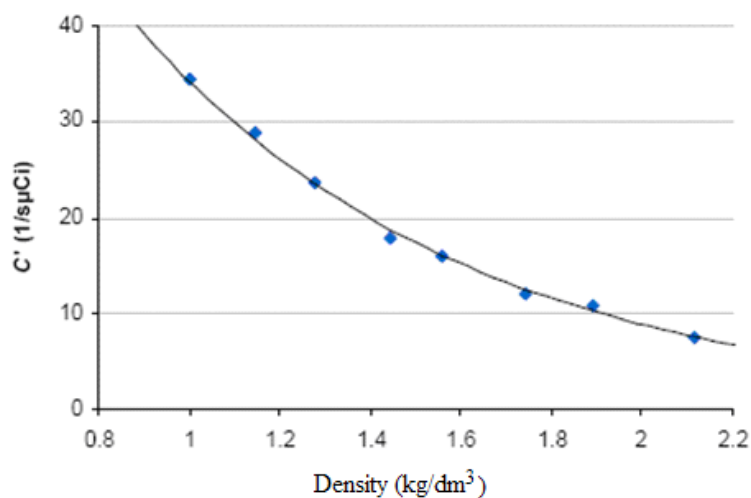


Figure 3.6: Calibration curve for the density measurement (Tij, 2007). The quantity on the vertical axis is the count rate, corrected for the activity of the source, unit = $\text{s}^{-1} \mu\text{Ci}^{-1}$ ($1 \mu\text{Ci} = 37 \cdot 10^3 \text{ Bq}$).

where α_0 and β_0 are constants, which depend on the depth of the source. The values of α_0 and β_0 for different depths have been determined from calibration. This calibration consisted of measuring the count rates for known densities at a constant depth. A logarithmic fit was made through the data points from these measurements (Figure 3.6), and from this fit the values for α_0 and β_0 are determined. This procedure is repeated for different depths. When the RhoC is used in the field, the depth of the source can fall between the depths for which α_0 and β_0 are determined. On this depth the values for α_0 and β_0 are interpolated.

3.1.5 Calculating density profile from density measurements

A stratified structure of the sediment means the erosive behavior changes when a certain amount of erosion has occurred. This means it is important for the modeling of this erosion to have information on the vertical stratification of the sediment. A profile of the density over the depth would yield more insight into the stratification. However, the density measured by the RhoC is an average density over the pathway (l_2-l_1) between the source and the detector. In Figure 3.7 this pathway can be both the path between AD or BD:

$$\bar{\rho}_{l_2-l_1} = \frac{\int_{l_1}^{l_2} \rho(l) dl}{l_2 - l_1} \quad (3.2)$$

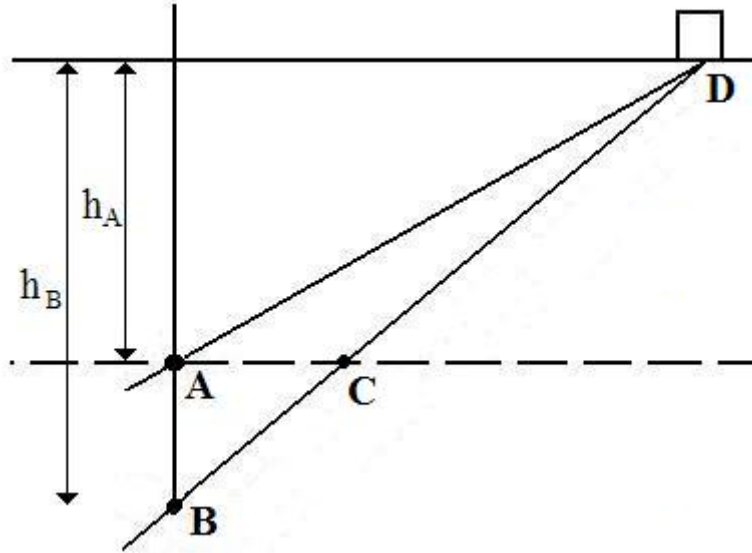


Figure 3.7: Density measured by RhoC is depth averaged along pathways AD and BD.

If the assumption is made that there is no horizontal gradient in density, then the average density between points C and D (see Figure 3.7) is equal to the density between points A and D. However, the shape of $\rho(l)$ for pathway AD will be different from the shape of $\rho(l)$ for pathway CD, because of the difference in length:

$$\bar{\rho}_{AD} = \frac{\int_A^D \rho(l_{AD}) dl_{AD}}{AD} = \bar{\rho}_{CD} = \frac{\int_C^D \rho(l_{BD}) dl_{BD}}{CD} \quad (3.3)$$

$$\frac{\int_A^D \rho(l_{AD}) dl_{AD}}{\int_C^D \rho(l_{BD}) dl_{BD}} = \frac{AD}{CD} \quad (3.4)$$

$$\int_C^D \rho(l_{BD}) dl_{BD} = \frac{CD}{AD} \int_A^D \rho(l_{AD}) dl_{AD} = CD \cdot \bar{\rho}_{AD} \quad (3.5)$$

The difference in depth-averaged density measured in points A and B should be caused by the density of the soil between points B and C:

$$\bar{\rho}_{BD} = \frac{\int_B^D \rho(l_{BD}) dl_{BD}}{BD} \quad (3.6)$$

$$\begin{aligned} \bar{\rho}_{BD} \cdot BD &= \int_B^D \rho(l_{BD}) dl_{BD} = \int_B^C \rho(l_{BD}) dl_{BD} + \int_C^D \rho(l_{BD}) dl_{BD} \\ &= \bar{\rho}_{BC} \cdot BC + \bar{\rho}_{CD} \cdot CD = \bar{\rho}_{BC} \cdot BC + \bar{\rho}_{AD} \cdot CD \end{aligned} \quad (3.7)$$

$$\bar{\rho}_{BC} = \frac{\bar{\rho}_{BD} \cdot BD - \bar{\rho}_{AD} \cdot CD}{BC} \quad (3.8)$$

This means that the depth-averaged densities measured by the RhoC are converted into a density profile over depth according to the following equation:

$$\bar{\rho}_{AB} = \bar{\rho}_{BC} = \frac{\bar{\rho}_{BD} \cdot h_B - \bar{\rho}_{AD} \cdot h_A}{h_B - h_A} \quad (3.9)$$

where $\bar{\rho}_{AB}$ is the average density [kg/m^3] between two measurement points (points A and B), $\bar{\rho}_{AD}$ and $\bar{\rho}_{BD}$ are the depth average densities in points A and B measured by the RhoC, and h_A and h_B are the depths of points A and B below the surface.

3.1.6 Detection of water content

For the detection of the soil water content various methods were evaluated by the manufacturer. From these methods a technique based on Time domain Reflectometry (TDR) was chosen because of its accuracy and ease of use (Tijs, 2007). Time Domain Reflectometry is a method for measuring the dielectric constant of the soil. The dielectric constant K [-] is also known as the relative dielectric permittivity. The permittivity is a measure of a material's ability to polarize in response to an electric field, thus reducing the electric field inside the material. The propagation velocity v [m/s] of an electromagnetic wave through a medium depends on the dielectric constant of that

medium. In case of the TDR device, the medium consists of a set of metallic rods and the soil surrounding those rods. An electromagnetic wave sent down the medium will be reflected at the end of the rods. This means that if the length of the path and the travel time of a wave through a medium are known, the dielectric constant is calculated according to:

$$K = \left(\frac{ct}{2L} \right)^2 \quad (3.10)$$

where c [m/s] is the speed of light, t [s] is the reflection time, and L [m] is the length of the rods (see Figure 3.8).

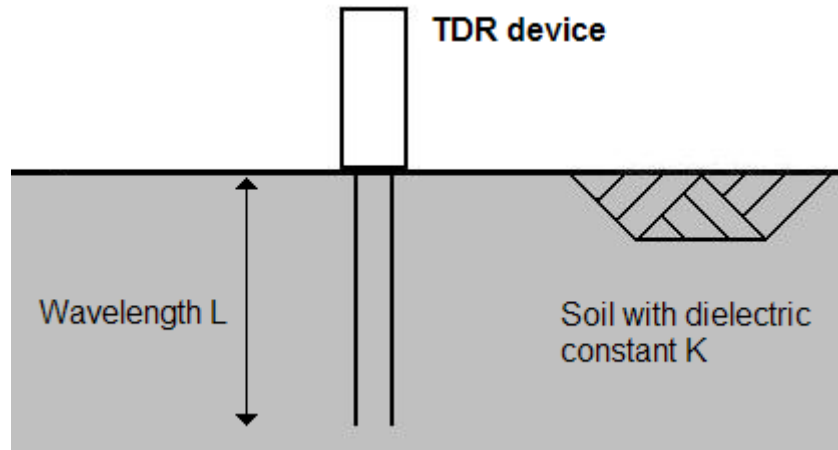


Figure 3.8: Schematized water content detection using Time Domain Reflectometry.

The dielectric constant of the soil surrounding the rods depends heavily on its water content and is independent on bulk density, temperature, salinity, or mineral composition. There is no exact equation to convert dielectric constant into water content. Instead, an empirical relation is used. This means every TDR device is calibrated beforehand.

When an electromagnetic wave travels through a conducting medium, its amplitude is attenuated due to conduction losses within the medium. The degree of attenuation increases with increasing conductivity of the medium. In soil the conductivity is usually determined by the concentration of ions in the pore water. This means the measured attenuation of the signal can be converted into salinity using an empirical relation. However, the constants in this function depend on temperature. This means the temperature has to be known. If the salinity of the soil becomes too high, the amplitude of the signal becomes too weakened for the TDR device to detect. Complete attenuation already occurs at concentrations of 0.64 g NaCl per liter for a two rod probe (Mojid *et al.*, 1998). Since seawater already contains 30 to 35 g NaCl per liter, the ordinary TDR technique becomes useless in the marine environment. This problem is countered by insulating the rods with a coating which limits the contact between rods and soil. With this insulation the TDR is able to measure water contents in soils with salt concentrations up to 50 g NaCl per liter. Disadvantages of insulating the rods are reduced sensitivity and the negative influence of damage to the coating.

The measurement with the TDR device is performed by inserting two 15 cm long insulated rods into the soil. When the system is ordered to perform a measurement, the

TDR determines the dielectric constant of the soil by sending an electronic pulse into the soil along the rods and measuring the time it takes to reflect. The TDR device is already calibrated to convert the dielectric constant into water content on its own, and can not be altered to give any other kind of output. To counter the attenuating effect of dissolved salts on the reflection of the signal, the rods are insulated with a plastic coating. If this coating is damaged or worn, the rods are replaced.

3.1.7 Measurement procedure

A measurement series begins by placing the RhoC on the sediment and pushing the TDR-rods and the rod containing the source into the soil. When this is done the user will start a radiometric measurement to determine the background radiation coming from nothing but the sediment. The measurement is finished as soon as two stopping criteria are met: a time criterion and an accuracy criterion, both of which are to be determined by the user beforehand. The accuracy of this measurement is important, as it both affects the calculation of the soil composition and the density. Simultaneously with the background the density and water content are measured, and coordinates from the GPS are recorded. This first part of the procedure will take between ten to twenty minutes, depending on the required accuracy and the type of sediment. Sandy soils, which contain fewer nuclides, in general cause longer measurement durations than muddy soils.

As soon as both stopping criteria are met, the RhoC stops the measurement, and the user can pull the rods upwards over any desired distance. When a new depth of the rods has been set, the user can order the RhoC to perform a ‘density only’ measurement. In this case the device will measure the density between the detector and the new location of the source using the background spectrum measured in the first step. Besides this the logger will also record an output from the TDR-device. This density measurement will stop as soon as sufficient accuracy has been reached, which in general takes between 30 second and 1 minute. The handheld tablet computer stores all the output coming from the detector in the form of energy spectra before applying the spectrum analysis. In this way the user can always check or alter the stabilization process afterwards if that is needed.

When the user has gathered enough density measurements on one location, the rods are retracted from the soil, and the RhoC is transported to a new location to start a new series of measurements.

3.2 Laboratory calibration tests RhoC

3.2.1 Experimental set-up

To determine the performance of the RhoC under controlled circumstances, tests are performed in the laboratory. The experimental set-up consists of a watertight wooden box with known dimensions and volume (see Figure 3.9). For each test the box is filled with either dry sand, sand saturated with water, or a dry mixture of sand and silt. The tests on wet and dry sand are performed to give insight into the influence of water on the accuracy of the density measurement. However, the maximum density of dry sand is limited by its minimum porosity (see Figure 2.5). To perform tests on dry sediments with higher densities than that of dry sand, a sand-silt mixture is made. This mixture of 75% sand and 25% silt has a relatively low porosity, and therefore a high density (see Table 3.1).

Filling	Lowest density (kg/m ³)	Highest density (kg/m ³)	Saturation
100% sand	1358	1627	0 %
100% sand	1919	1973	100 %
75% sand – 25% silt	1566	1880	0 %

Table 3.1: Types of filling with the lowest and highest bulk densities obtained during the tests.

On each type of filling at least three measurement series are performed to determine the accuracy, repeatability and reproducibility of the density measurement:

- Two series in the same horizontal location. For each series the probe is placed on four different vertical positions. In each position the density is measured ten times.
- One series on a different horizontal location. Also in this series four different vertical positions are measured with ten measurements in each position.

For all these series the settings for the logger are the same. The tests are performed according to the same procedure as described in Paragraph 3.1.7. The logger completes a density measurement when the statistical error is within 5 %, and when the measurement has run for at least 30 seconds. To investigate the influence of the duration of the measurement, one extra series is performed on the sand-silt mixture. In this series the density measurement is repeated three times for 7 different measurement times, ranging from 20 to 60 seconds.

3.2.2 Tests on dry sand

Before the box is filled, it is placed on top of a table which can be mechanically vibrated. The sand is poured into the box using a bucket. The weight of each bucket load of sand is measured with a balance before pouring. After each bucket load is poured into the box, the sand is spread out across the box by hand. After filling, the position of the surface level inside the box is measured using a ruler. In this way level the volume of the filling is calculated. From the volume and mass the density is determined.

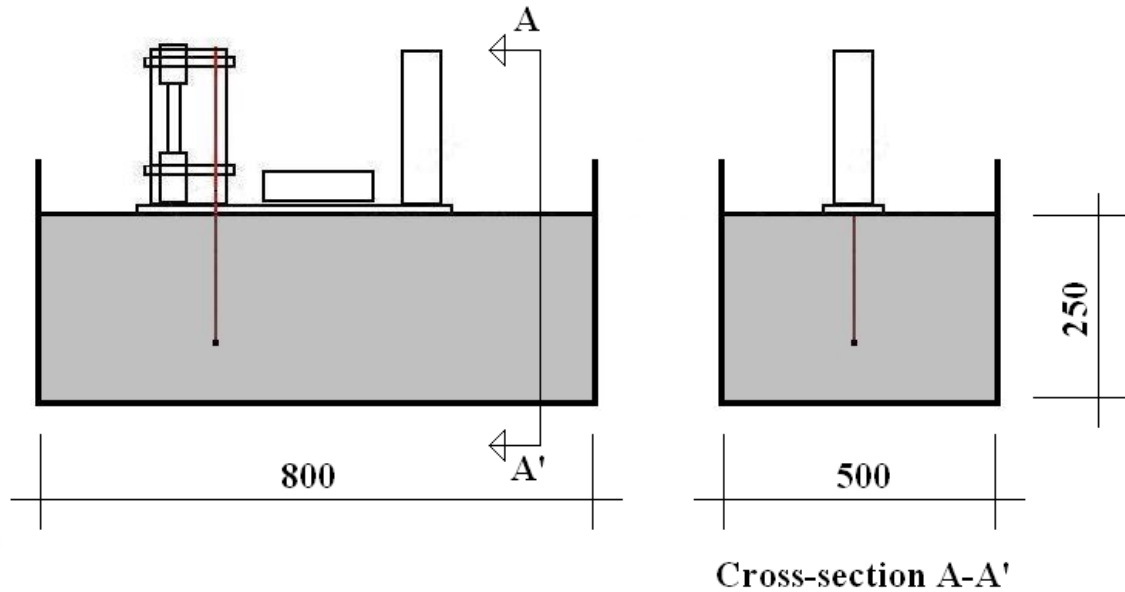


Figure 3.9: Sketch of laboratory set-up (dimensions in mm). Shown are the box filled with sand with the RhoC on top of the sand.

Next the RhoC is placed on top of the surface level for the first series of tests (Figure 3.9). After these series are completed, the RhoC is removed, and a wooden lid is placed on top of the surface level. The lid is weighed down with concrete blocks in order to obtain a homogeneous density throughout the box and to prevent sand from leaving the box. The box is vibrated for 90 seconds at 120 Hz. The concrete blocks and the lid are then removed. The vertical position of the surface level is measured again, and the RhoC is placed on the sand for the second series of tests. The procedure of vibrating and measuring is repeated twice.

3.2.3 Tests on saturated sand

In order to obtain a fully saturated sand mass, the box is filled for roughly one-third of its volume with water (Figure 3.10a) first. Before pouring the water into the box, the weight of this water is measured with a balance. Next the sand is added until the water level is roughly equal to the level of the sand. The remaining water on top of the sand is siphoned off (Figure 3.10b/c), and the weight of this water is measured again using the balance. The remaining part of this test is performed in the same way the test on dry sand is performed, with measurements of the RhoC followed by vibration, followed by more measurements of the RhoC. After each vibration the sand will have compacted, leaving a layer of water on top of the sand. This water is siphoned off and weighed before measurement with the RhoC.

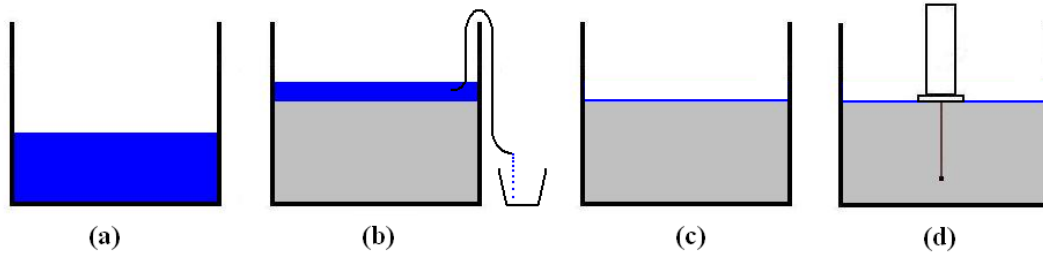


Figure 3.10: Experimental set-up for saturated sand: In (a) the box is filled with water. In (b) the sand is added, and the excess water is siphoned off, until the water level and the level of the sand are equal (c). When this is done, the RhoC is placed on the sand (d).

3.2.4 Tests on sand-silt mixture

For the sand-silt mixture a ratio of 25% silt and 75% sand is chosen, because of the relatively low porosity of this mixture. To mix both types of sediment, sand and silt are poured into a cement mixer in the appropriate ratio. After mixing, the mixture is put into buckets. The buckets are weighed, and the contents are poured into the box. The remaining part of this test is performed in the same way the test on dry sand is performed (measurement, vibration, measurement, etc.).

3.3 Field locations

3.3.1 Western Scheldt estuary

The Western Scheldt is the estuary of the Scheldt River basin. This basin stretches from the north of France to the Dutch-Belgian border and covers approximately 21,000 km². The freshwater discharge is totally dependant on rainfall, and measures on average about 120 m³/s. The discharge is rather limited in comparison to the amount of water that flows in and out of the Western Scheldt due to tide; in the course of one tidal cycle the tide brings in about 10⁹ m³ of water, while the total river discharge over the same period is only 5.3*10⁶ m³ on average. This makes the Western Scheldt a tide dominated well-mixed estuary (Jacobs, 2006).

The suspended and settled sediments in the Western Scheldt can have both a marine and a fluvial origin (Verlaan, 1998). The limited discharge of the Scheldt River causes the tide to propagate relatively far up the estuary, carrying marine sediment with it. The amount of deposited marine sediment is largest in the western part of the mixing zone, and gradually decreases in eastward direction. Vice versa most of the fluvial sediment is deposited in the eastern part of the estuary, and its contribution to the total sediment composition diminishes rapidly downstream of the Dutch-Belgian border.

The sediment is spatially segregated both in east-west direction as well as over the different morphological elements (see van Eck, 1999). Coarse sediments are mostly found in the channels, while most of the finer sediments are found on intertidal areas stretching out from the riverbanks. Tidal flats in the middle of the estuary consist of a mixture of sediment types. In general, the average grain size increases towards the mouth of the estuary (see Appendix A). While the ratio between the sand- and mud-fraction can vary over space and time, the ratio between silt and clay within the mud-fraction is more or less constant 0.25 over the entire Western Scheldt (Van Ledden, 2003). The clay in the

Western Scheldt consists of a mixture of Illite, Kaolinite, and Smectite minerals. The activity of this clay is around 1 or 2.

3.3.2 Field sites

The field tests for the MEDUSA RhoC were performed on 4 tidal flats in the Western Scheldt; Plaat van Walsoorden, Plaat van Valkenisse, Molenplaat, and Saeftinghe (see Figure 3.11). These tidal flats exhibit differences in the types of occurring sediments. The Saeftinghe flat is the muddiest. All the other flats have smaller mud deposits, with the Valkenisse flat being the most sandy.

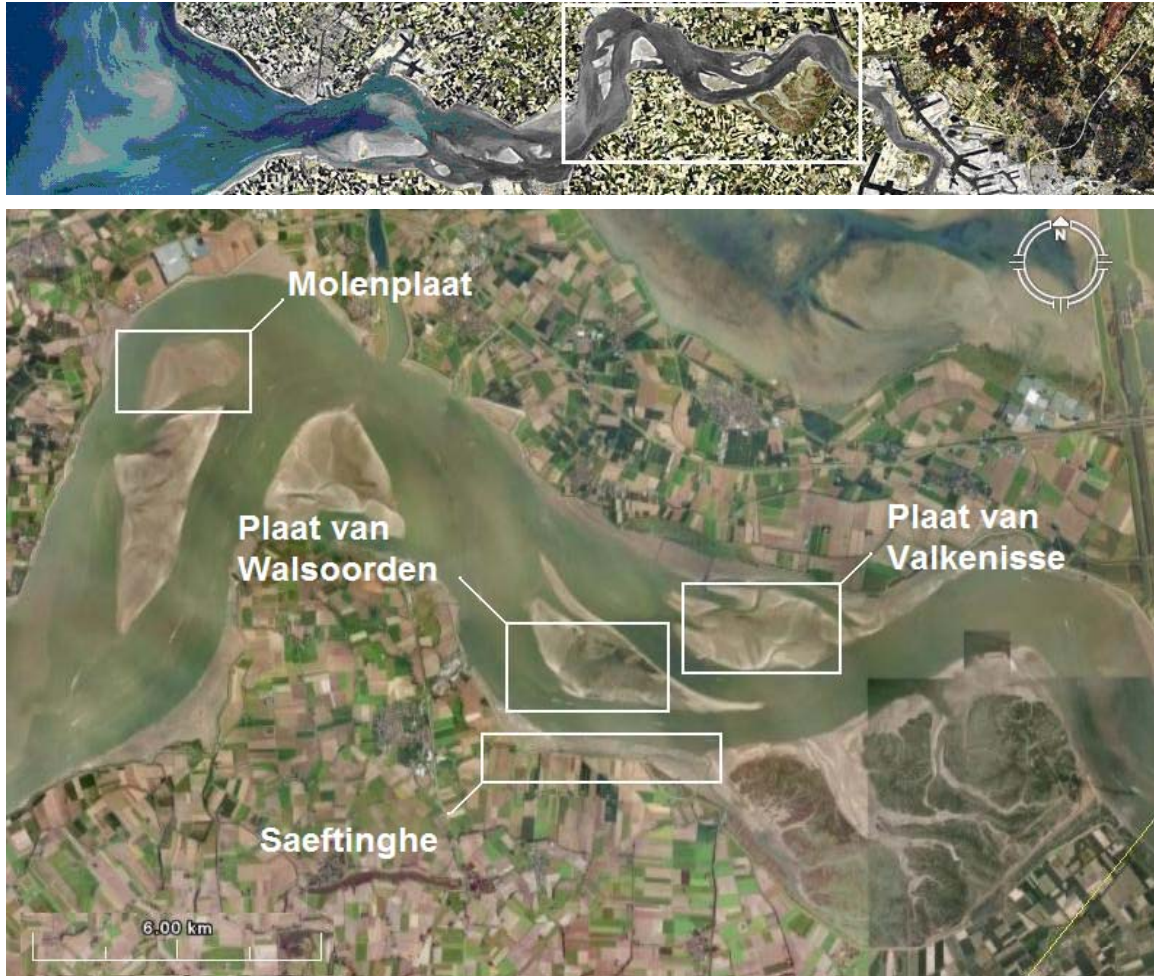


Figure 3.11: Western Scheldt estuary: the area of interest with the sampled tidal flats (scalebar in the lower figure = 6 km) (source: Google Earth).

The sampling locations on the flats correspond to a grid of sampling locations set out by NIOO researchers. The choice to let the sampling locations for this research coincide with locations sampled by NIOO was made to make comparison of results of previous studies possible. The grids set out by NIOO contain far more points than necessary for the research of this thesis. The selection of sampling points was made in such a way, that the acquired data set would span a wide variety of sediment types, from muddy to sandy.

3.3.3 Obtaining sediment cores

To calibrate the RhoC, three different types of sediment cores are taken at the same locations. The first type, labeled as A-sample, consists of a core from the surface to a depth of 20 cm. The A-sample is used to determine activity concentrations in the laboratory. This type of sample is collected by pushing a PVC-cylinder 20 cm long and 10 cm in diameter into the soil. The core is then extracted and sealed it with plastic caps. The second type of sample, labeled as B-sample, is collected the same way as the A-sample, only for this sample a PVC-cylinder with an inner diameter of 5 cm is used. The B-sample is used for optional extra analyses. The third type of sample is labeled as C-sample, and will be used for the determination of density, water content and fraction sizes in the laboratory. The C-samples are collected using 30 cm long plexiglass cylinders with an inner diameter of 3.6 cm. The cylinder is pushed downward into the soil, while at the same time a plunger inside the tube is kept on the same level as the surface of the soil by slightly pulling the plunger upward (Figure 3.12a). Once the required depth is reached, both the plunger and the cylinder are pulled upward. In this way the upper surface of the sample inside the cylinder does not get pushed into the soil along with the tube. Also, there is no risk of the sample sliding out of the cylinder as it is pulled out of the soil. All three sample types were stored upright and transported to the laboratory in a cooler box. At the laboratory all samples were stored in freezers at -20°C before any further treatment.

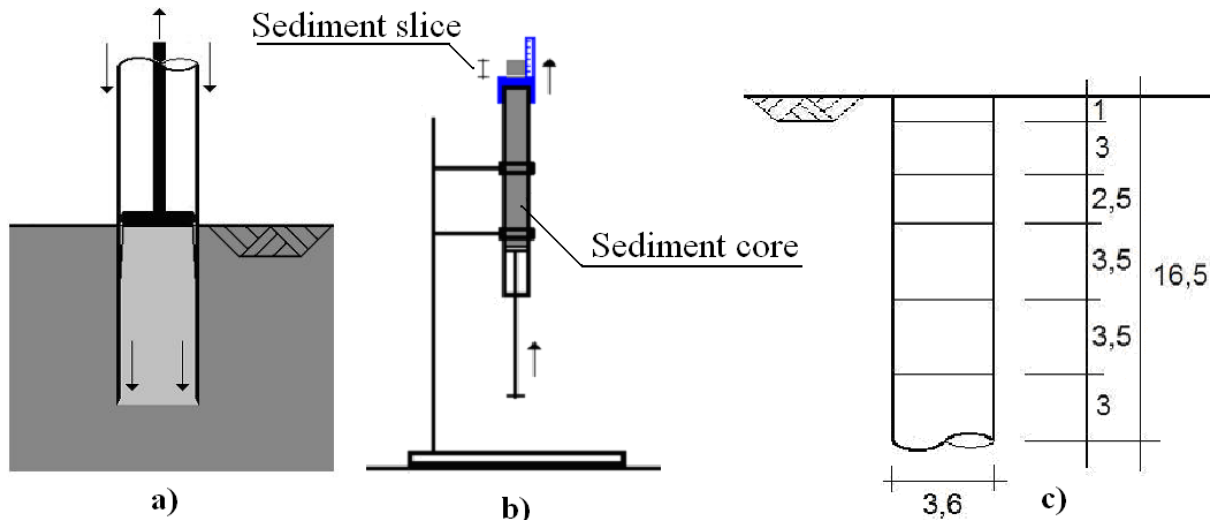


Figure 3.12: Method for collecting and slicing sediment core samples: a) Pressing a core cylinder into the soil. b) Laboratory setup used for slicing sediment cores. c) Thickness of the core slices (dimensions in cm).

To get an indication of the salinity within the soil, the salinity is measured using a conductivity meter. At the same time the temperature within the soil is also measured.

At each sampling location several photographs of the top layer and the surroundings are taken to be used as reference later on. The top layer photographs also include a ruler, so that it is possible to derive the dimensions of bed forms, if any.

3.4 Lab analysis of sediment cores

3.4.1 Determination of density and water content

For the determination of profiles of density and water content over the depth, the C-samples are cut into cylinder-shaped slices using the setup shown in Figure 3.12b. The slices are cut at predetermined height intervals (Figure 3.12c). With this height, along with the known diameter of the cylinder, the volume of every slice is calculated. Immediately after the slice has been cut, it is carefully put into an airtight plastic bag, of which the weight has been measured beforehand. The bag with the slice is then weighed on a balance. From the mass of the slice and its volume the density is calculated:

$$\rho_{bulk} = \frac{M_{wet}}{V_{slice}} \quad (3.11)$$

where V_{slice} [m³] is the volume of the slice, and M_{wet} [kg] is the mass of the wet sample. After weighing, the bags containing the samples are opened and put in a freezer. When they are sufficiently frozen again, the bags are placed in a freeze-dryer for two days. In the freeze dryer the frozen water in the samples sublimates, leaving the organic matter in the sample undisturbed. After two days the samples are taken out of the freeze-dryer and weighed again. From the difference in weight the water content is calculated using the following equation:

$$W = \frac{M_{wet} - M_{dry}}{M_{dry}} \quad (3.12)$$

where W [%] is the water content, and M_{dry} [kg] is the mass of the sample after drying. When the dry weight of a sediment slice is known, also the dry density ρ_{dry} [kg/m³] is calculated:

$$\rho_{dry} = \frac{M_{dry}}{V_{slice}} \quad (3.13)$$

From this density also the porosity, the degree of saturation, and the maximum possible density is calculated:

$$n = 1 - \frac{\rho_{dry}}{\rho_{sed}} \quad \text{with } \rho_{sed} = 2650 \text{ kg/m}^3 \quad (3.14)$$

$$S = \frac{\rho - \rho_{dry}}{n\rho_w} \quad (3.15)$$

$$\rho_{max} = n\rho_w + (1 - n)\rho_{sed} \quad (3.16)$$

The measurements of the salinity of the pore water revealed an average salinity of 5 grams of salt per liter. Therefore, a value of 1005 kg/m³ is taken for the density of the pore water ρ_w .

3.4.2 Grain size analysis

To determine the grain size distribution a Malvern Mastersizer 2000 is used, which applies laser diffraction spectrometry. The Mastersizer used for this thesis is located at NIOO, and is calibrated for Western Scheldt sediments.

Before an analysis is performed, every sample has to be pre-treated to remove the organic and inorganic carbon content. This pre-treatment begins by adding 3 doses of 5 ml 30% hydrogen peroxide (H_2O_2) to roughly 10 grams of freeze-dried sediment in a measuring cup of 250 ml. The cup containing a mixture of sediment and peroxide is placed in crushed ice and left standing for 24 hours. The mixture is then cooked for roughly 10 minutes to remove all the peroxide left after reaction with the organic carbon. After cooling down an excess of 16.5 ml 1 molar hydrochloric acid solution will be added to the sample in 3 stages to remove carbonates or any other inorganic carbon. This mixture is then boiled again for 15 minutes. After cooling down the cup is filled to the top with demineralised water. The cup is left standing for 24 hours to allow the sediment to settle. After this period the fluid on top of the sediment is siphoned off, and the cup is filled to the top again with demineralised water. After another 24 hours the fluid is siphoned off again, and the wet sediment is put into a small plastic cup. After freezing and freeze-drying, the sample is ready for grain size analysis with the Malvern Mastersizer. The Malvern analysis itself takes 7 minutes per sample. During this analysis the sediment is kept from flocculating with ultrasonic waves. The output comes in the form of 7 different fraction sizes, as well as d_{10} , d_{50} , and d_{90} .

In order to assess the influence of (the removal of) the carbon content on the grain size distribution, 24 sediment samples are analyzed with the Malvern before and after treatment.

3.4.3 Determination of organic content

Before the pre-treatment takes place, a couple of milligrams of each sample is set aside for carbon content analysis. This analysis consists of two separate measurements; one for the total carbon content, and another for the organic carbon content. The inorganic carbon content is the difference between organic and total carbon content.

For the determination of the total carbon content 12 mg of homogenized freeze dried sediment is incinerated. The amount of CO_2 released in the combustion is measured using a gas chromatograph. From this amount the percentage of total carbon is calculated.

The determination of the organic carbon content is similar to the determination of the total carbon content, with the only difference that the samples are pre-treated with hydrochloric acid to remove the inorganic carbon such as carbonates.

3.4.4 Radiometric analysis

To generate the fingerprints required to translate the activity concentrations from the field into mud contents, the activity concentrations of the A-samples are determined in the lab. The sample is put in a Marinelli beaker and placed on top of a gamma ray detector inside a 10 cm lead shielding to prevent other background radiation from entering the detector. Before measurement takes place, the entire sample is weighed. This weight is converted to dry weight by subtracting the water content. From the dry weight and the measured activity, the activity concentration is determined.

4 Results

4.1 Laboratory calibration tests

4.1.1 Measurement of background radiation

The sand and silt used for these tests are hardly radioactive. Therefore, most of the background radiation comes from the room outside the box. When the position of the RhoC has not changed between series, the values for the activity concentrations of ^{40}K , ^{235}Th , and ^{238}U should be comparable. The results of the laboratory calibration tests show that the standard deviation of all the measurements together is only slightly larger than the average statistical deviation calculated by the RhoC for ^{40}K and ^{238}U (see Table 4.1). For ^{232}Th the deviation from the experiments is even smaller than the error given by the RhoC. This means the error given by the RhoC is probably correct.

Nuclide	Average activity concentration (Bq/kg)	Standard deviation experiments	Average standard deviation according to RhoC
^{40}K	215.01	7.58	6.31
^{232}Th	24.75	1.01	0.80
^{238}U	24.94	1.12	1.25

Table 4.1: Average activity concentrations of all lab measurements.

4.1.2 Density measurements

Appendix B shows the results of all density measurement series performed in the lab. Each of the groups of ten measurements which are performed on the same vertical position show a certain spread around a mean. This mean is still different from the real average density (see Figure 4.1 for examples). The spread of the ten measurements around this mean is expressed in a standard deviation. The average of the standard deviations of all these groups is 15 kg/m^3 . As mentioned before, the measured density differs from the real average density, which is seen in Figure 4.2. The offset⁴ seems to be negative for lower densities, and positive for higher densities. The average offset for the low densities is 3%. The average offset for the high densities is 2%. The field measurements also show an offset, although this offset is almost always positive, and on average larger than 2%.

In Figure 4.1 it is observed that the average of all measurements for one depth measured by the RhoC varies over the depth. This is explained by the fact that the density calculated for the entire box by dividing its weight by its volume (see Paragraph 3.2.1) is an average density. Locally the density can be higher or lower than this average.

⁴ The offset is defined in this thesis as a percentage of the density measured by the RhoC. The offset is calculated by dividing the difference between the RhoC density and the “real” density by the RhoC density. A positive offset means the RhoC density is higher than the real density.

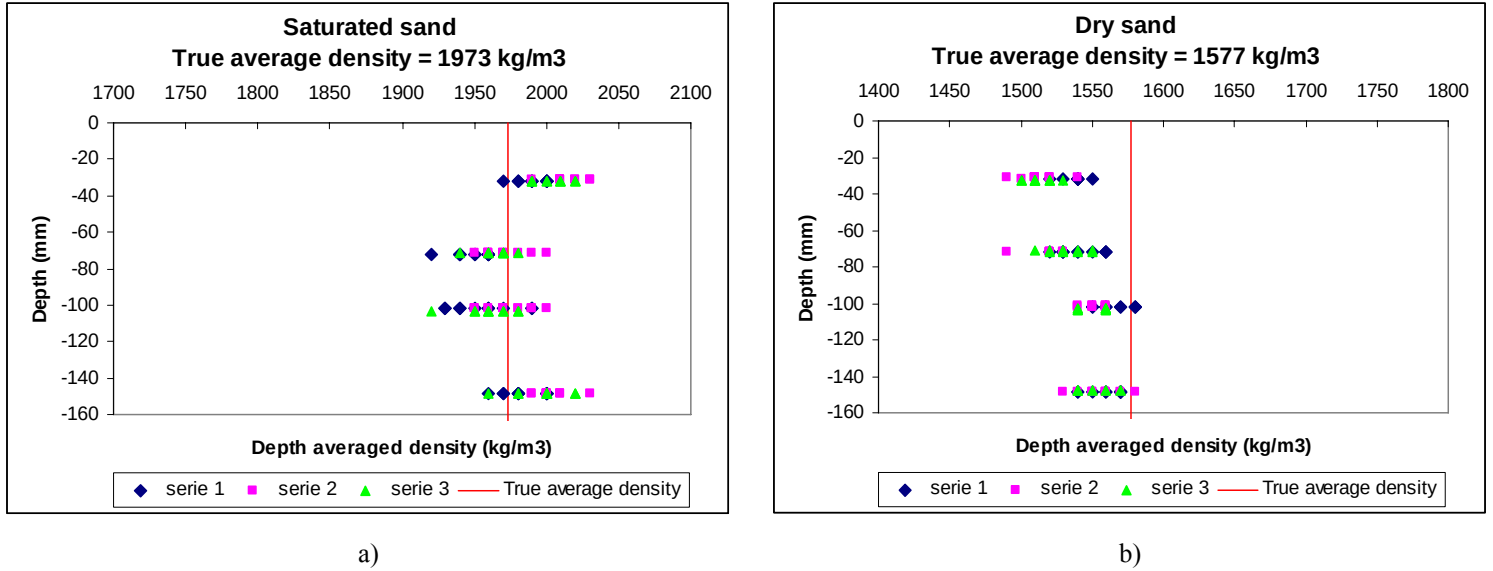


Figure 4.1: Densities measured by the RhoC under controlled circumstances. The results in a) are from the tests using saturated compacted sand. The results in b) are from the tests using dry compacted sand.

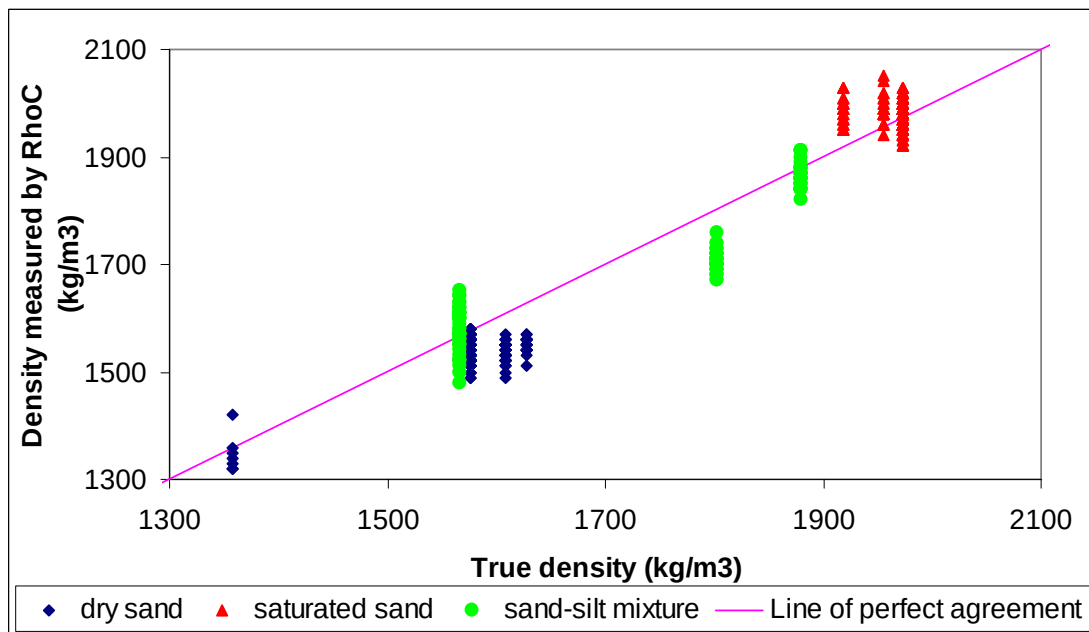


Figure 4.2: Measured density vs. real density (lab experiments).

4.2 General results field locations

The field locations showed a variety of sediment types, presence of organic matter, and stratification. The Valkenisse flat was the most sandy. The sediment of this tidal flat also contained the least amount of organic matter, although the organic matter content on all the field sites was low, and never above 5%. The tidal flat near Saeftinghe was the most

muddy, and also displayed the largest stratification in density or mud content. The sediment of this flat also contained on average the most organic matter, although vegetation and algae mats were scarce. The Walsoorden flat displayed the largest variations in sediment types and bed forms. The high part of the flat consists of clayey material and is covered with salt marsh vegetation. The lower parts of this flat are sandier and are not vegetated. These areas are dominated by large sand ripples and dunes. The Molenplaat flat is sandy at its upstream and downstream edges, and muddy in the middle. This muddy part is intersected by small streams, which cut through the top layer of the mud. This can create large variations in conditions on small spatial scales. Measurement points MPT 18 and MPT18/2 were taken 5 meters apart from each other; the first one on an undisturbed part of the flat, and the second one on the point bar of a stream. Results for the densities, mud contents, water contents and carbon contents show considerable variation between these two measurement points (see Figures D.27 to D.30 in the appendix).

The cores show different degrees of stratification. For this thesis the degree of stratification is defined simply as the absolute difference in bulk density between two adjoining slices. The largest difference in density between two slices is 436 kg/m^3 (location S18), and the average difference is 85 kg/m^3 . This difference decreases with increasing depth for most cores (Figure 4.3a). The sandy cores ($\xi_{\text{mu}} < 10\%$) are mostly stratified in the upper 5 cm of the sediment (Figure 4.3b). As the average mud content of the cores increases, the degree of stratification becomes smaller for the top layer, and slightly increases for deeper layers (see Figure 4.3c and d). This means the upper 10 cm of sediment are more homogenous for muddy locations than for sandy locations. A possible explanation for this is that muddy sediments contain more living organisms which perturb and mix the upper layers of sediment. The reason why the average degree of stratification for all samples looks like Figure 4.3a is simply because there are more sandy samples than muddy samples (the average mud content of all samples is 15%).

Appendix D contains the results of all the field data from the MEDUSA RhoC and the cores analyzed in the lab. The results are organized per tidal flat. For each flat the sample locations are shown. For each sample location the depth averaged density, the density per slice, the sand content, the water content, the carbon content, and a photograph of the top layer are shown. The figures for the densities also show the dry density (ρ_{dry}) and the maximum saturated density (ρ_{max}). From the densities and grain size distributions measured in the lab the sand-silt ratio and the porosity are calculated. Figure 4.4 shows the granular porosity versus the sand fraction for all the sample locations together.

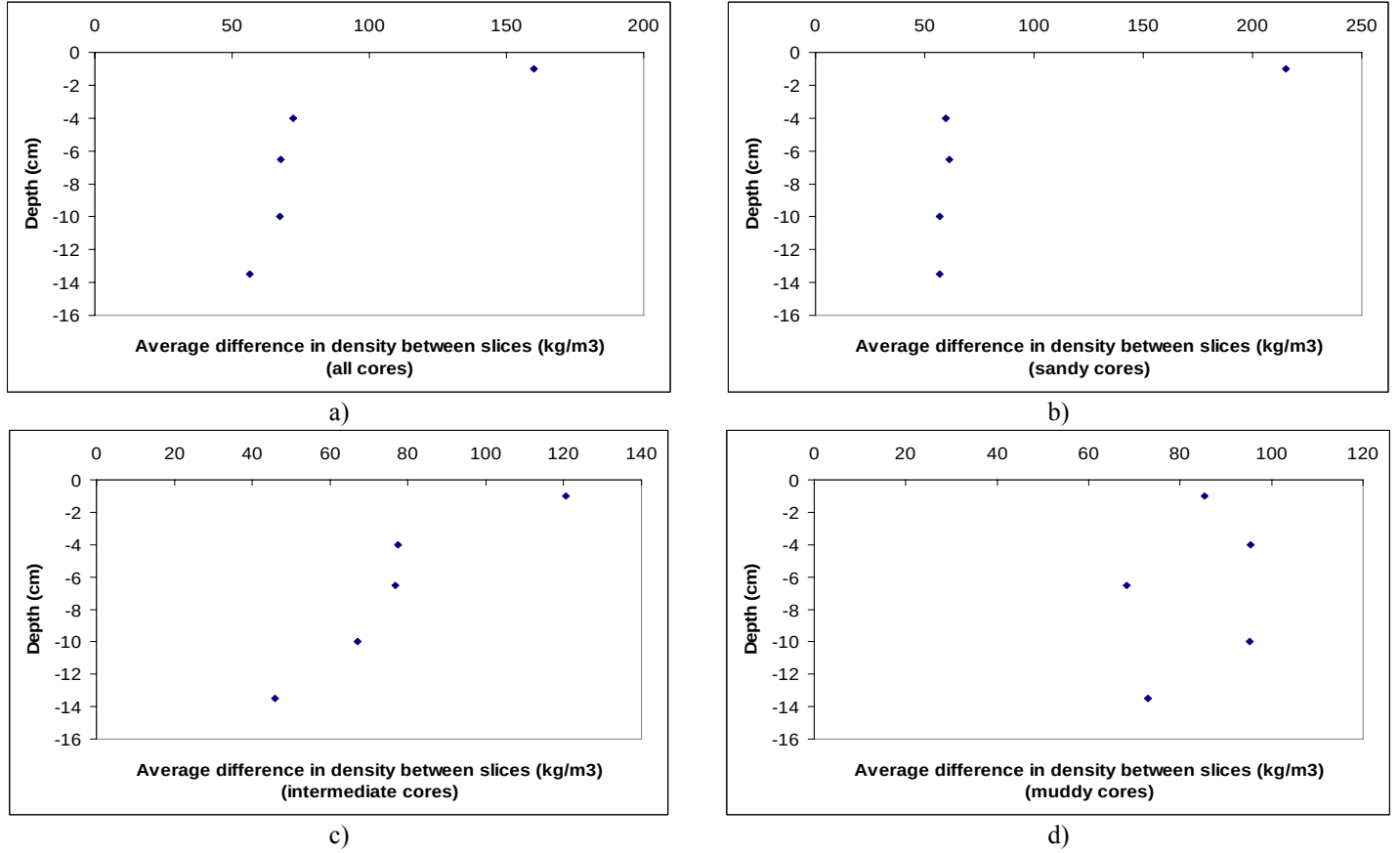


Figure 4.3: Average degrees of stratification over the depth. In a) the values are averages for all sample cores. In b) only the sandy cores ($\xi_{\text{mu}} < 10\%$) are considered. In c) only the intermediate cores ($10\% < \xi_{\text{mu}} < 25\%$) are considered. In d) only the muddy samples ($\xi_{\text{mu}} > 25\%$) are considered.

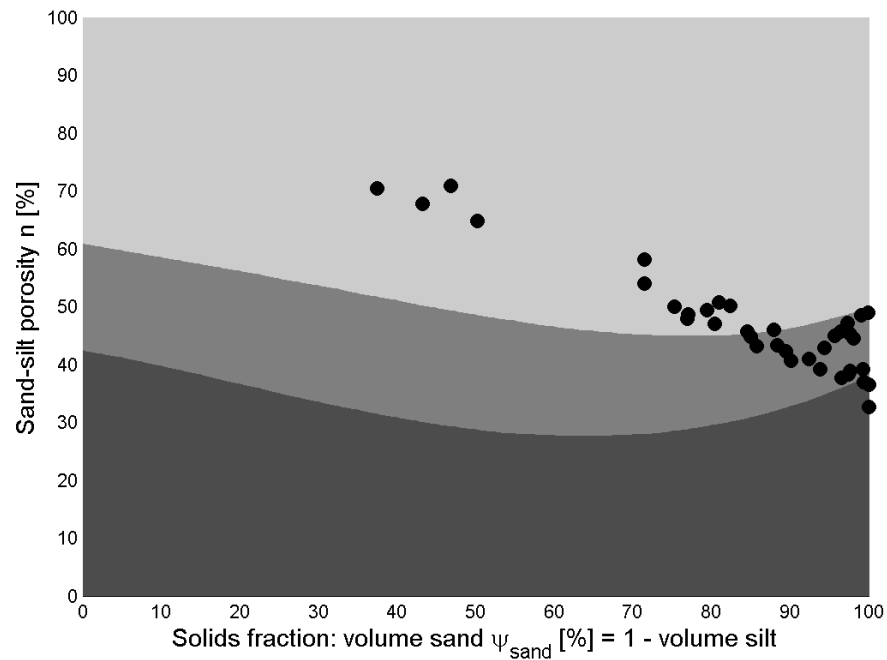


Figure 4.4: Depth averaged granular porosity and sand fraction of all samples.

The sand-, silt-, and clay contents of all the sample locations are visualized in the sand-silt-clay triangle in Figure 4.5. The same is done for the sand-, mud-, and organic matter contents in Figure 4.6. The data in Figure 4.5 shows a strong correlation ($r^2 = 0.96$) between silt- and clay content. Figure 4.6 and Figure 4.7 also show a strong correlation ($r^2 = 0.86$) between mud content and organic matter content.

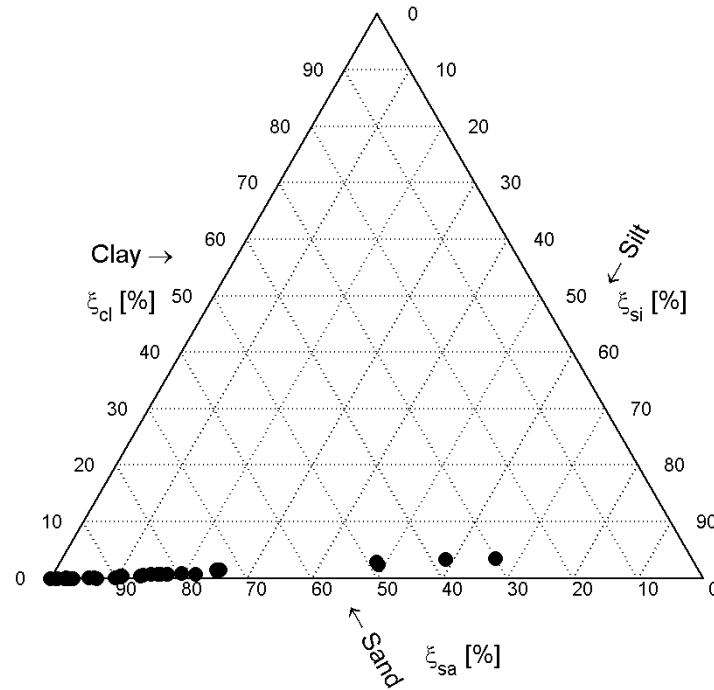


Figure 4.5: Sand-silt-clay triangle containing depth averaged contents of all sample locations.

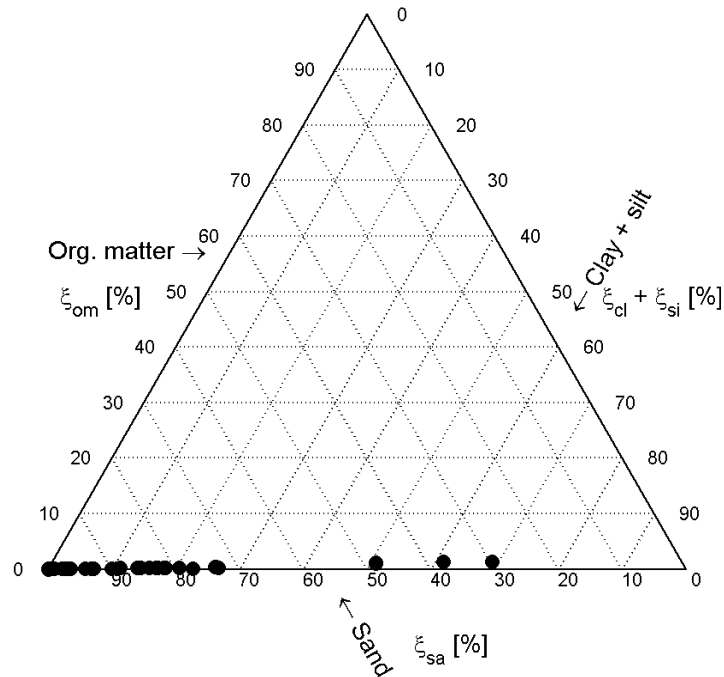


Figure 4.6: Sand-mud-organic matter triangle containing depth averaged contents of all sample locations.

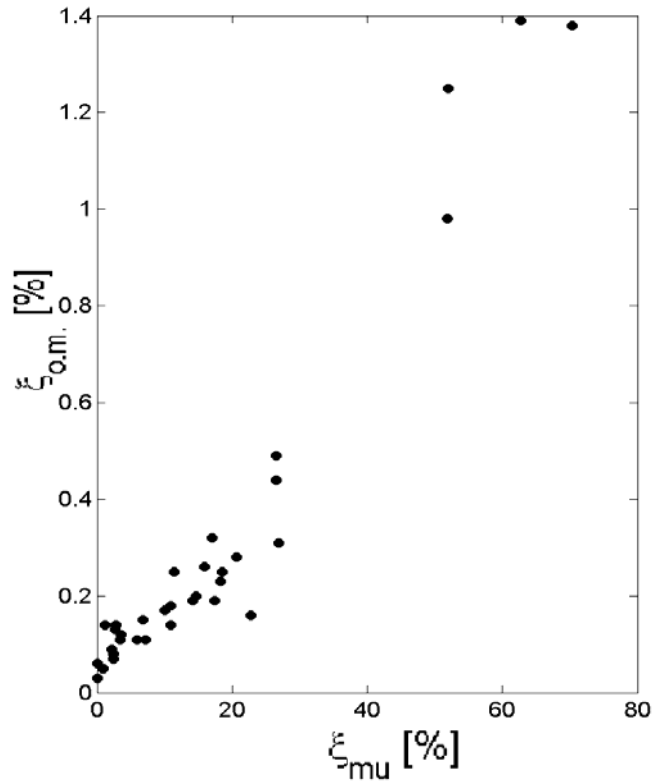


Figure 4.7: Organic matter content set out against the mud content.

Figure 4.8 shows the bulk density and sediment composition of all sample slices. It shows a weak correlation between bulk density and mud content.

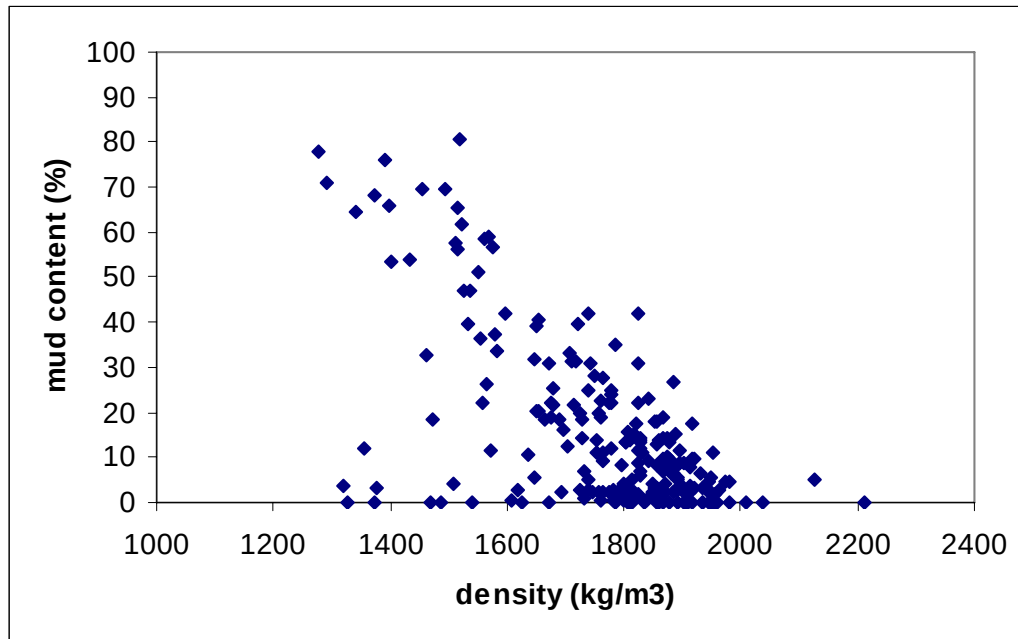


Figure 4.8: Bulk density and mud content for all field samples.

For 13 A-samples the plasticity limits are determined according to (ASTM D4318, 2000). From these limits the plasticity index W_{PI} is derived (see Figure 4.9). This figure shows the relation between W_{PI} and the clay content ξ_{cl} . From this data a critical clay content $\xi_{cl,0}$ of 0% and an activity A_{cl} of 6.55 are derived. This activity seems rather high for Western Scheldt clay. This is likely due to underestimation of the clay content by the Malvern analysis. If the clay content is assumed to be one fourth of the mud content, the activity becomes 1.41.

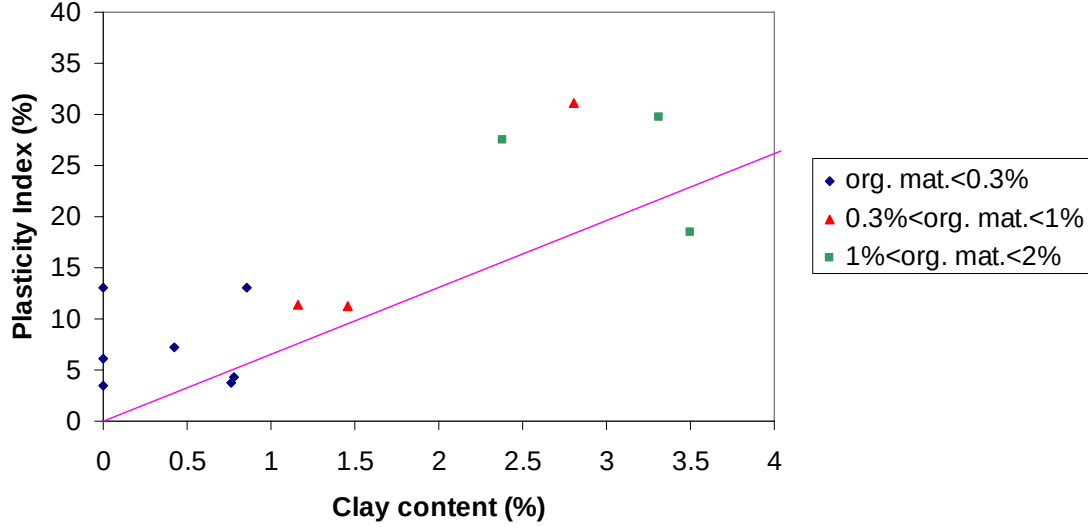


Figure 4.9: Activity plot of Western Scheldt sediments. The critical clay content $\xi_{cl,0}$ is 0%, and the activity A_{cl} is 6.55.

4.3 Measurement of sediment composition

4.3.1 Mud contents and activity concentrations

In Appendix D the sand, silt, and clay contents over the depth are shown for each location (e.g. figure D.4a). Appendix D also contains the output of the radiometric measurements for each tidal flat (e.g. figure D.2). Each graph for one tidal flat has two datasets: the activity concentrations measured in the field using the RhoC, and the activity concentrations measured in the laboratory on sediment samples from the field. The RhoC actually measures the activity concentration of the bulk including the pore water. This means that these values are lower than the concentrations measured in the laboratory, which are activity concentrations of the dry solids. Therefore, the activity concentrations measured in the field are corrected for the presence of water according to the following equation:

$$C_{solids} = C_{bulk} (1 + W) \quad (4.1)$$

where C_{solids} is the activity concentration of the solids, and C_{bulk} is the activity concentration of the bulk, which the RhoC actually measures. Figure 4.10 to Figure 4.12 give a typical example of radiometric measurements, in this case for the Saeftinghe flat. The fit lines of laboratory and field measurements agree nicely, although two distinctions are identified. The first distinction is that for Potassium and Uranium the fit through the

field measurements has a different slope compared to the fit through the lab values. The second distinction is that the spread in the Uranium concentration is generally larger than the spread in the Potassium or Thorium concentrations.

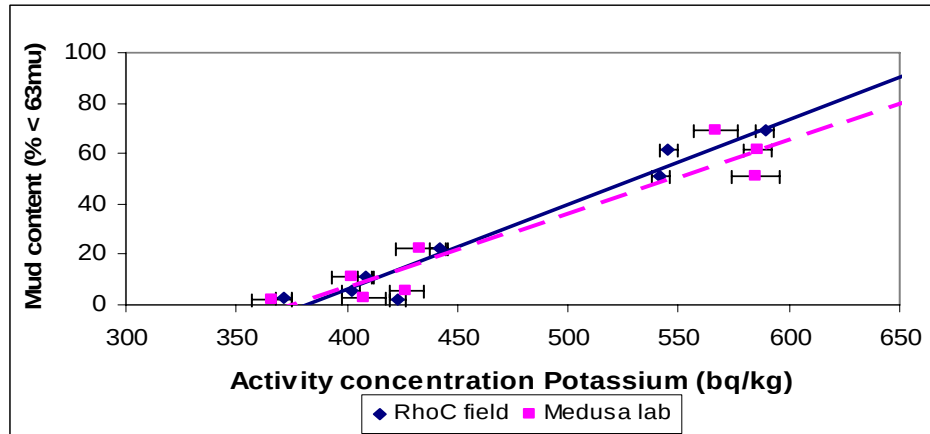


Figure 4.10: Relation mud content and activity concentration of Potassium (^{40}K) for Saeftinghe, measured in field and laboratory. The lines indicate the linear best fit through the data points.

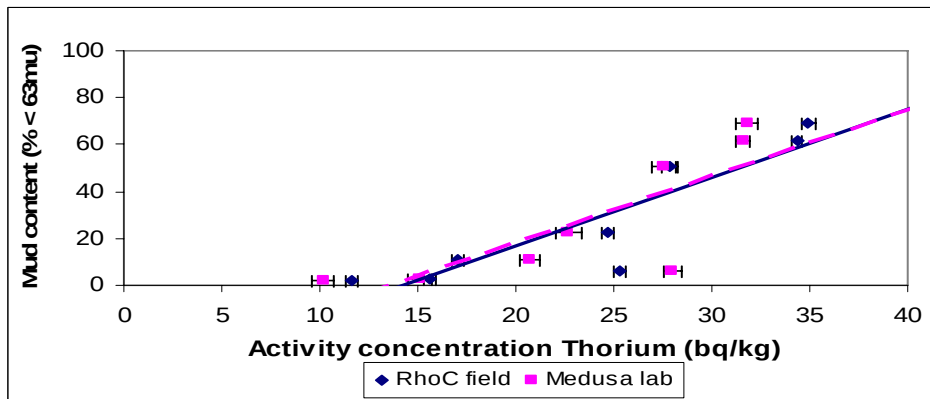


Figure 4.11: Relation mud content and activity concentration of Thorium (^{232}Th) for Saeftinghe, measured in field and laboratory. The lines indicate the linear best fit through the data points.

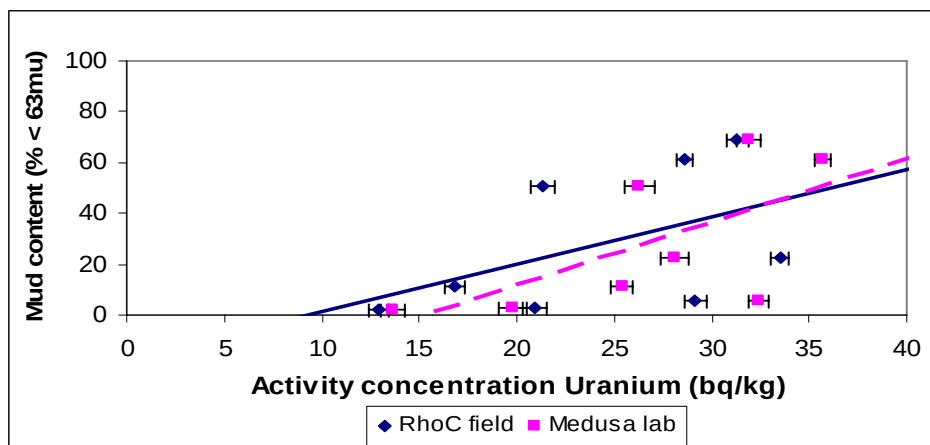


Figure 4.12: Relation mud content and activity concentration of Uranium (^{238}U) for Saeftinghe, measured in field and laboratory. The lines indicate the linear best fit through the data points.

4.3.2 Influence of pre-treatment on grain size distribution.

A pre-treatment of the sediment samples described in Paragraph 3.4.2 is performed in order to remove the organic and inorganic carbon content. For 24 samples the grain size distribution was determined not only after pre-treatment, but also before. This makes it possible to assess the influence of the carbon content on the grain size distribution. The pre-treatment causes the average grain size to decrease for most samples. This effect is as expected, because organic matter can bond particles together. The differences in grain size distributions seem to depend on the carbon content of the sediment (Figure 4.13). The effect is more prominent in muddy samples, which have larger carbon content because of the correlation between mud and carbon content (see figure 4.7 for this correlation). This relation makes it possible to determine the organic matter content from the mud content measured by the RhoC. Because the organic matter content is also related to the change in contents due to pre-treatment, it is possible to determine the mud and clay contents that exist in the field. The pre-treatment should have no effect on the fingerprinting procedure other than the effect on the distribution described above. Radiometric measurements are always performed on untreated samples. Therefore, the only effect of treatment is that the mud content derived from fingerprints will be larger than the mud content which actually exists in the field.

4.4 Measurement of vertical density profiles

In appendix C two vertical density profiles are shown for each location. The first figure shows the depth averaged values of the dry density, measured density and maximum density derived from the core slices using Equations 3.11, 3.13, and 3.16. The averages in these figures are averages taken from the surface down. This figure also shows the data of the RhoC, which are already a depth averaged value. The second figure shows the vertical density profiles of the dry density, measured density and maximum density, all from the slices, as well as the density profile derived from the RhoC measurement using Equation 3.9. A few typical results are shown in Figure 4.14 through Figure 4.16. These figures display some features which are also visible in other density profiles in Appendix C. The real density of the slices (labeled “*rho slices*” in the figures) is hardly ever equal to the maximum density (labeled “*rho max*”, see Equation 3.16). The density from the RhoC is higher than the real density in almost all locations. This offset seems to be structural, but is not equal for all profiles. Another feature of the density profiles that is very prominent in Figure 4.14b, are the large jumps in the profile derived from the RhoC data. The magnitude of these oscillations in other profiles is in general less than in Figure 4.14b. The oscillations can even be totally absent (Figure 4.15b).

Like Appendix C, Appendix D also contains vertical density profiles. The difference between these profiles and the profiles in Appendix C is that in Appendix D the profiles are shown with a correction applied to them. This correction is further explained in Paragraph 5.2.4.

Results

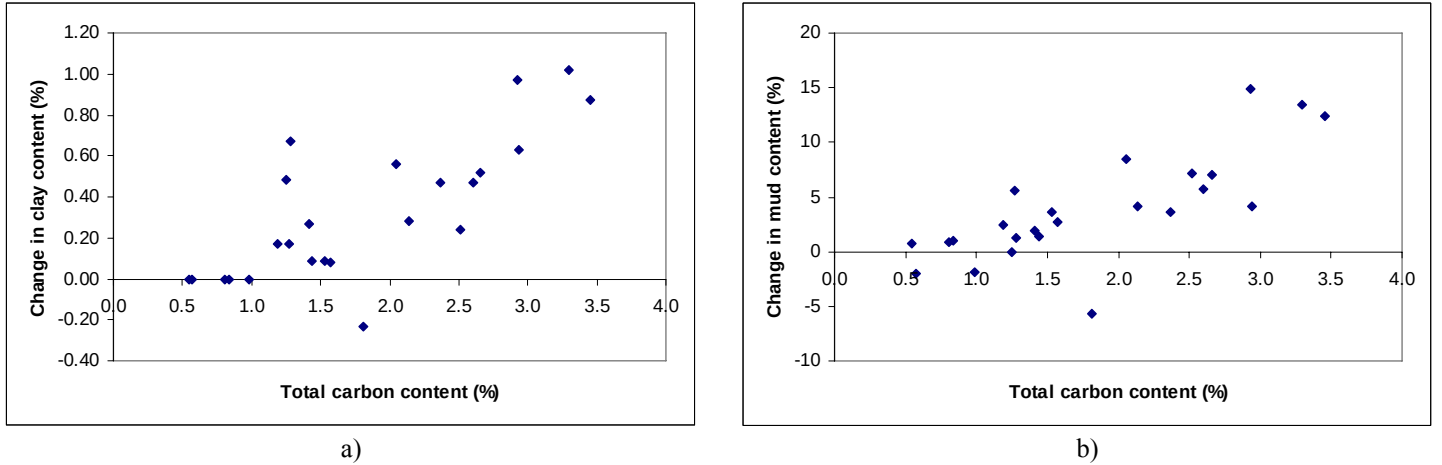


Figure 4.13: Influence of carbon content on grain sizes. In a) the influence on the clay content ξ_{cl} is displayed, in b) the influence on the mud content ξ_{mu} . The values on the y-axis are the absolute changes in contents.

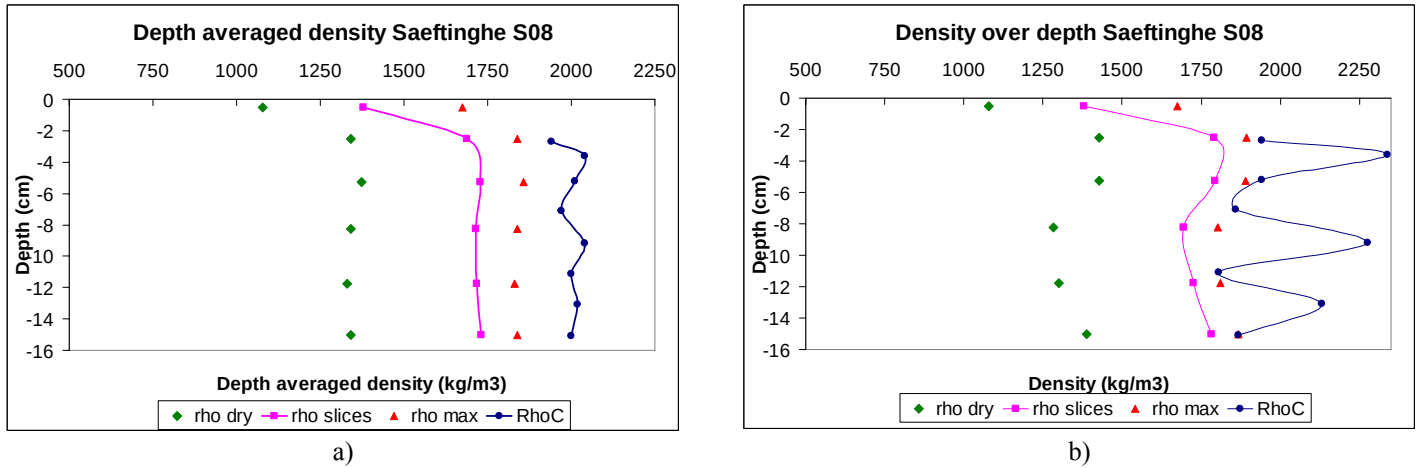


Figure 4.14: Density measurements of RhoC and lab slices, location S08: a) Depth averaged density (top-down). b) Density over depth per slice.

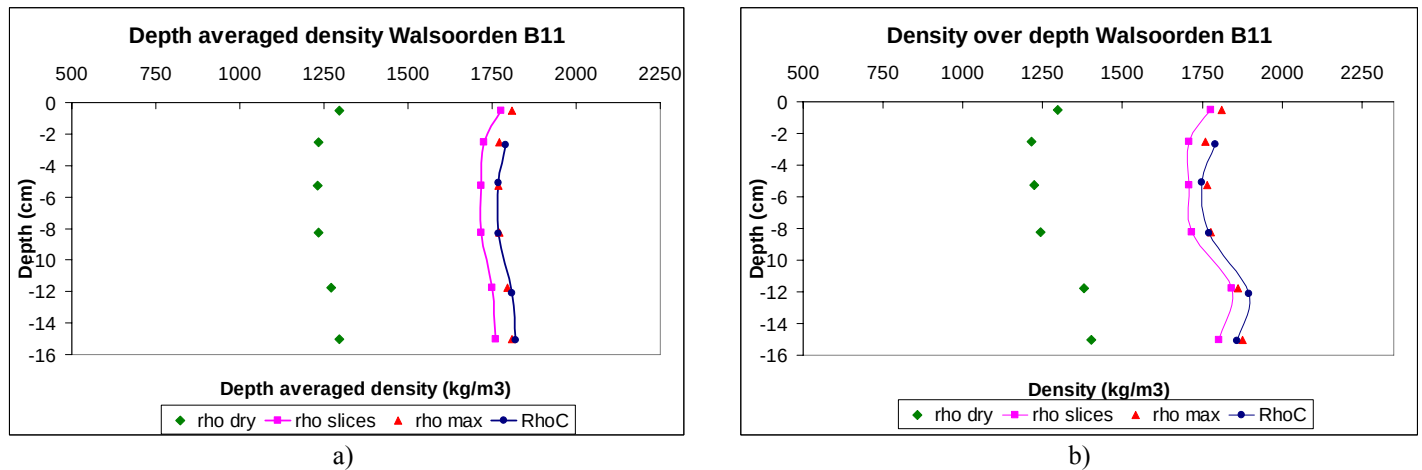


Figure 4.15: Density measurements of RhoC and lab slices, location B11: a) Depth averaged density (top-down). b) Density over depth per slice.

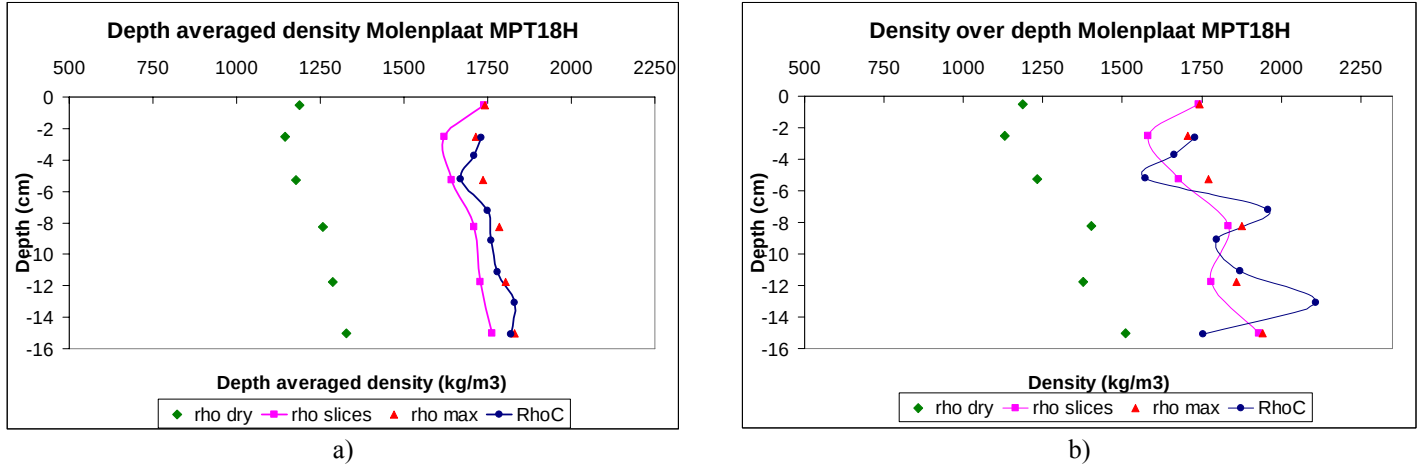


Figure 4.16: Density measurements of RhoC and lab slices, location MPT18H: a) Depth averaged density (top-down). b) Density over depth per slice.

4.5 Measurement of water content

The water contents shown in the graphs in Appendix D are the water contents determined from the core slices according to Equation 3.12. The profiles of the water content can be uniform (the blue line in Figure 4.17a), but can also be dominated by large transitions (Figure 4.17b). Another observation is that the water content never drops below 20% for any of the cores. The profiles of the saturation often show more variation than the water content. These profiles sometimes also reveal measurement errors as they rise above 100% (Figure 4.17b), which is an impossibility by definition.

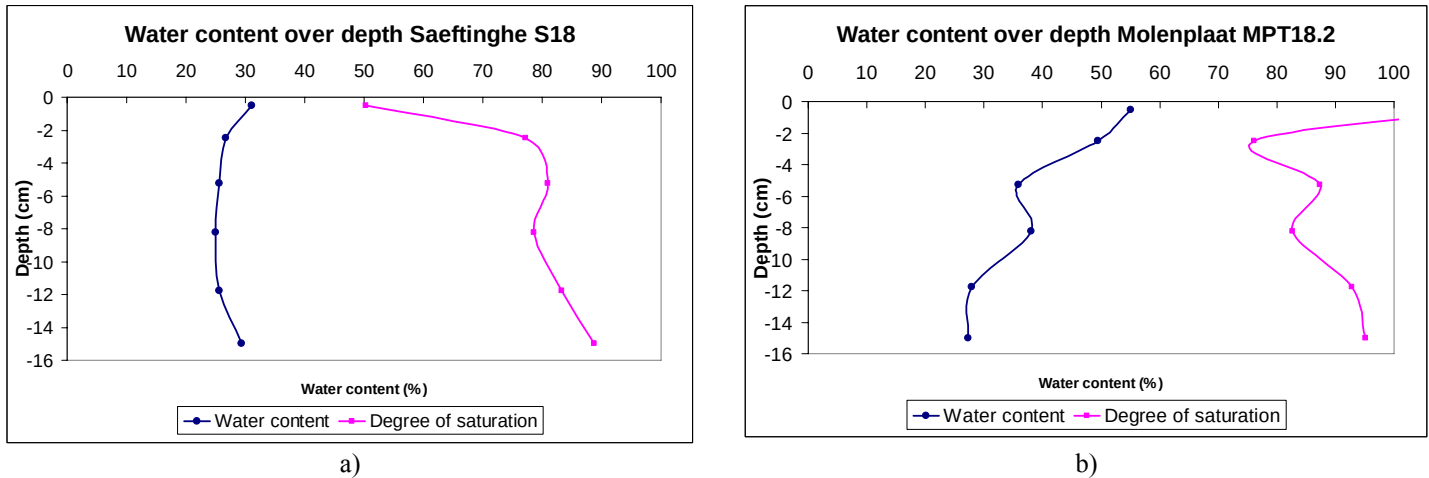


Figure 4.17: Water content and saturation derived from core slices: a) Saeftinghe, location S18 b) Molenplaat, location MPT18.2

The profiles of the water content over depth made by the RhoC are not included in these graphs, since the measurements from the Western Scheldt show no correlation to the real water content (Figure 4.18), not even for the deepest measurement where the TDR-probes are pushed into the soil over their full length. Also, the TDR often gave no reading of the water content at all. The manufacturer has indicated that the TDR has probably been malfunctioning. Therefore, the data from the TDR will not be used for

further conclusions. The malfunctioning TDR has been replaced, and a quick test was performed on a mixture of 2 kilo's of water and 8 kilo's of sand, so the water content was 25%. The output of the TDR was 32%. Further testing of the TDR under controlled circumstances is recommended.

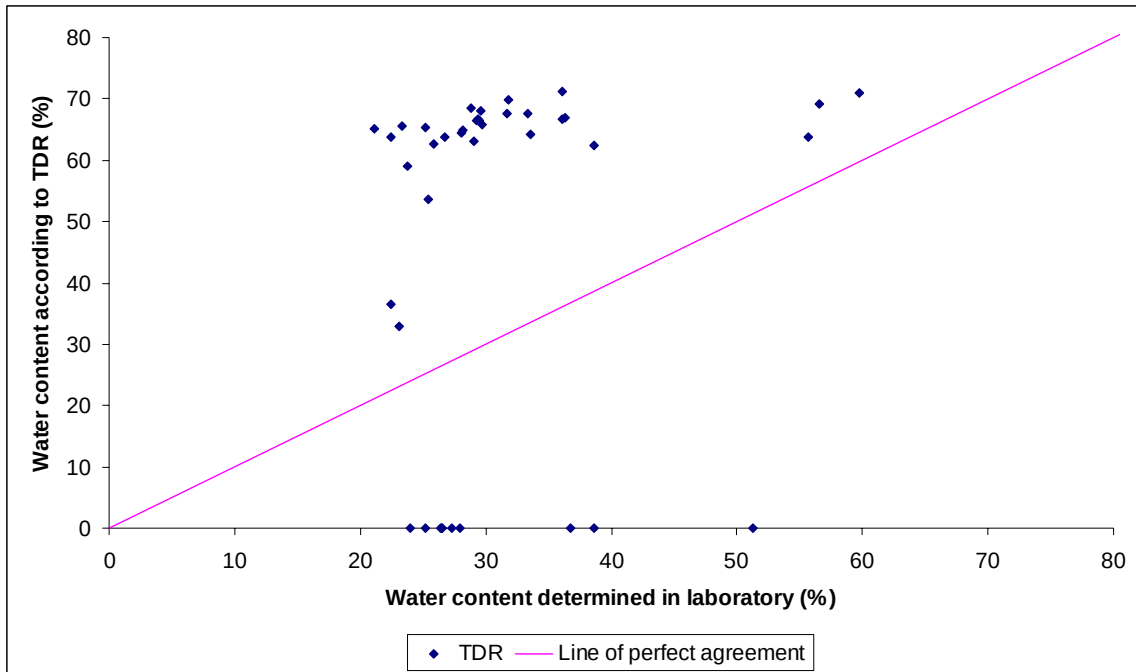


Figure 4.18: Water content measured with TDR and water content measured from core slices.

5 Discussion

5.1 Sediment composition

5.1.1 Applying the fingerprint determined from laboratory data

To determine mud contents from radiometric measurements alone, first the fingerprint must be established. This procedure has to be performed once for each tidal flat, and involves the following steps: first sediment samples have to be collected. These samples should give an adequate representation of all the different sediment types present on the tidal flat. Besides this sampling, the RhoC is used on any number of other locations to measure activity concentrations. The mud content and activity concentrations of the samples are determined in the laboratory. From the mud content and activity concentrations the fingerprint is derived. This fingerprint is then used to calculate mud contents from activity concentrations measured on the other locations on the tidal flat using the RhoC.

Appendix E shows for each tidal flat the fingerprint derived from the activity concentrations determined in the laboratory. When fingerprints of different tidal flats are compared to each other, they show differences in both the slope of the linear fits, as well as their intersections with the 0% and 100% mud content levels. It is yet unclear what causes these differences between tidal flats. It might be due to the difference in origin of the sediment. An example of the fingerprints, in this case the fingerprint for the Molenplaat flat, is given in Table 5.1. When applying this fingerprint, the radiometric data measured by the RhoC is used as input into Equation 2.19 to compute ξ_{mu} . In Figure 5.1 the computed values for ξ_{mu} for the Molenplaat are compared to the real ξ_{mu} measured with the Malvern. It is seen that this fingerprint in combination with this data yields a good estimation of the mud content. The correlation is good ($r^2 = 0.90$), and the normalized root mean squared error is small (NRMSE = 11%). The lab-fingerprints of the other tidal flats yield more or less the same errors, except for the Valkenisse tidal flat. For this tidal flat the correlation is poor ($r^2 = 0.56$), and the error is relatively large (NRMSE = 26%). One possible explanation for this is that the quality of the fingerprint for Valkenisse is poor, because it is based on samples with a maximum mud content of only 16%. The fingerprints for the other tidal flats are based on samples with maximum mud contents of more than 25%.

lab fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	1209.52	44.82	48.21
mud content = 0%	300.40	8.21	10.76

Table 5.1: Fingerprint derived from laboratory data for the Molenplaat flat. The values are the activity concentrations [Bq/kg] at the indicated mud contents.

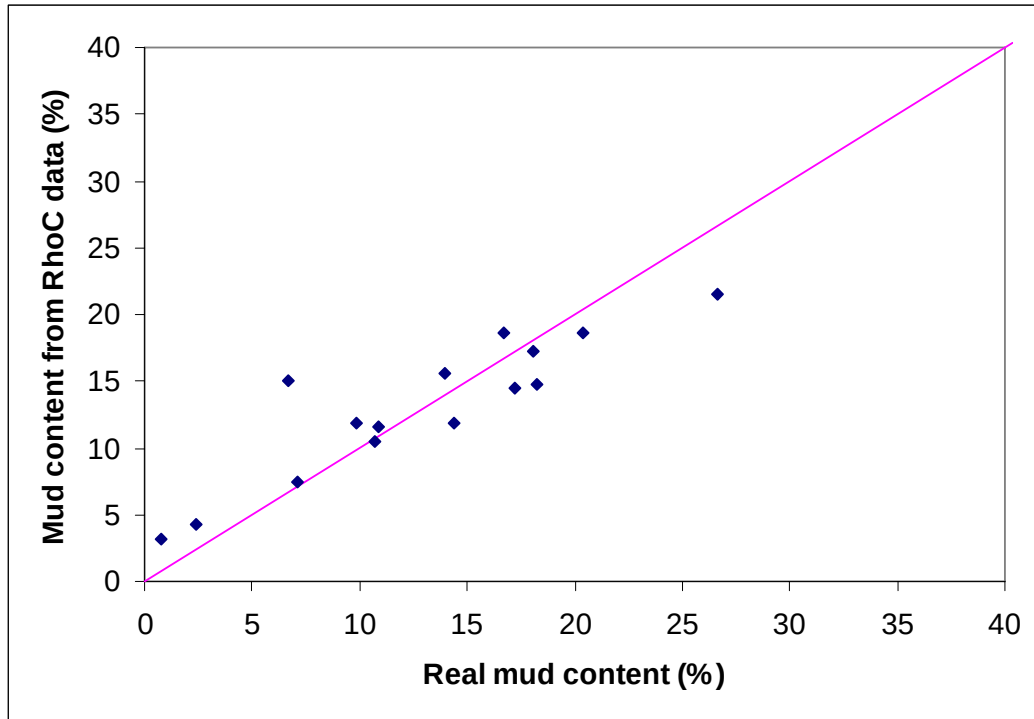


Figure 5.1: Mud contents according to activity concentrations for the Molenplaat measured by the RhoC. The contents are computed using the fingerprint determined in the lab. The continuous line indicates the line of perfect agreement.

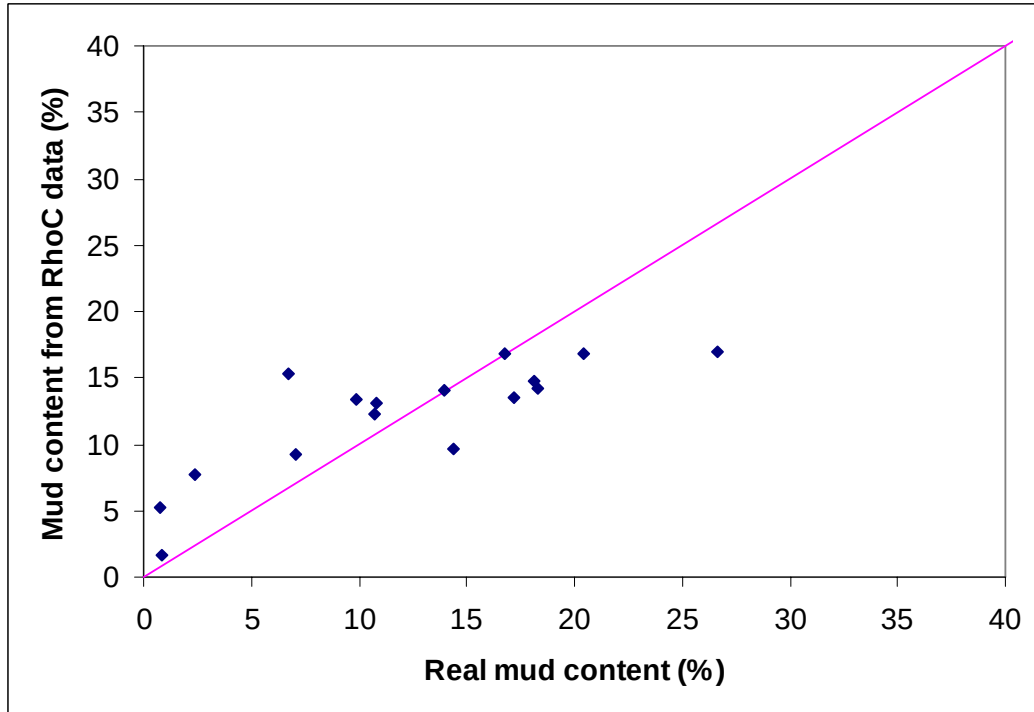


Figure 5.2: Mud contents according to activity concentrations for the Molenplaat measured by the RhoC. The contents are computed using the fingerprints determined from the field data corrected for the presence of water. The continuous line indicates the line of perfect agreement.

5.1.2 Applying the fingerprint determined from RhoC data

As mentioned before in Paragraph 4.3.1, the activity concentrations measured in the field are corrected for the presence of water, so that the activity concentration is not a concentration of the bulk, but of the solids. If these corrected values are used to generate fingerprints, these fingerprints return results that are almost identical to the results from using the fingerprints derived from the laboratory-measurements. Figure 5.2 shows the comparison between the mud contents derived using this field fingerprint (see Table 5.2) and the real mud contents. The figure shows the same correlation ($r^2 = 0.90$) and a smaller error (NRMSE = 11%). This means the fingerprint derived from the RhoC data is preferable over the fingerprint derived from the laboratory measurements.

Field fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	894.61	43.06	53.68
mud content = 0%	351.63	8.44	6.28

Table 5.2: Fingerprint derived from field data for the Molenplaat flat. The values are the activity concentrations [Bq/kg] at the indicated mud contents.

For the other tidal flats the correlation and error between real and computed mud contents is given in Table 5.3. For all tidal flats the error between calculated and real mud contents does not change much between the different fingerprints. The scatter in mud contents calculated from the field fingerprint is equal to the scatter from the laboratory fingerprint. The quality of the results for the Valkenisse flat is rather poor for both fingerprints.

	Molenplaat		Saeftinghe		Walsoorden		Valkenisse	
	r^2	NRMSE	r^2	NRMSE	r^2	NRMSE	r^2	NRMSE
Field fingerprint	0.90	10.45	0.90	15.13	0.98	6.19	0.56	26.17
laboratory fingerprint	0.90	10.80	0.90	15.71	0.98	9.37	0.56	25.88

Table 5.3: Correlation coefficients (r^2) and normalized root mean square errors (NRMSE) [%] of calculated mud contents for all tidal flats for both field and laboratory data.

From the values in Table 5.3 it seems that both fingerprints are almost equally accurate. This means that the field fingerprint is just as applicable as the laboratory fingerprint.

The use of the RhoC measurements to generate the fingerprint means that the procedure described at the beginning of this paragraph changes. The determination of the activity concentration in the laboratory is no longer required. Instead, the RhoC is used to measure activity concentrations and water contents at the sample locations (see Figure 5.3).

- Step 1: Activity concentrations and water contents are measured in the field using the RhoC. Sediment samples are collected in the field.
- Step 2: The samples are taken to the laboratory to determine the mud content (see Paragraph 3.4.2).
- Step 3: From the mud contents and activity concentrations the fingerprints are derived.
- Step 4: Activity concentrations and water contents are measured in the field using the RhoC.

Step 5: The activity concentrations of the solids are translated into mud contents with the fingerprints (see Equation 2.19).

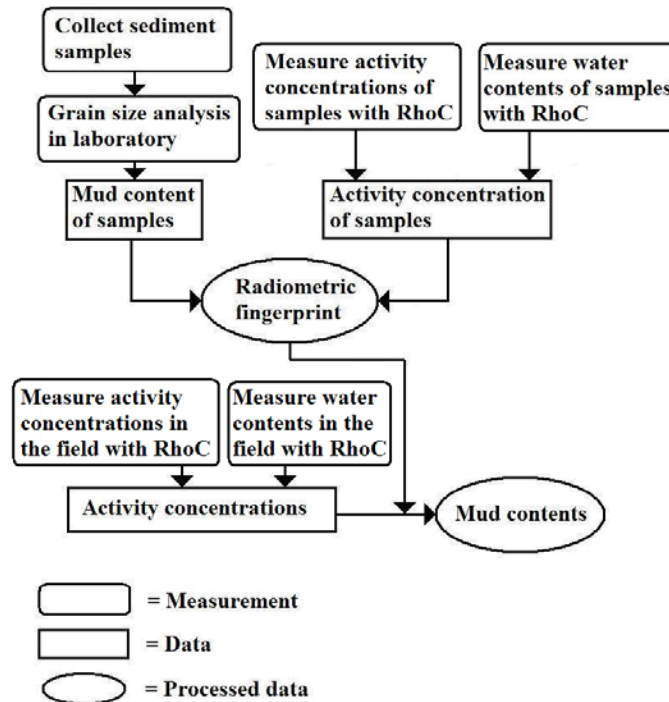


Figure 5.3: New schematic outline of the process of radiometric determination of sediment composition.

5.2 Vertical density profile

5.2.1 Offset and oscillations in density measurement

The method of deriving the density from the core slices described in Paragraph 3.4.1 is tried and tested, but still has inaccuracies. This inaccuracy comes mostly from the fact that the slices are not always perfect cylinders, giving rise to errors in the determination of the volume of the slice. This error is largest in the top slice, because the top layer of the top slice is not always flat. The error for the top slice is estimated 15 to 20%, while the error for the lower slices is estimated around 5%. In spite of these errors, the results from this method are in this thesis always referred to as the “real” density.

The offset and the oscillations in the RhoC density profiles are roughly similar in size for most locations. The offset and oscillations are also roughly equal to real transitions in density that occur in the sediment. This makes it difficult to distinguish the offset and the oscillating behavior from the genuine trend of the profile. Therefore, the offset is defined here as the difference between the depth averaged profiles measured in the lab and field. The offset of all locations is on average 8% of the RhoC density. The maximum positive offset is 17% (location Walsoorden W44). Only in one of the locations a negative offset occurs (location Walsoorden B12). The size of the offset shows no correlation to the average density, depth, mud content, water content, or carbon content. The only property that seems to correlate to the offset is the saturation (Figure 5.4). This could be explained by the way in which the sediment cores are collected and transported. Although great

care has been taken to preserve the state of the cores in which they existed in the soil, it was still observed that some water seeped out of the sediment during transport, before the cores were frozen. However, when the densities measured by the RhoC are compared to the maximum possible density ρ_{max} calculated from the cores using Equation 3.16, the offset is still observed, although it is smaller (4%). So even if the pores in the sediment of the cores were completely saturated, the density of the cores would still be smaller on average than the density measured by the RhoC. In the laboratory experiment an offset of 2% was observed for completely saturated samples (see Paragraph 4.1.2). The same tests on dry samples revealed a negative offset. According to the relation shown in Figure 5.4 this offset should be positive, and much larger than the offset for saturated samples. Therefore, the relation shown in Figure 5.4 is only used to correct the offset for the sediment cores taken for this study (see Paragraph 5.2.4). The relation can not be used in future application of the RhoC. For the future use of RhoC a constant density offset correction of 2% is recommended.

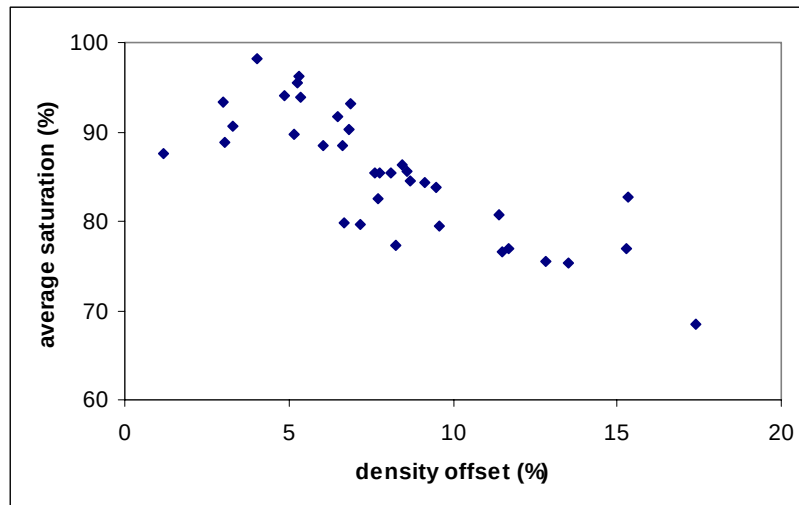


Figure 5.4: Depth average density offset and depth average saturation for all locations.

The oscillations vary in intensity between locations. The largest difference between two successive points in one profile is 31% (location Molenplaat ‘punt 5’). The density measured in the sediment cores does show transitions with the same magnitude, but only for the top layer. The accuracy of the density measurement in the lab of this top layer is questionable, because of the method for density determination (see Paragraph 3.4.1). The surface of the top layer slice is not exactly flat, making determination of the volume of this top layer slice difficult. If the transitions between the top two slices are ignored, the largest transition in density measured in the sediment cores is 18% (location Saeftinghe S11).

The profiles for the locations on the Walsoorden and Valkenisse flats show considerable less oscillating behavior than the Molenplaat and Saeftinghe flats. The only variable regarding the RhoC that has changed between these flats is the number of density measurements. On the Walsoorden and Valkenisse flats only five measurements were taken over a depth of 15 cm. On Molenplaat and Saeftinghe eight measurements were taken over the same depth, so the vertical distance between measurements was smaller.

5.2.2 Influence of measurement time

To assess the influence of the duration of the measurement on the accuracy of the density measurement, one of the tests in the lab is performed with different minimum durations of measurement ranging from 20 seconds to 1 minute. The logger software does not allow durations shorter than 20 seconds. The stopping criterion for minimum accuracy was disabled, so that the measurement always stopped at the minimum duration, and not when a minimum error was obtained. The measurement was performed three times for each duration of measurement. The real density inside the box for this set-up was 1800 kg/m^3 . Figure 5.5 shows that the output of the RhoC converges. The scatter in density seems to converge proportional to $t^{-0.5}$, which is expected according to Poisson statistics. The output of the RhoC does not vary much for duration times above 35 seconds. This means that for practical application a duration of a measurement above 35 seconds is not necessary, because the accuracy of the measurement does not improve significantly.

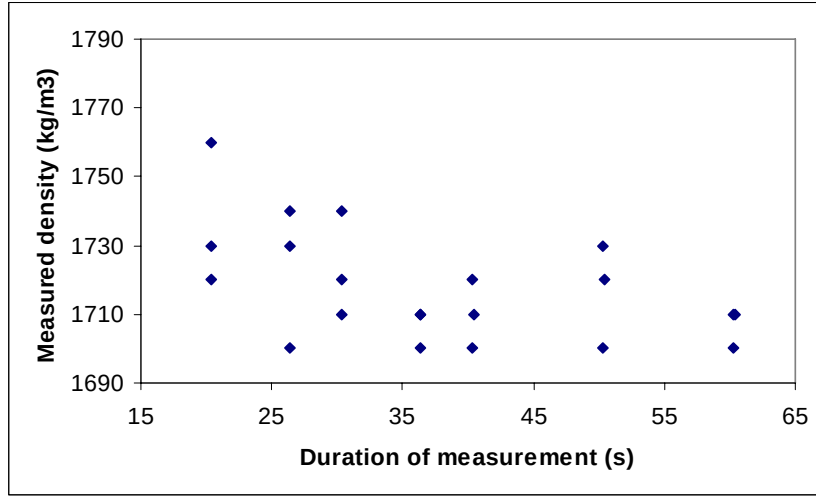


Figure 5.5: Measurement duration versus density.

5.2.3 Analysis of errors on vertical density profile

Theory of error propagation

In Paragraphs 4.4 and 5.2.1 it is observed that the profiles for $\rho(z)$ calculated from the RhoC data display large oscillations. One possibility for the origin of these oscillations is the method used to calculate these density profiles, described in Paragraph 3.1.5. The inaccuracies in this method are explained with an error analysis:

$$\bar{\rho}_{AB} = \frac{\bar{\rho}_B \cdot h_B - \bar{\rho}_A \cdot h_A}{(h_B - h_A)} \quad (5.1)$$

$$\bar{\rho}_{AB} = \frac{h_B}{h_B - h_A} \bar{\rho}_B - \frac{h_A}{h_B - h_A} \bar{\rho}_A \quad (5.2)$$

If the errors in the measurement of the depths h_A and h_B are ignored, the error in the calculated density $\Delta \bar{\rho}_{AB}$ becomes:

$$\Delta \bar{\rho}_{AB} = \frac{h_B}{h_B - h_A} \Delta \bar{\rho}_B + \frac{h_A}{h_B - h_A} \Delta \bar{\rho}_A \quad (5.3)$$

This means that the error in the density calculated from the values measured by the RhoC increases with larger depth (h_B). Also, if the distance between measurement points ($h_B - h_A$) decreases, the error becomes larger.

The same analysis also shows that an error in the calculated density is caused by inaccuracies in the measurement of the depth. If the errors in measurements of the densities are ignored, the error in the calculated density $\Delta \bar{\rho}_{AB}$ becomes:

$$\Delta \bar{\rho}_{AB} = \left| \frac{\bar{\rho}_B}{h_B - h_A} - \frac{\bar{\rho}_B \cdot h_B - \bar{\rho}_A \cdot h_A}{(h_B - h_A)^2} \right| \Delta h_B + \left| -\frac{\bar{\rho}_A}{h_B - h_A} + \frac{\bar{\rho}_B \cdot h_B - \bar{\rho}_A \cdot h_A}{(h_B - h_A)^2} \right| \Delta h_A \quad (5.4)$$

This means that the error of the calculated density caused by errors in depth measurements becomes smaller for larger distance between the measurement points ($h_B - h_A$). If the differences in measured density between measurement points ($\bar{\rho}_B - \bar{\rho}_A$) becomes larger, the error increases.

Simulating error propagation

The errors calculated in Equations 5.3 and 5.4 are visible in simple simulations. The following figures depict simulations where a vertical density profile is converted into depth-averaged densities from the surface down. These averages are then reconverted into a density profile using Equation 3.9. A simulation shows that this procedure results in an output exactly equal to the input (see Figure 5.6a), as long as the values for $\bar{\rho}_A$ and $\bar{\rho}_B$ are identical to the depth averaged density calculated from the true density profile. If the values for the input of Equation 3.9 ($\bar{\rho}_A$ and $\bar{\rho}_B$) are not exactly the same as the values calculated from the true density profile, for instance because of truncation or a superimposed error, the error in the calculated density profile increases over the depth (see Figure 5.6b). The vertical distance between measurement points in Figure 5.6a and b is taken 3 cm. If this distance is taken smaller, the error increases (Figure 5.6c and d).

According to Equation 5.4 the error caused by the error in the measurement of the depth depends on the vertical distance between measurement points. It also depends on the difference in average density. This behavior is also visible in a simulation (Figure 5.7). In this simulation the errors in measured density ($\Delta \bar{\rho}_A$ and $\Delta \bar{\rho}_B$) are zero, while the truncation error for the depth is ± 0.4 cm. The decay of the error over the depth is explained by the changes in depth averaged density. In the density profile of Figure 5.7 this change is largest at the jump from 1300 kg/m^3 to 1900 kg/m^3 . For the depth averaged density this means an increase between points of 5%. Although the depth averaged density continues to rise below the jump, the differences in depth averaged density decreases over depth.

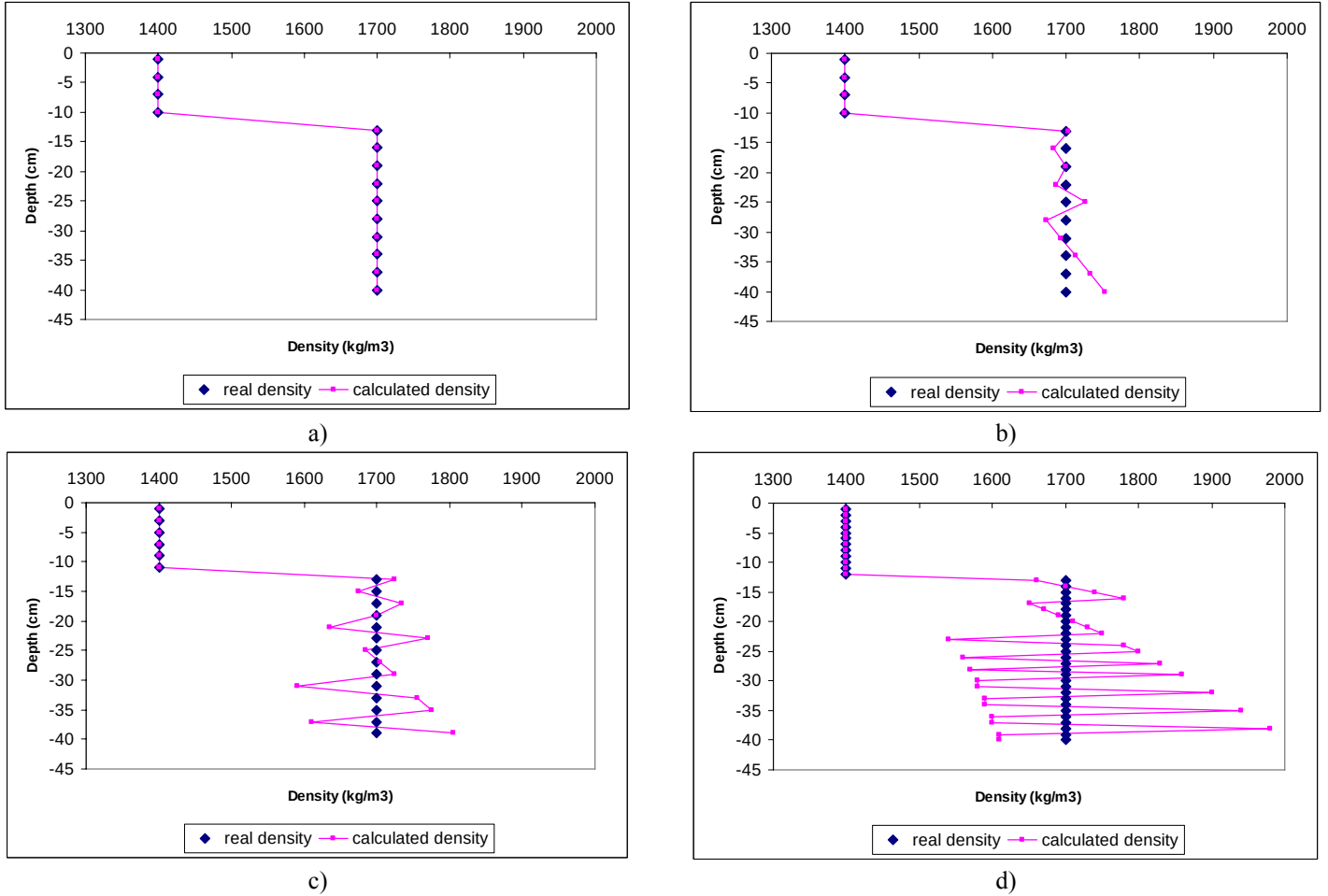


Figure 5.6: Calculated density profiles over depth (red lines) and simulated density profiles (blue dots): a) no error in input values for calculated density. b) input with truncation error of maximally $\pm 4 \text{ kg/m}^3$, vertical distance between points is 3 cm. c) input with truncation error of $\pm 4 \text{ kg/m}^3$, vertical distance between points is 2 cm. d) input with truncation error of $\pm 4 \text{ kg/m}^3$, vertical distance between points is 1 cm.

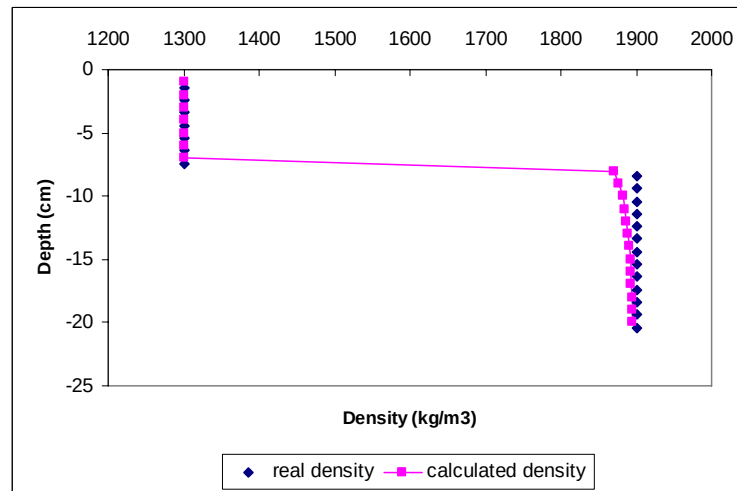


Figure 5.7: Calculated density profile over depth and simulated density profile (with no error in measured density, and a maximum truncation error for the depth of $\pm 0.4 \text{ cm}$).

Comparison with field data

The profiles of the calculated density in Figure 5.6 show an unstable oscillating behavior. The same behavior is seen in some of the density profiles measured in the field. This erratic behavior of the density calculated from the RhoC output is not primarily an effect of truncation errors. It is caused by the random error in measurement. The density measured by the RhoC should be regarded as a stochastic variable with a certain mean and deviation. One measurement is merely one possible realization of this variable. The laboratory tests show that even under unchanged circumstances, the RhoC still gives a scatter in results with a standard deviation for the density of 15 kg/m^3 . In the simulation this randomness is implemented using a random number generator. This generator gives values for the depth averaged density by generating normally distributed values around a mean. If there is no offset, this mean should be equal to the real depth averaged density. When the values for the density generated in this way are used to calculate the density over depth, the density profiles show the same variety as seen in the density profiles in Appendix C. When the real profile measured in the field is used as input for the simulation, the output has the same oscillations for most of the simulation runs (Figure 5.8). This seems to confirm the hypothesis that the oscillations are caused by errors in measurement rather than actual transitions in density.

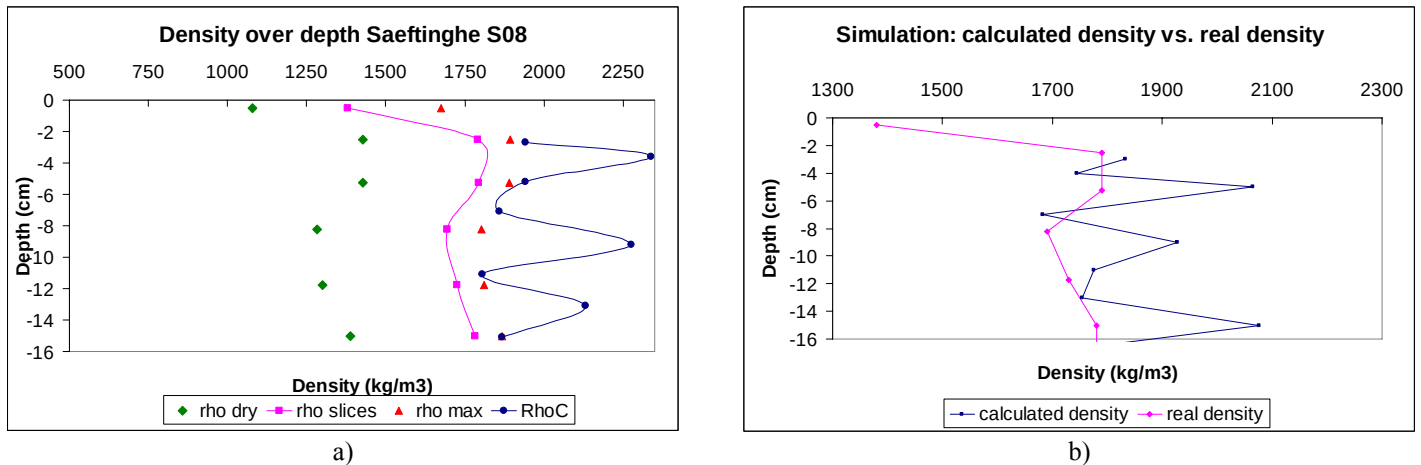


Figure 5.8: Examples of density profile in the field and from a simulation. The blue line indicates the profile measured by the RhoC and converted with Equation 3.9. Figure a) shows the real and measured profiles at location S-08. The profile of the real density has been used as an input for the simulation. One example of a possible result is given in b).

The observation in Figure 5.6 that the error should become larger with smaller vertical distances between measurement points is also visible in the field data. As mentioned in Paragraph 5.2.1, the oscillations in the RhoC density profiles from the Walsoorden and Valkenisse flats are less pronounced than the oscillations in the Molenplaat and Saeftinghe profiles. This is explained by the fact that the vertical distance between measurement points is 3 cm on average for Walsoorden and Valkenisse flats, and less than 2 cm for Molenplaat and Saeftinghe.

5.2.4 Re-calculating density over depth from RhoC data

As it is obvious the method used to calculate the density profile over depth described in Paragraph 3.1.5 is not stable, a different method has to be used. In order to dampen the

extremes in the profile, the densities of the RhoC are used to compute averages consisting of three of the RhoC densities. For each depth this average consists of the RhoC density from the same depth and the two RhoC densities measured above and below that depth (see Figure 5.9). For instance, in Figure 5.9 the value for $\bar{\rho}_1$ is the average of $\bar{\rho}_A$ and $\bar{\rho}_B$. The value for $\bar{\rho}_2$ is the average of $\bar{\rho}_A$, $\bar{\rho}_B$, and $\bar{\rho}_C$. On these averages a correction for the offset is applied. This correction is based on the relation between the offset and the saturation as is seen in Figure 5.4. The average degree of saturation of the sample core is used to estimate the offset. This offset is then subtracted from $\bar{\rho}_1$ to $\bar{\rho}_5$. The values for $\bar{\rho}_1$ to $\bar{\rho}_5$ are then used as input into Equation 3.9 to get the profile of $\rho(z)$. The result of taking these averages is that the extremes that cause the oscillations are smoothed.

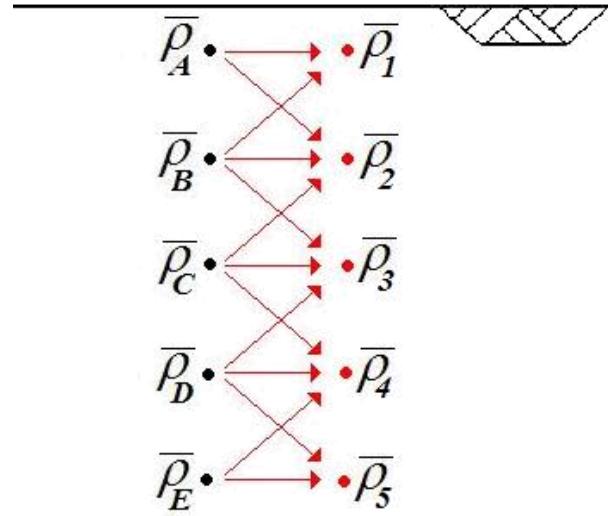
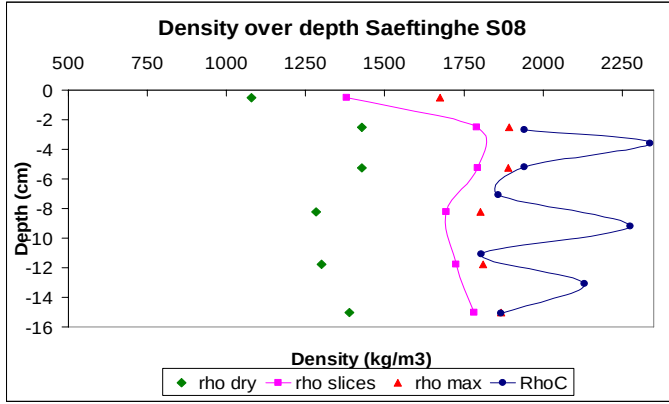
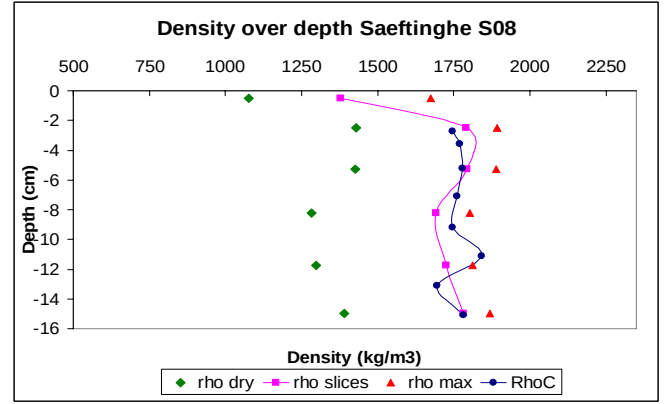


Figure 5.9: RhoC densities ($\rho_A \dots \rho_E$) are used to compute averages ($\rho_1 \dots \rho_5$).

In Figure 5.10 to Figure 5.12 some typical results of this method are presented. Figure 5.10 and Figure 5.11 show that this method improves the shape of the profile. Some of the oscillations still exist, but the shape of the real profile is much better recognizable. However, in some cases, as shown in Figure 5.12, this method dampens the variations in densities too much, and the calculated density profile does not follow the variations in density as they exist in reality.

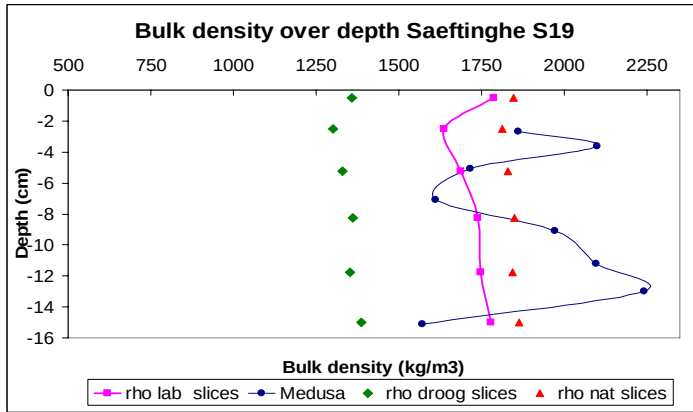


a)

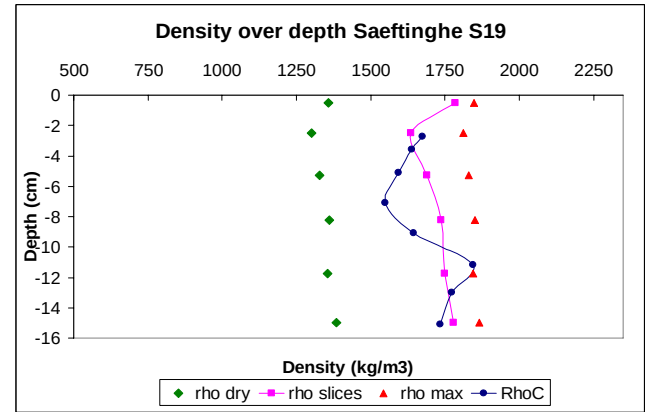


b)

Figure 5.10: Density profiles from RhoC measurements, location Saeftinghe S08: a) calculated using Equation 3.9 without correction. b) calculated using 4th order linear fit, Equation 3.9 and offset correction.

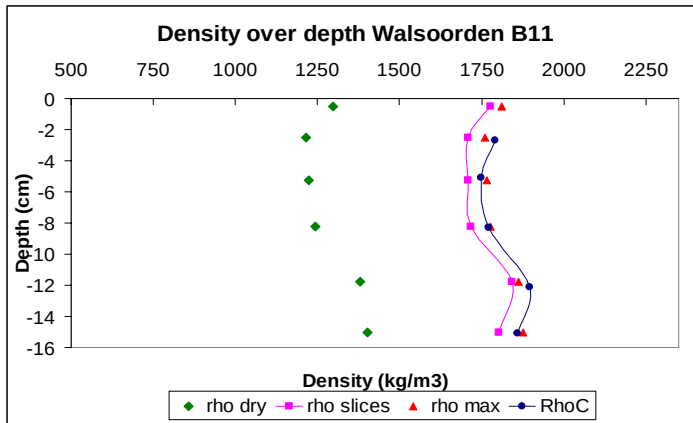


a)

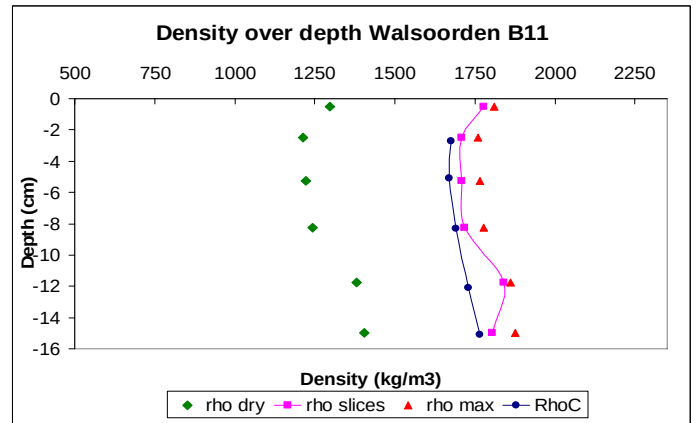


b)

Figure 5.11: Density profiles from RhoC measurements, location Molenplaat punt 8: a) calculated using Equation 3.9 without correction. b) calculated using 4th order linear fit, Equation 3.9 and offset correction.



a)



b)

Figure 5.12: Density profiles from RhoC measurements, location Saeftinghe S10: a) calculated using Equation 3.9 without correction. b) calculated using 4th order linear fit, Equation 3.9 and offset correction.

5.3 Practical applicability

Now that the MEDUSA RhoC device has been tested in the field and laboratory, an assessment is made of its practical applicability. This is done by looking at the necessary steps that have to be made when using the RhoC in the field. This total procedure from beginning to end is summarized in Figure 5.13.

When the RhoC system is applied on a tidal flat for the first time, first the fingerprint has to be determined. To do this, sediment samples are collected from several locations. At the same locations the activity concentrations and water contents are measured with RhoC. These samples should give an adequate representation of all the different sediment types present on the tidal flat. Besides these sample locations, the RhoC is used on any number of locations to measure activity concentrations, depth averaged density profiles, and depth averaged water content profiles. The samples are analyzed on mud content in the laboratory. From this data the fingerprint is derived. When the fingerprint is generated, the mud contents for the other locations are calculated. Besides that, the depth averaged densities and water contents are converted into profiles.

Once the fingerprint is known, sediment sampling is no longer needed, and nothing but the RhoC is required for field measurement. The device comes equipped with its own backpack, making it easy to carry. Per location the entire measurement procedure takes roughly twenty minutes. The total number of locations that is reached in the time that the tidal flat is not flooded also depends on the distances between measurement locations. With distances of several hundreds of meters the number of locations becomes somewhere between 10 and 20.

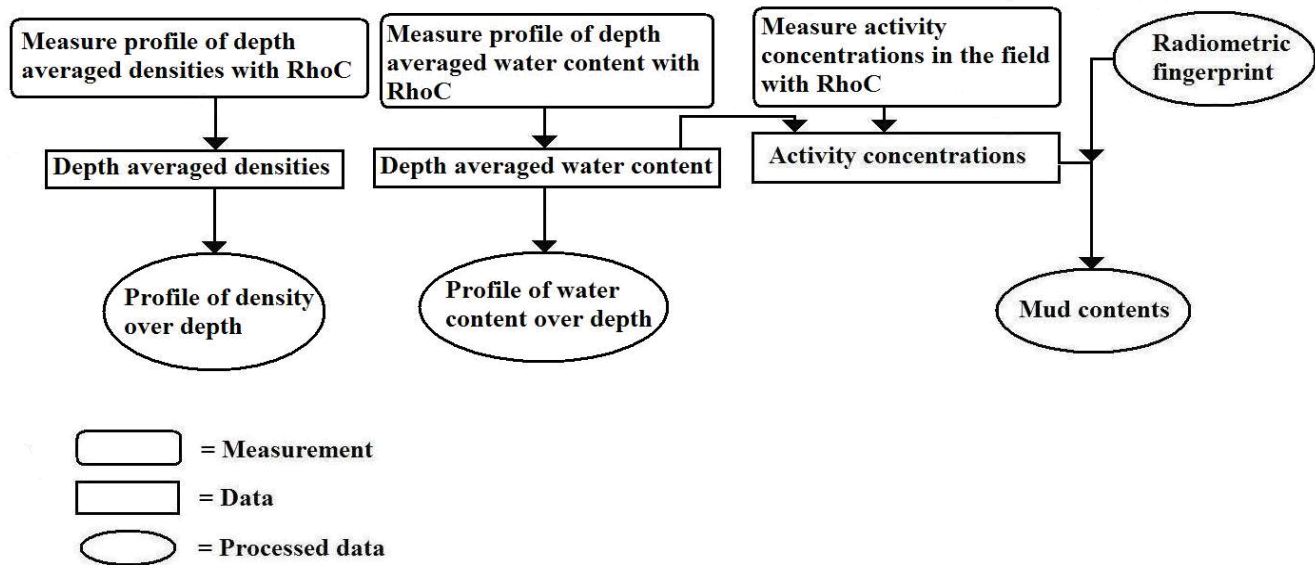


Figure 5.13: Total procedure for the application of the RhoC system on a tidal flat. The procedure to determine the fingerprint is shown in Figure 5.3.

5.4 General observations regarding sediment composition

The measurements taken in the field and laboratory show that properties such as density, composition, water content, and vertical structure are far from uniform, but show variability in space and over depth (see also Paragraph 4.2). The measurements also reveal several relations between various sediment properties which are very useful. The analyses on the sediment cores revealed fair to strong relations between several qualities. The mud content shows a strong correlation to the organic matter content, and also the silt and clay content are related to each other. This means that by measuring the mud content with the RhoC, also the clay, silt, and organic matter content are known. Another useful relation is the relation between mud content and density. This is useful for determining properties of the top layer. One disadvantage of the RhoC is that its accuracy of the density measurement above 2.5 cm is low. If the mud content of the top layer is measured through a different method, the density is derived through the relation between density and mud content.

The RhoC is designed only to measure mud content, bulk density, and water content. With the known relations more properties are derived. As mentioned, silt and clay contents are derived from the mud content. The clay content also makes it possible to determine the plasticity index (Equation 2.11). From the silt and sand content the sand fraction (Equation 2.6) is derived. The relation between sand fraction and porosity in Figure 4.4 makes it possible to derive the porosity. The location within this figure is important for determining the erosive behavior of the sediment. The porosity can also be calculated directly from the bulk density and water content (Equation 2.5), although for this approach it is necessary to know the saturation. The combination of water content and plasticity index also makes it possible to determine the relative water content (Equation 2.12). The relative water content is a useful parameter, because it is independent of forcing conditions, and is important for mechanical behavior such as erosion resistance.

6 Conclusions & recommendations

6.1 Conclusions

The aim of this thesis was to investigate the accuracy and applicability of the MEDUSA RhoC system with its new components. To do this, results were obtained with the RhoC and with traditional analyses, both in the lab and the field. Now these results have been compared with each other, conclusions are drawn on the overall performance of the system, the performance of each individual component, and the measurement procedure in general. Besides the conclusions regarding the MEDUSA RhoC system, the data from the field has given insight into relations between various sediment properties which are useful in linking the parameters measured by the RhoC to the mechanical behavior of the sediment.

The fingerprints derived from RhoC measurements return results that are comparable to the results from the fingerprints derived from laboratory measurements. However, this is only true if the RhoC can measure the water content accurately, which was not yet the case. The advantage of the “field” fingerprint is that it is not necessary to measure activity concentration in the laboratory anymore.

The laboratory calibration tests revealed that the value for the density calculated by the RhoC converges over the course of a measurement towards a final value. This value does not change much after 35 seconds of measurement. Therefore, a minimum duration of the density measurement of 35 seconds is recommended. When this duration for the density measurement is applied, the total time it takes to complete a measurement of the sediment composition and the density profile at one location is roughly 20 minutes.

The depth averaged density measured by the RhoC contains two errors: an average positive offset of 2% and a random error with a standard deviation of 15 kg/m³. This random error limits the accuracy of the profile of the density over the depth. Although the average value of the random error is constant, the error in the density profile grows stronger with depth. One way to limit this error is to increase the vertical distance between measurement points. However, this approach also limits the resolution. Another approach to increase the accuracy of the profiles is to perform more than one density measurement at each depth. However, this approach increases the total duration of measurements in the field. Yet another approach is to smooth out the extremes of the density measurements by taking averages out of adjoining density measurements. These averages are then used to calculate the profile of the density over depth. This last approach is recommended, as it returns the best results without reducing the resolution or increasing the total duration of measurements.

The sediment samples from the Western Scheldt revealed several relations between sediment properties. If the mud content is known, also the clay content, silt content, organic matter content, and water content are derived. Also, there seems to be a correlation between mud content and bulk density.

The MEDUSA RhoC system functions well in the field. Its applicability over large areas is only limited by the distances that have to be traveled, and the duration of a

measurement. In general, the MEDUSA RhoC system can supply valuable information on the composition, density, water content, and stratification of sediment. Although these properties are the only things the RhoC measures, the known relations between these properties and other parameters enable the user to derive much more qualities. This makes the MEDUSA RhoC system a valuable measuring device for sediment mapping, which can improve the quality of the input parameters for large-scale numerical models.

6.2 Recommendations

Offset

The cause and magnitude of the positive offset in the density measurement is not yet well understood. The offset in field measurements seems dependent on the saturation of the sediment. However, this dependency is not seen in laboratory measurement. Tijss (2007) hypothesized an offset as a function of the saturation. However, he hypothesized this offset would be negative, and would become more negative with lower saturation. It is recommended to investigate the behavior of this offset and the influence of the saturation under controlled circumstances.

TDR

The TDR was malfunctioning during the testing in the field and the laboratory. The TDR has since been reinstalled into the RhoC, but has not been tested sufficiently. To assess the TDR's accuracy and precision, it is recommended to perform tests under controlled circumstances. Also, it is recommended to investigate whether a vertical profile of the water content can be measured with the TDR.

Top layer

When the depth of the gamma ray source below the surface is less than 2.5 cm, the accuracy of the density measurement drops significantly. This is because with the source at this depth some of the emitted photons will travel through the air above the surface towards the detector. However, knowledge on the density of the top layer is very valuable. Therefore, it is recommended to investigate whether the accuracy of the density measurement of the layer above 2.5 cm can be improved in any way.

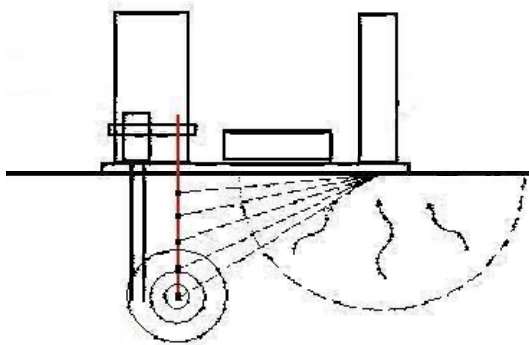
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Measuring sediment composition in the field using MEDUSA

Appendices



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Delft, February 2008

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Appendix A Sediment fraction distributions for the Western Scheldt

A.1 Median grain sizes

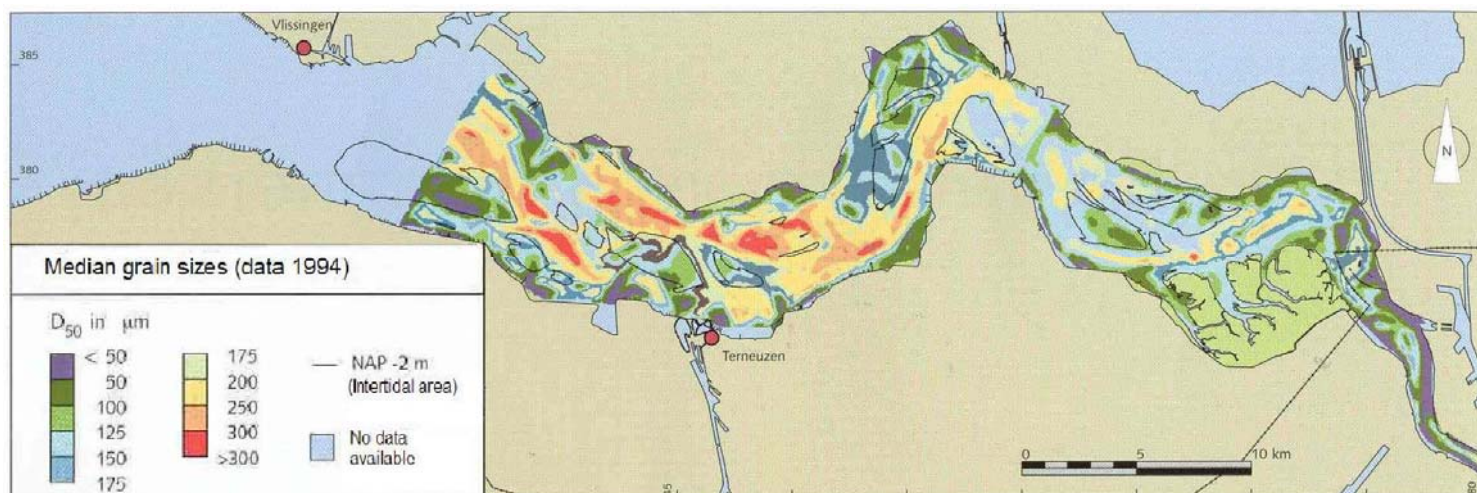


Figure 0.1: Median grain sizes in the Western Scheldt (source: Van Eck, 1999).

A.2 Mud contents

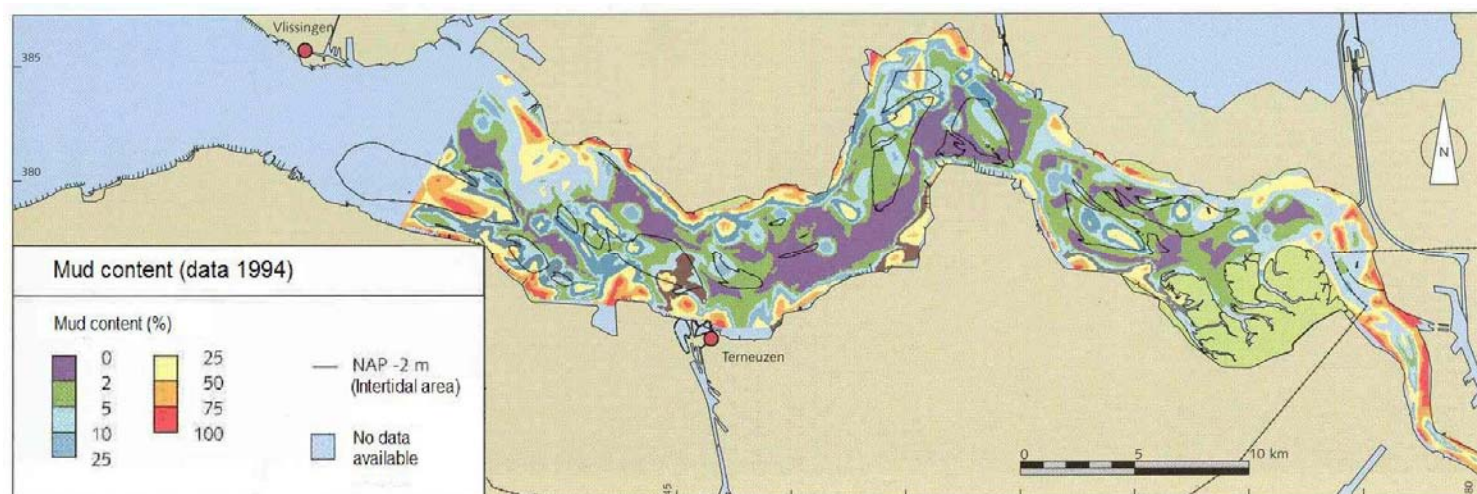


Figure 0.2: Mud contents in the Western Scheldt (source: Van Eck, 1999).

Appendix B Laboratory calibration tests

B.1 Tests on dry sand

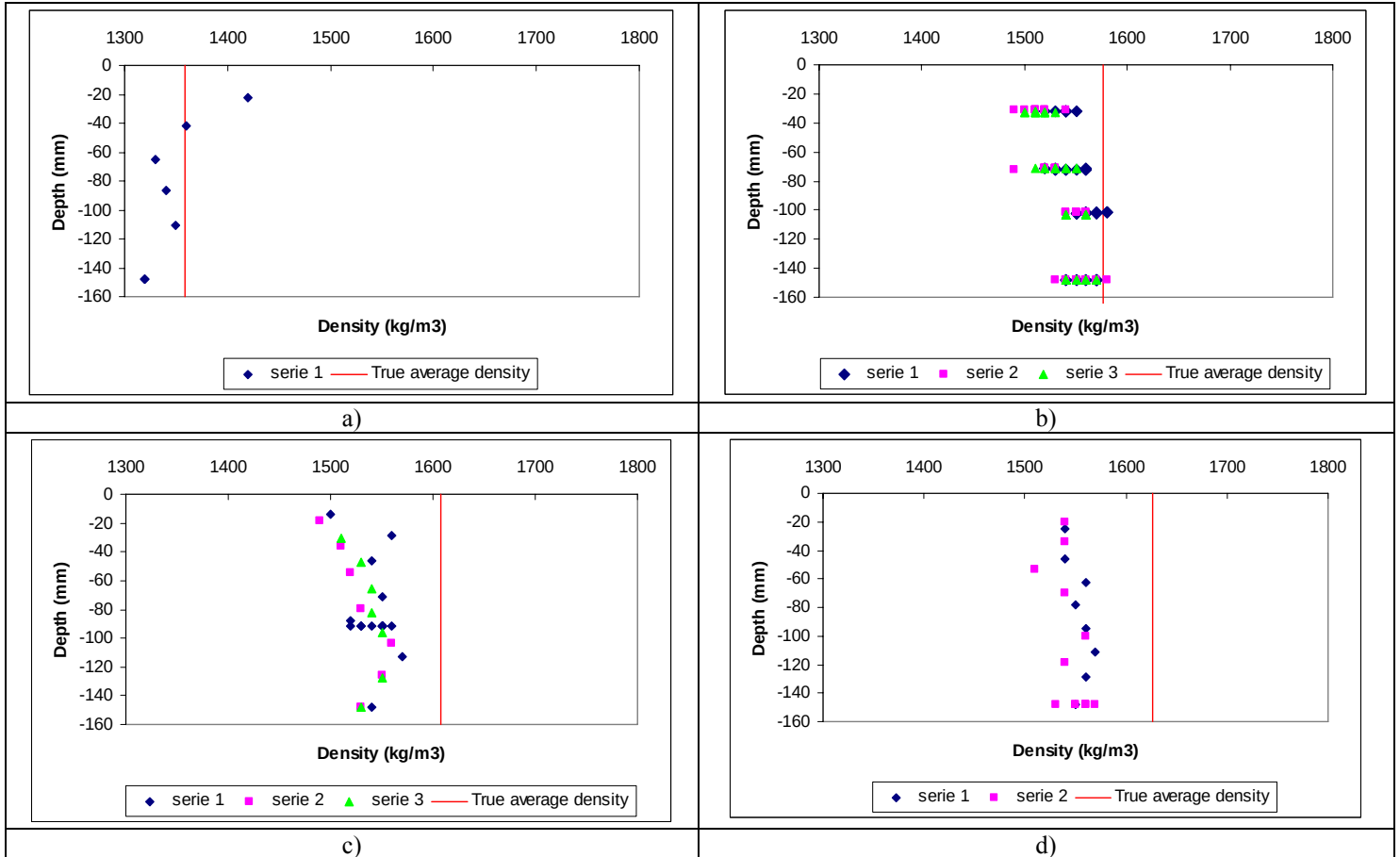
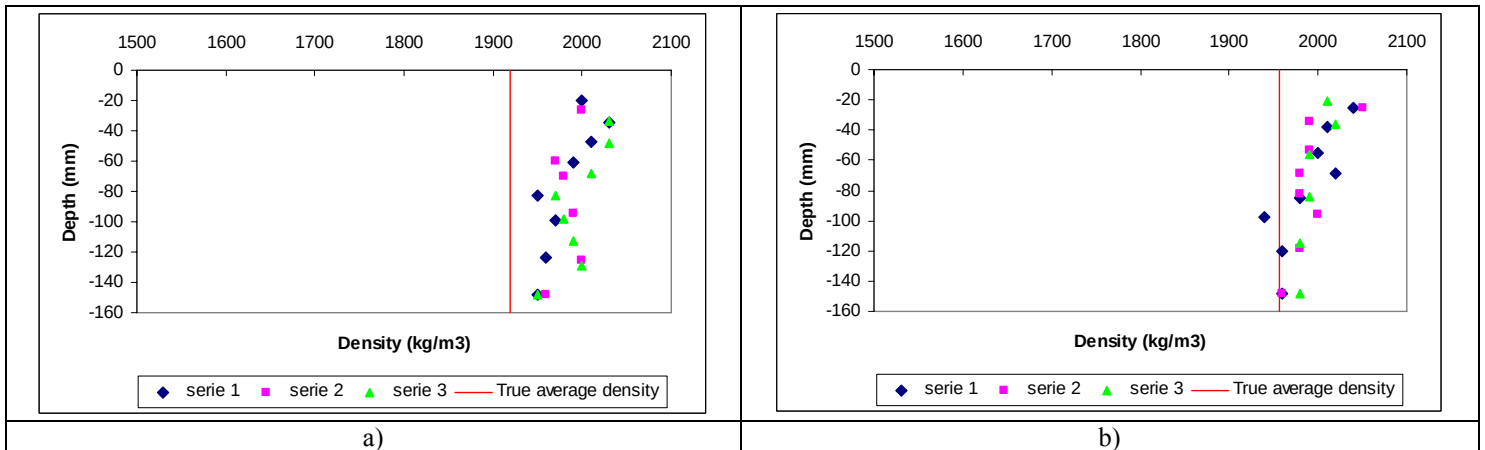


Figure 0.1: Densities measured by RhoC on dry sand under controlled circumstances. In a) the sand is not compacted, and has a density of 1358 kg/m³. In b) the sand is compacted once, and has a density of 1577 kg/m³. In c) the sand is compacted twice, and has a density of 1608 kg/m³. In d) the sand is compacted three times, and has a density of 1627 kg/m³.

B.2 Tests on saturated sand



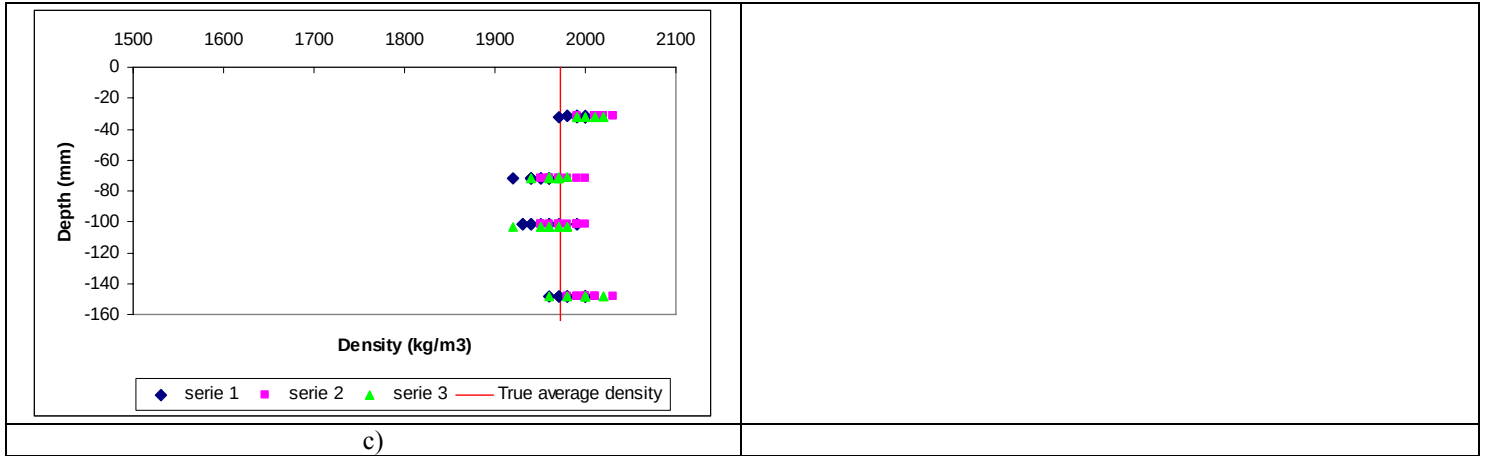


Figure 0.2: Densities measured by RhoC on saturated sand under controlled circumstances. In a) the sand is not compacted, and has a density of 1919 kg/m³. In b) the sand is compacted once, and has a density of 1956 kg/m³. In c) the sand is compacted twice, and has a density of 1973 kg/m³.

B.3 Tests on dry sand-silt mixture

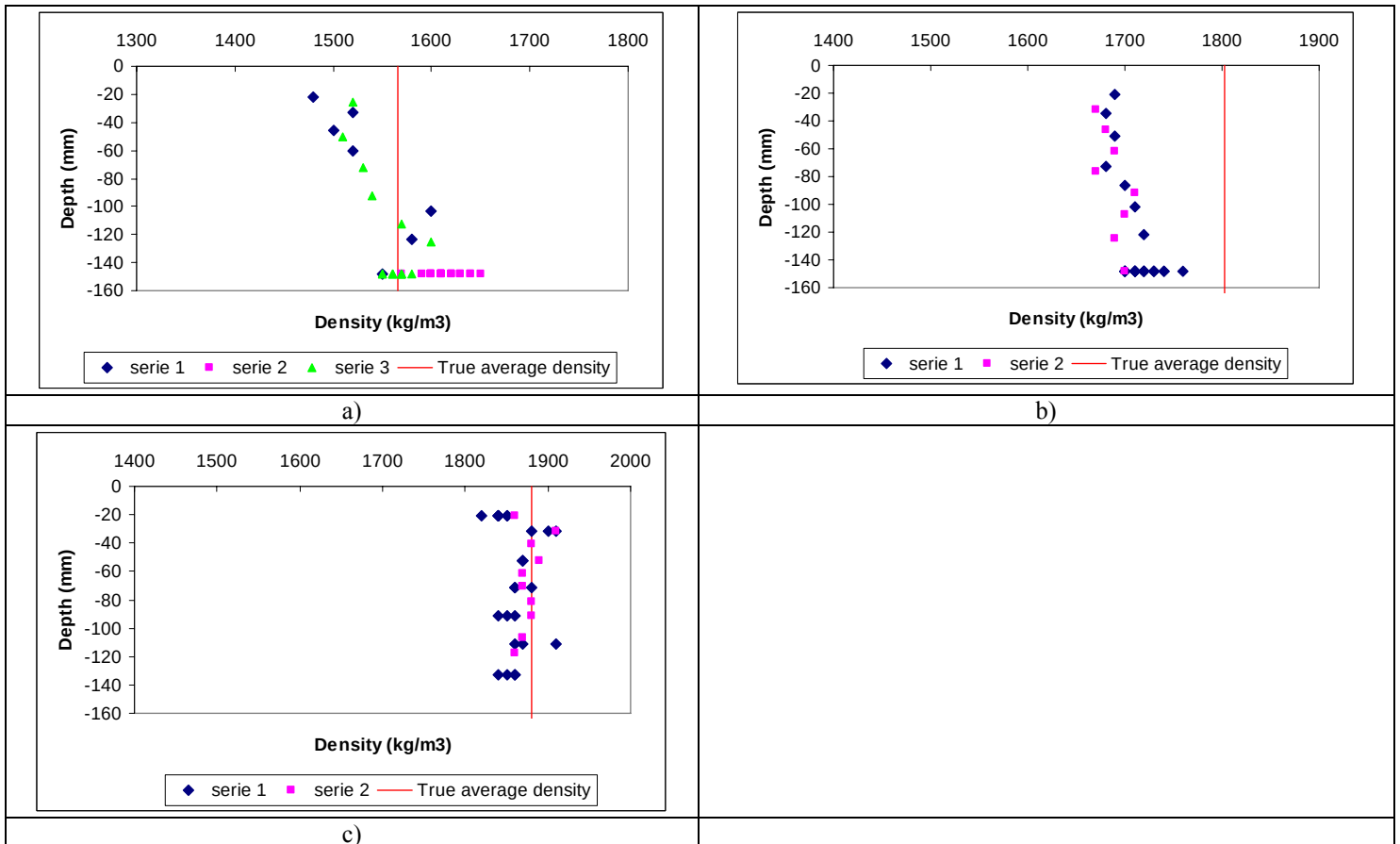


Figure 0.3: Densities measured by RhoC on dry sand-silt mixture under controlled circumstances. In a) the mixture is not compacted, and has a density of 1566 kg/m³. In b) the mixture is compacted once, and has a density of 1803 kg/m³. In c) the sand is compacted twice, and has a density of 1880 kg/m³.

Appendix C Vertical density profiles

C.1 Saeftinghe density measurements

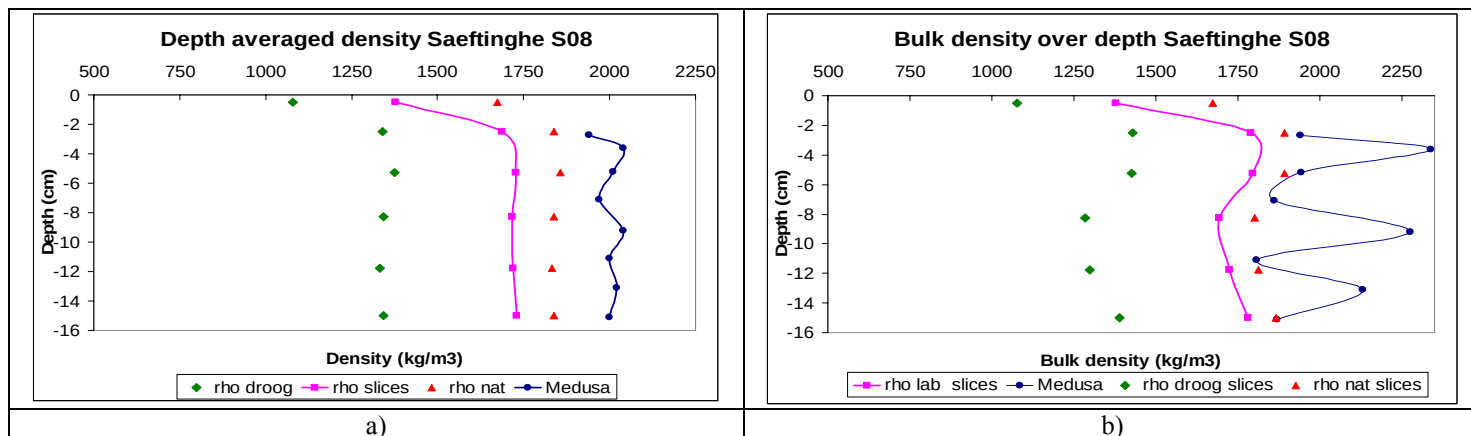


Figure 0.1: Density measurements of RhoC and lab slices, location S-08: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

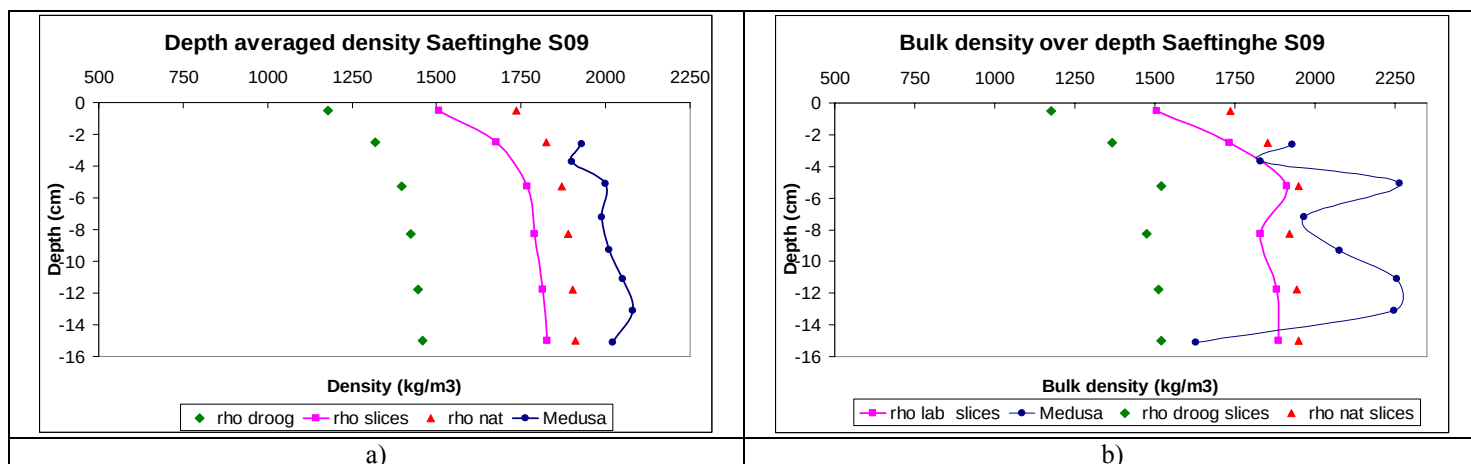


Figure 0.2: Density measurements of RhoC and lab slices, location S-09: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

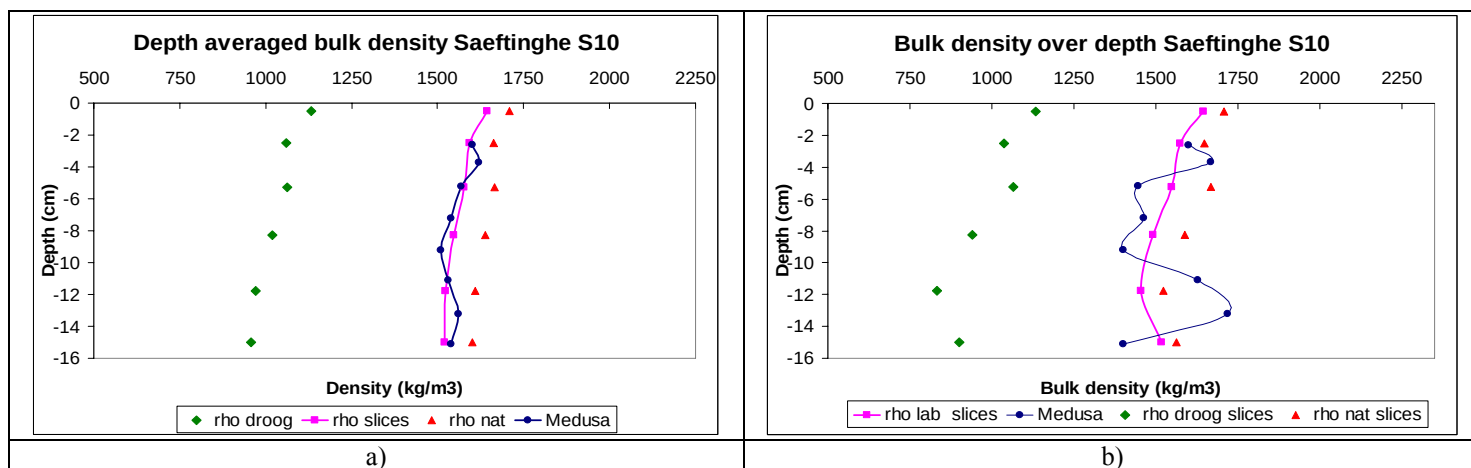


Figure 0.3: Density measurements of RhoC and lab slices, location S-08: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

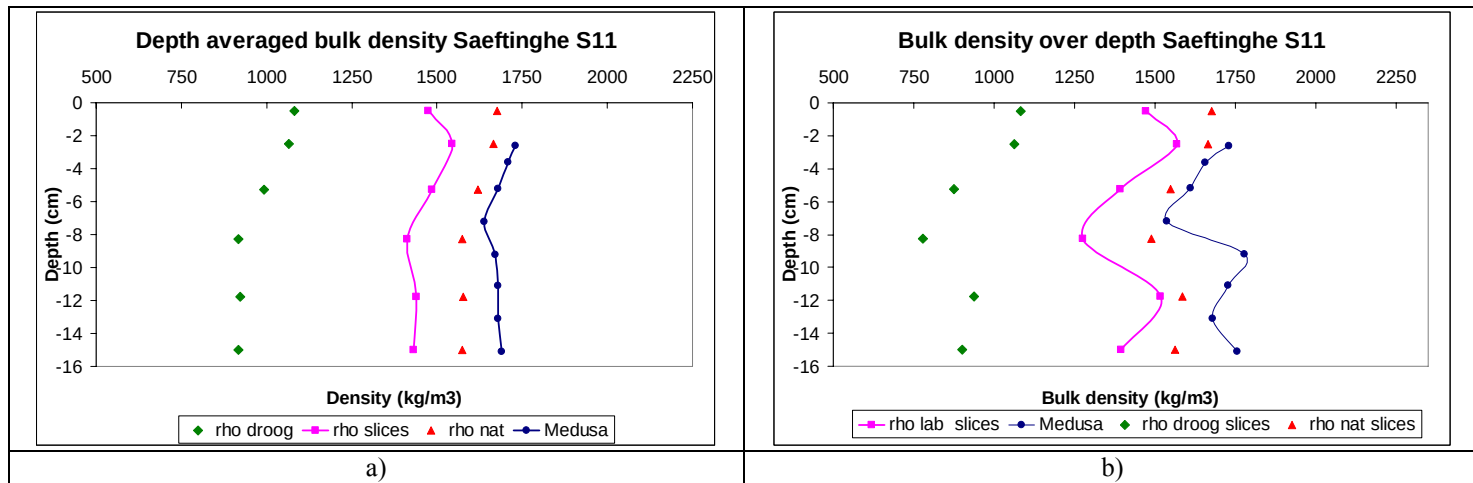


Figure 0.4: Density measurements of RhoC and lab slices, location S-11: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

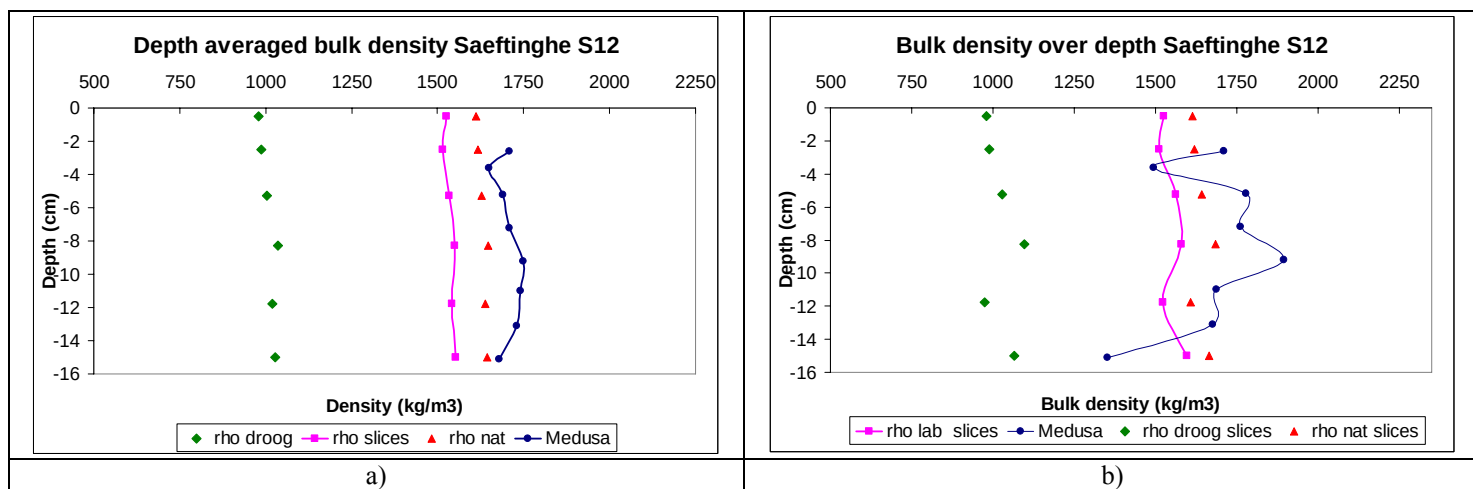


Figure 0.5: Density measurements of RhoC and lab slices, location S-12: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

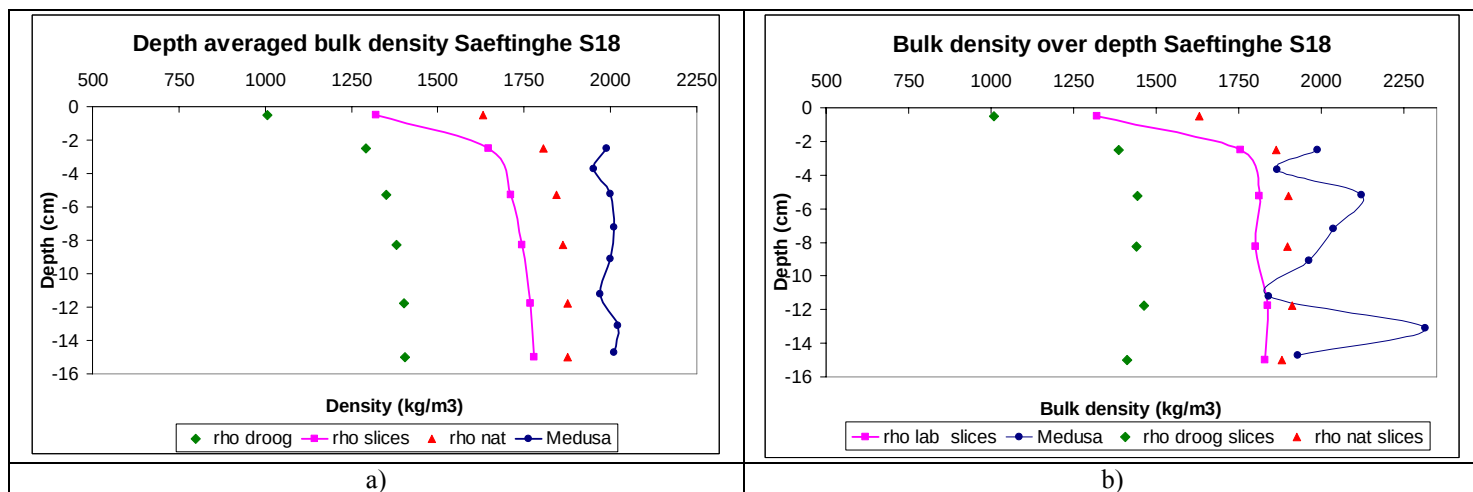


Figure 0.6: Density measurements of RhoC and lab slices, location S-18: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

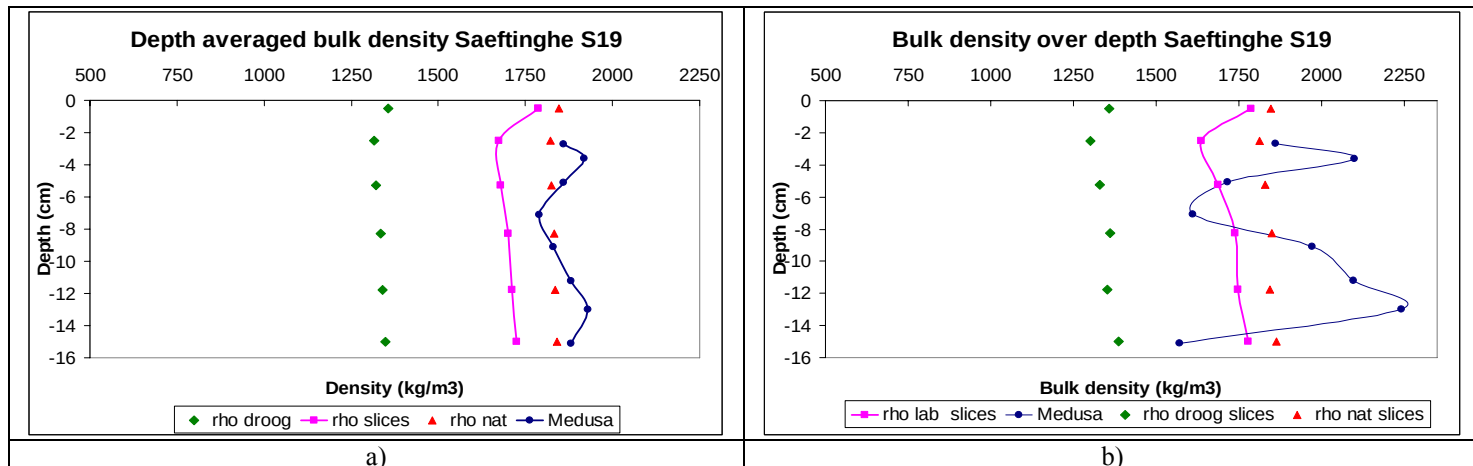


Figure 0.7: Density measurements of RhoC and lab slices, location S-19: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

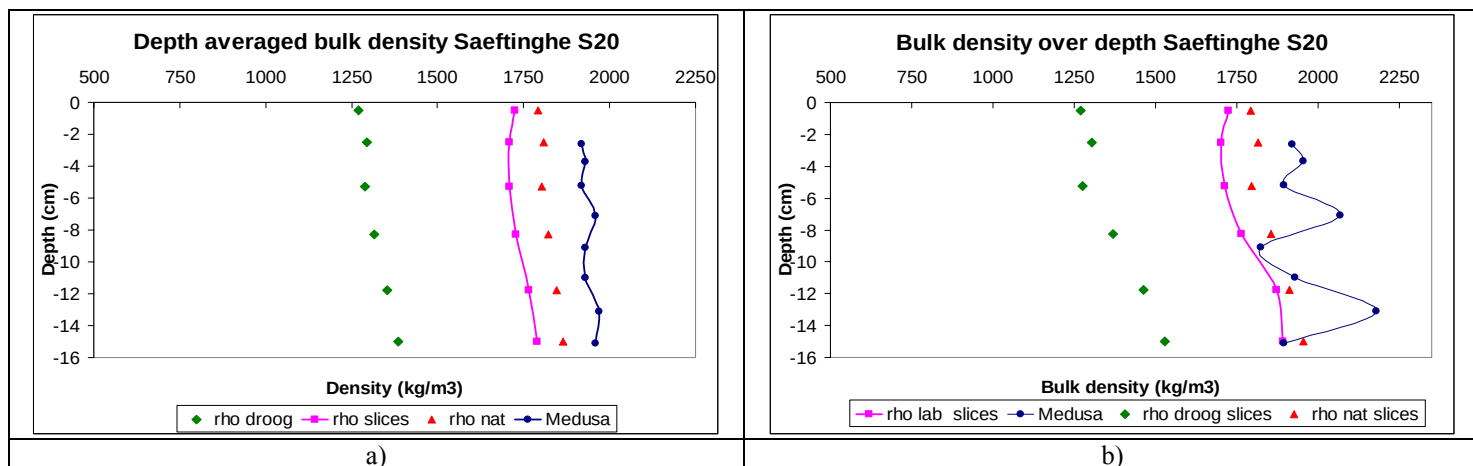


Figure 0.8: Density measurements of RhoC and lab slices, location S-20: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

C.2 Molenplaat density measurements

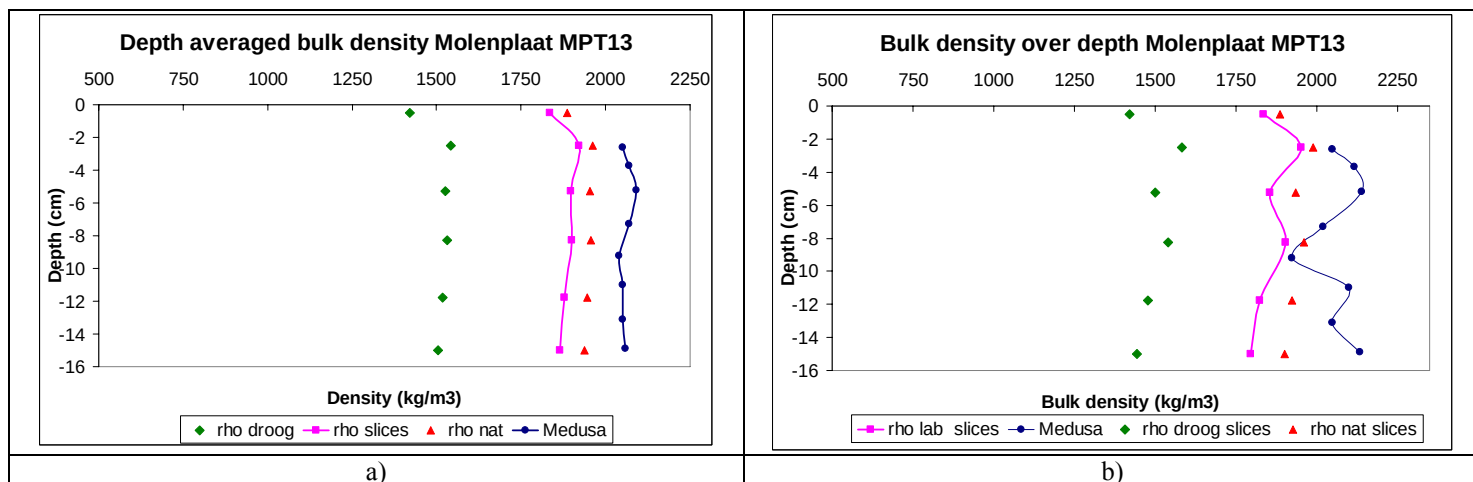


Figure 0.9: Density measurements of RhoC and lab slices, location MPT-13: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

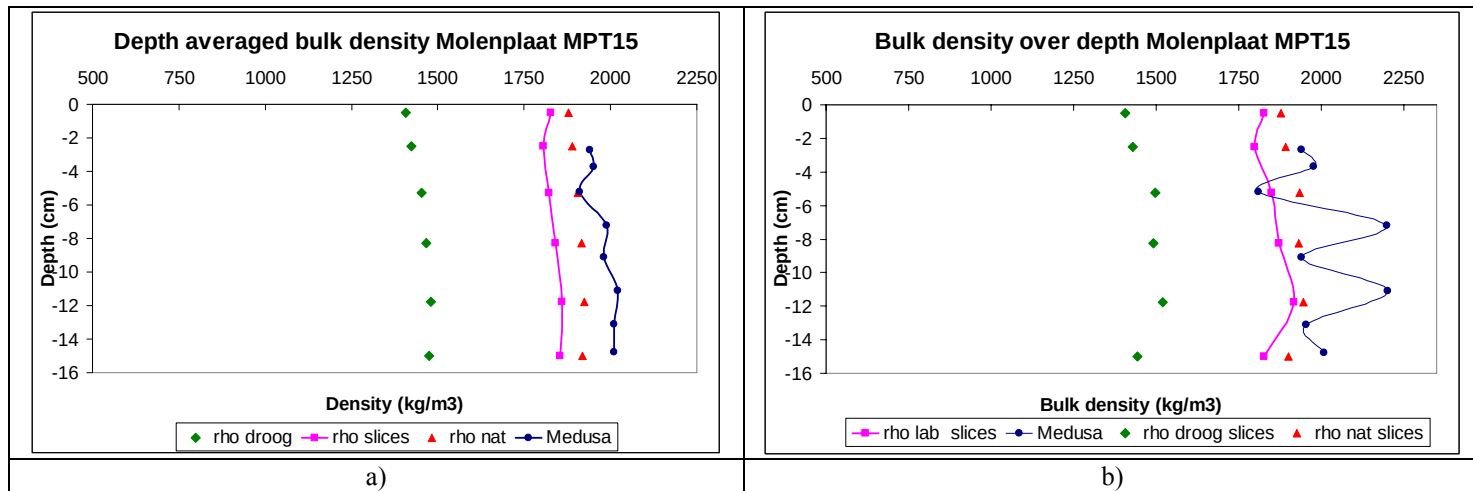


Figure 0.10: Density measurements of RhoC and lab slices, location MPT-15: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

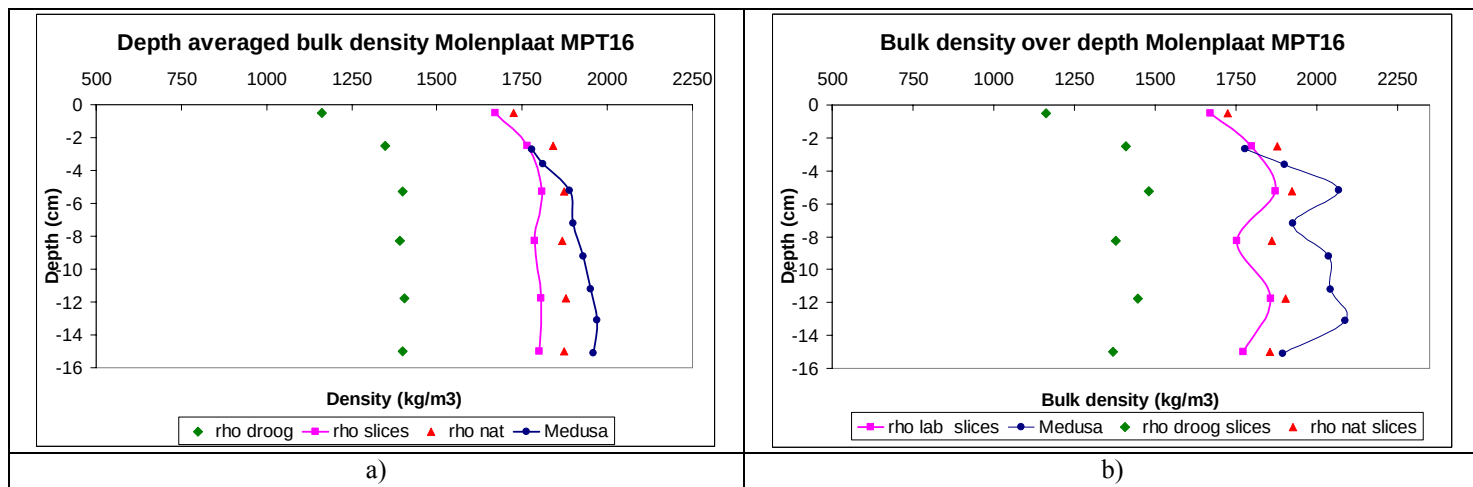


Figure 0.11: Density measurements of RhoC and lab slices, location MPT-16: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

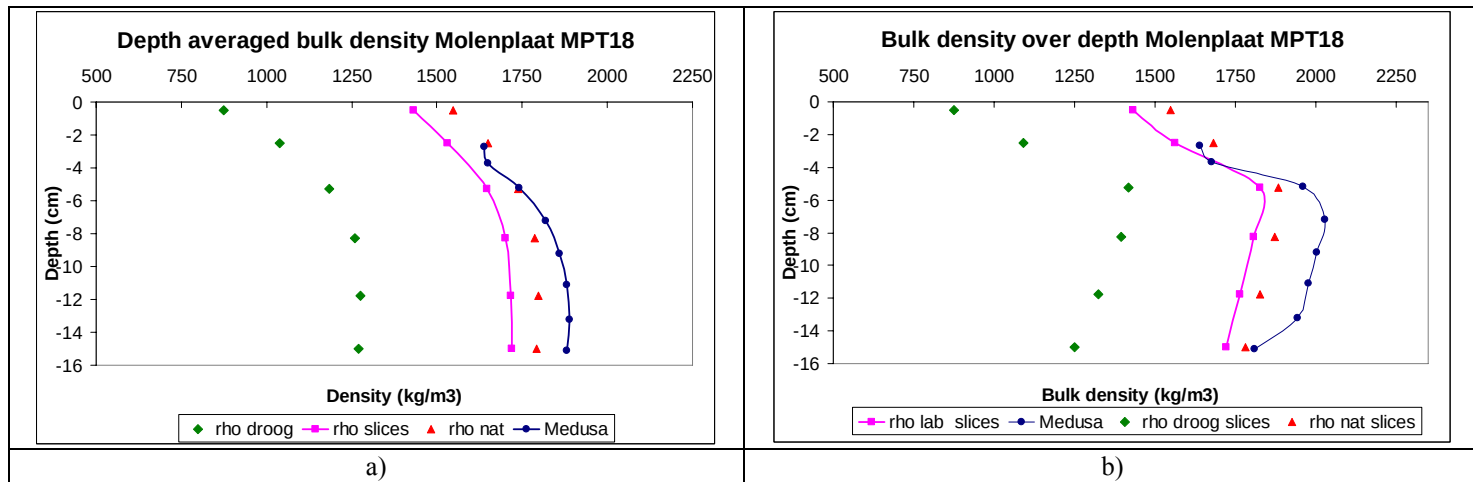


Figure 0.12: Density measurements of RhoC and lab slices, location MPT-18: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

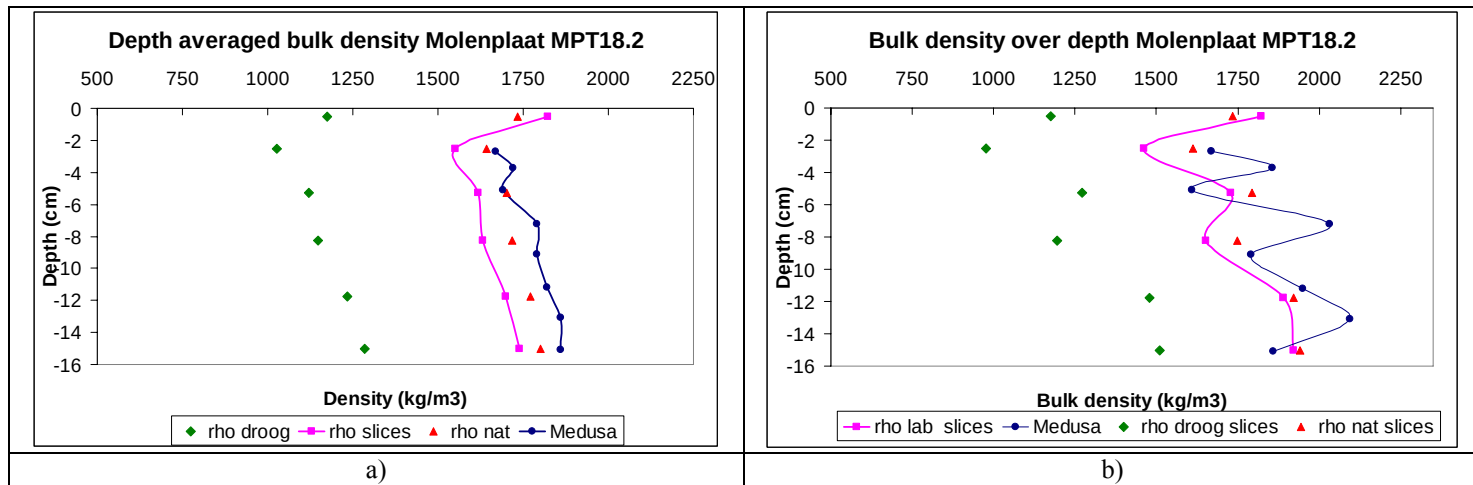


Figure 0.13: Density measurements of RhoC and lab slices, location MPT-18.2: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

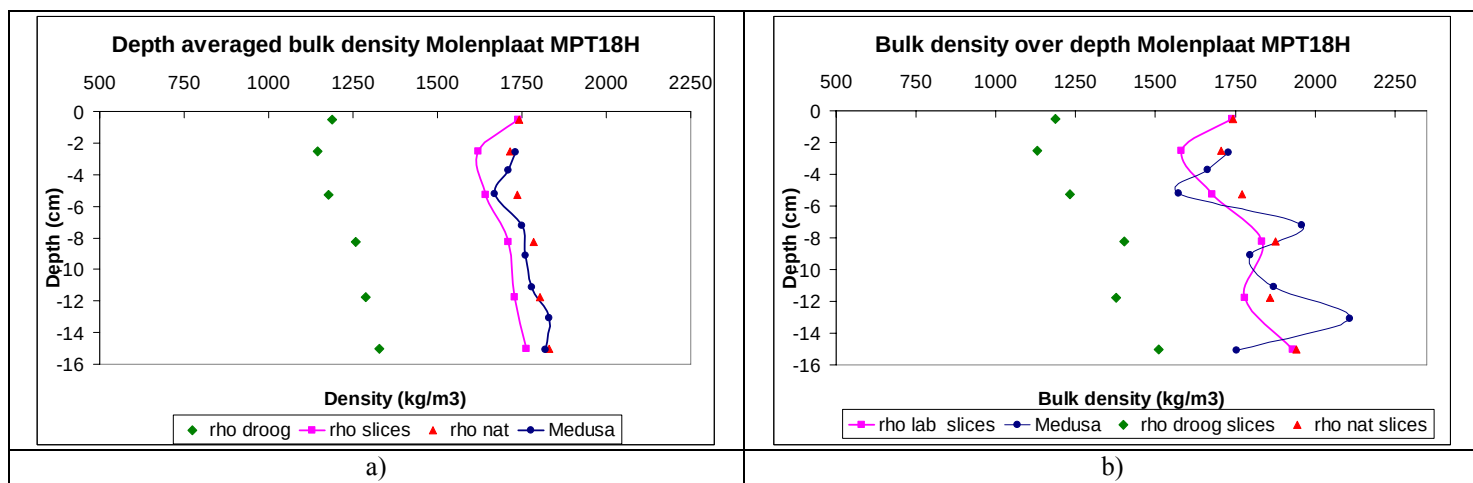


Figure 0.14: Density measurements of RhoC and lab slices, location MPT-18H: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

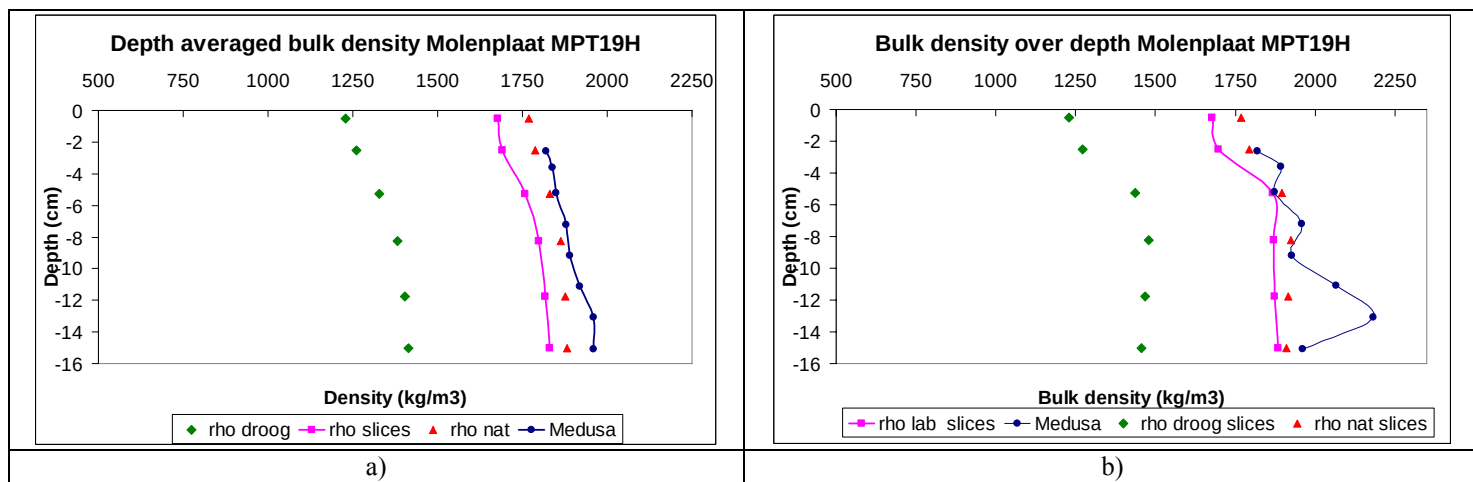


Figure 0.15: Density measurements of RhoC and lab slices, location MPT-19H: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

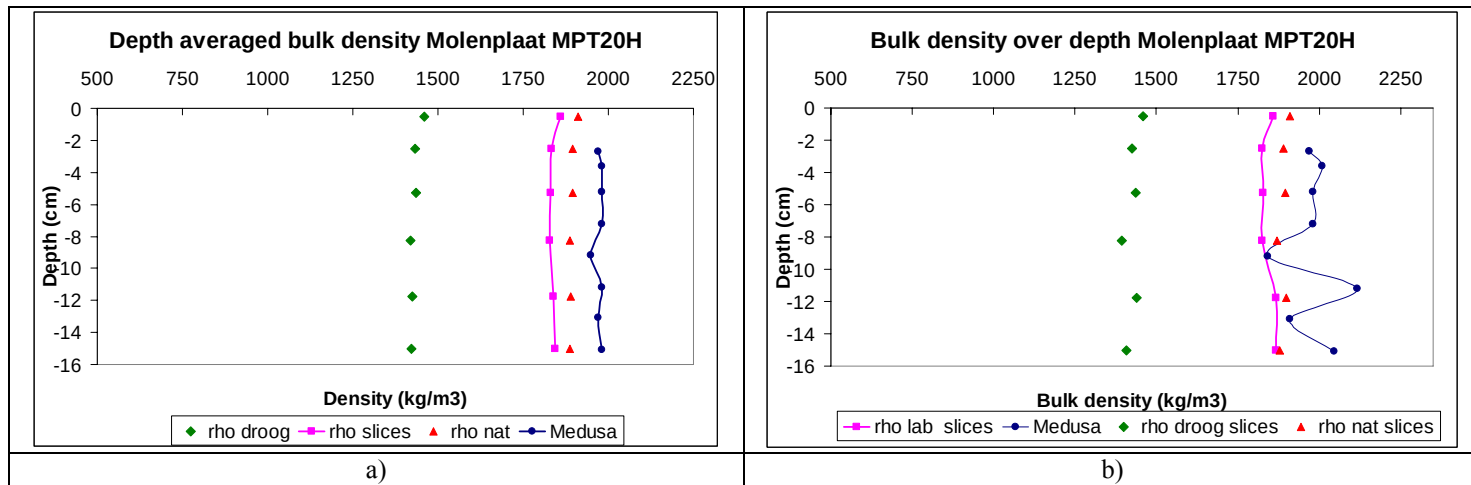


Figure 0.16: Density measurements of RhoC and lab slices, location MPT-20H: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

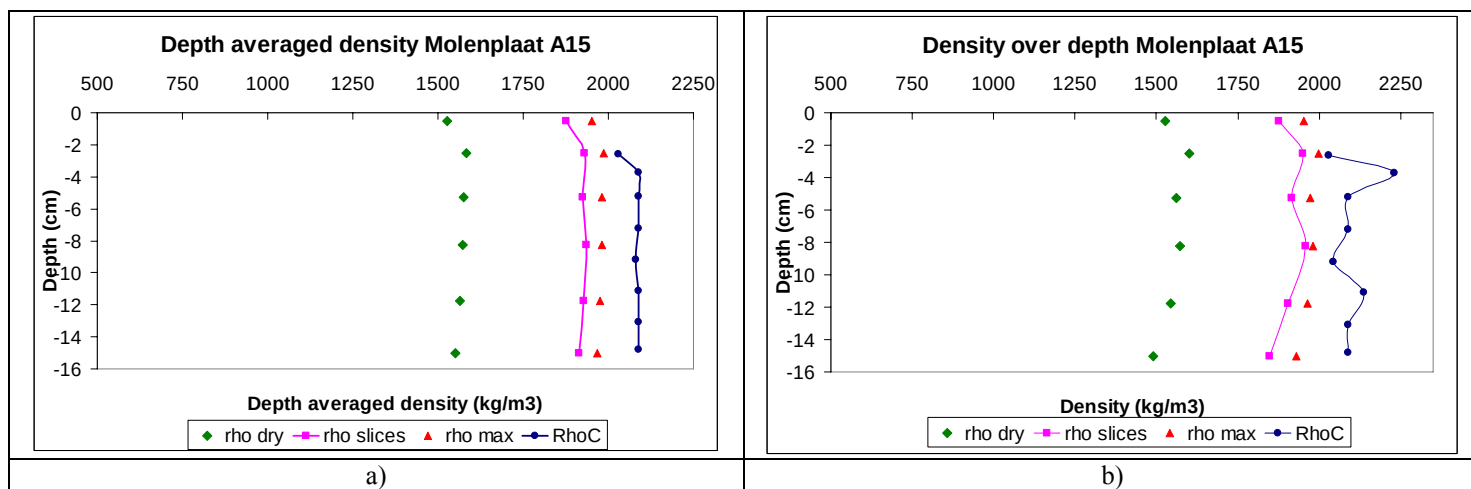


Figure 0.17: Density measurements of RhoC and lab slices, location A-15: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

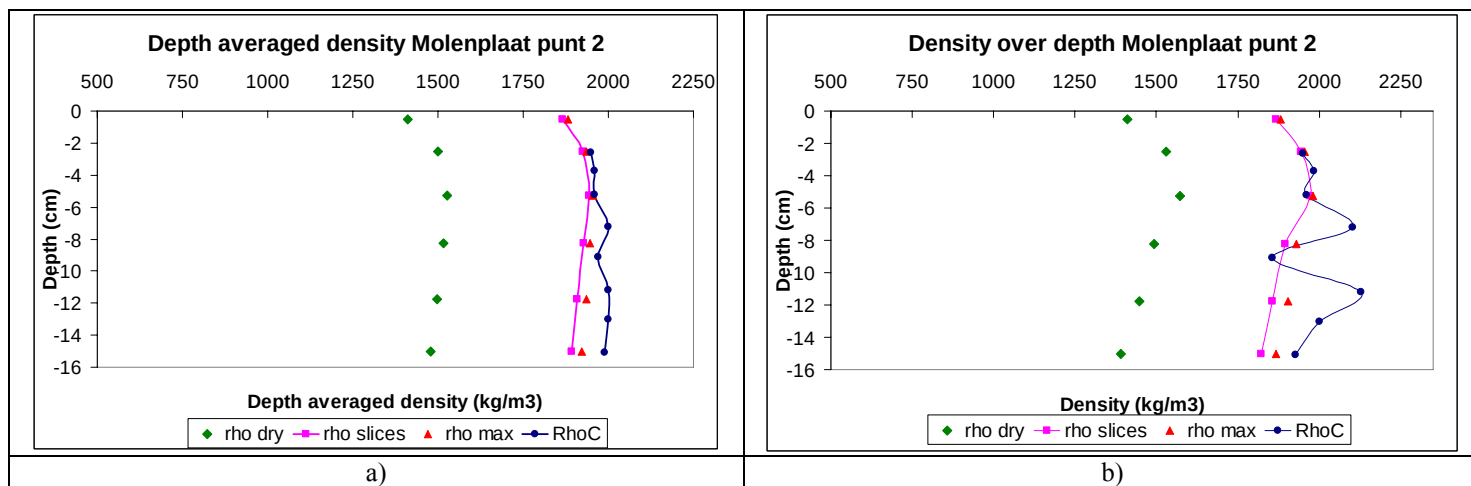


Figure 0.18: Density measurements of RhoC and lab slices, location punt 2: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

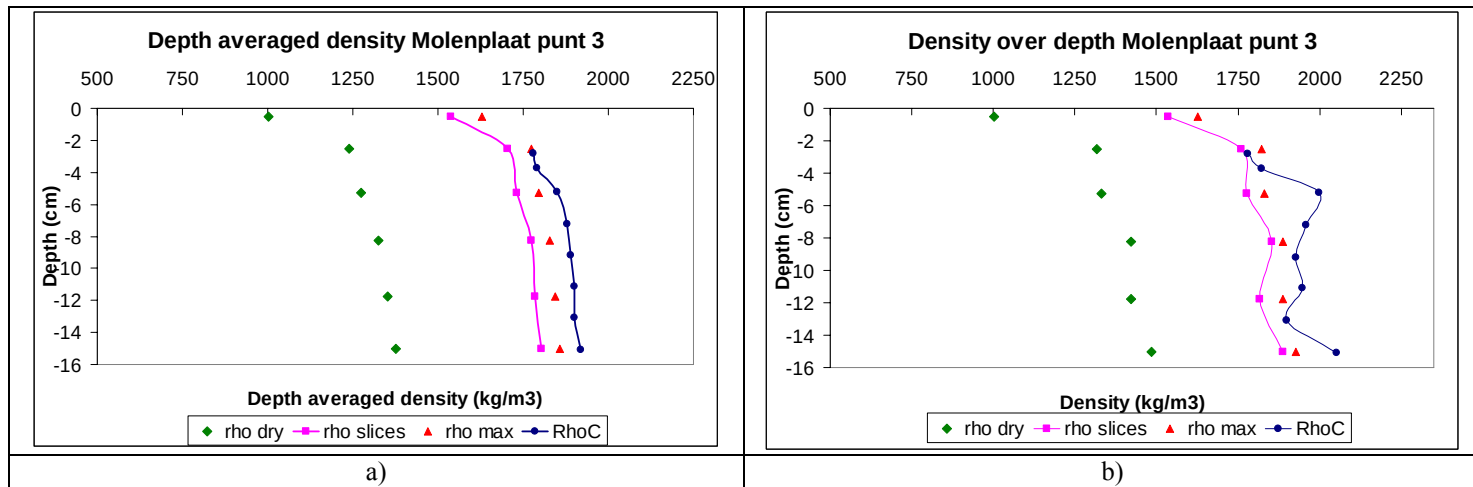


Figure 0.19: Density measurements of RhoC and lab slices, location punt 3: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

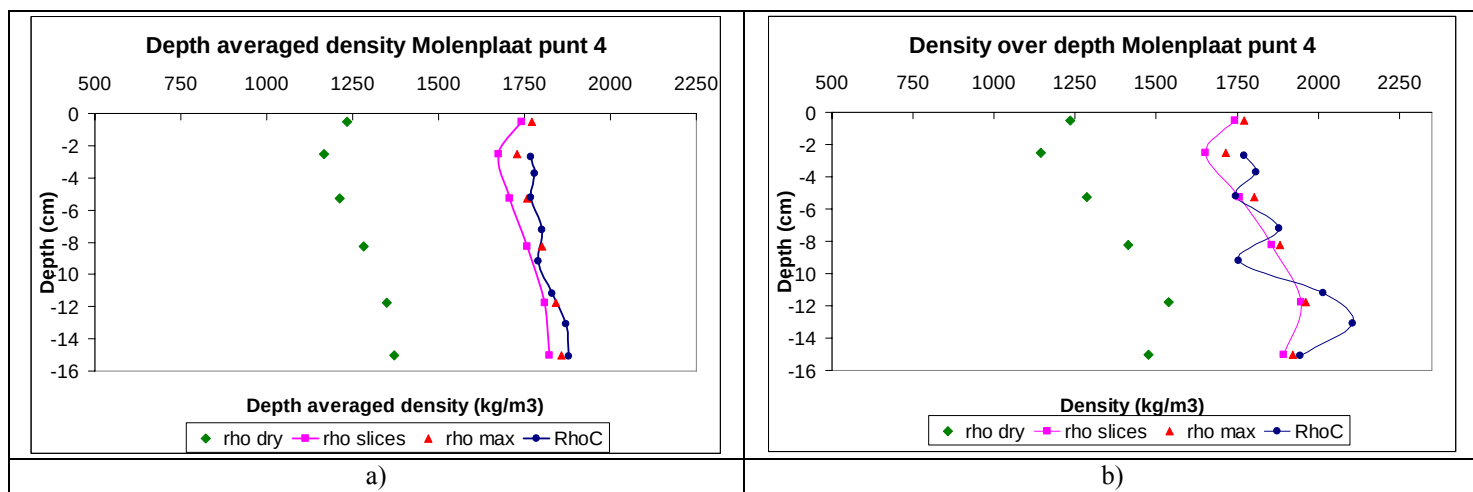


Figure 0.20: Density measurements of RhoC and lab slices, location punt 4: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

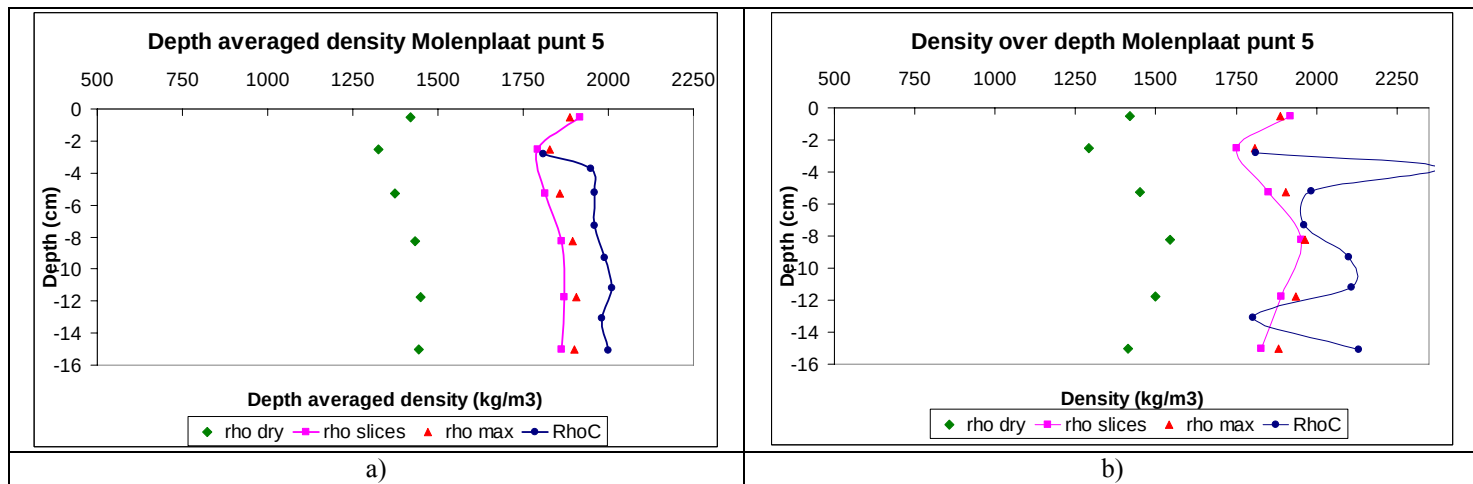


Figure 0.21: Density measurements of RhoC and lab slices, location punt 5: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

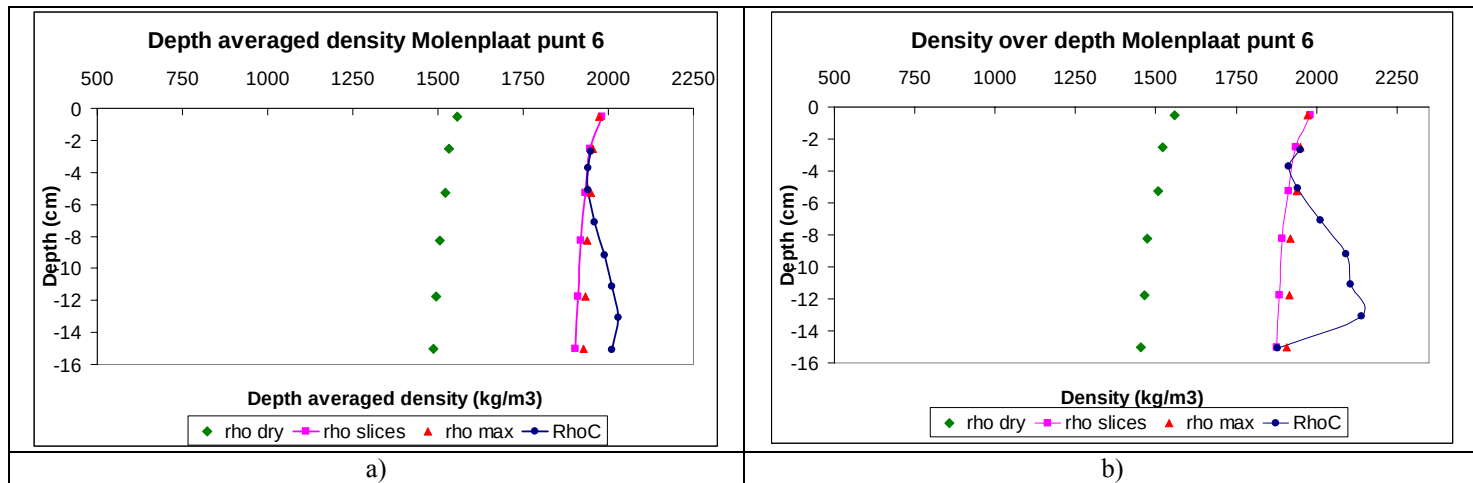


Figure 0.22: Density measurements of RhoC and lab slices, location punt 6: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

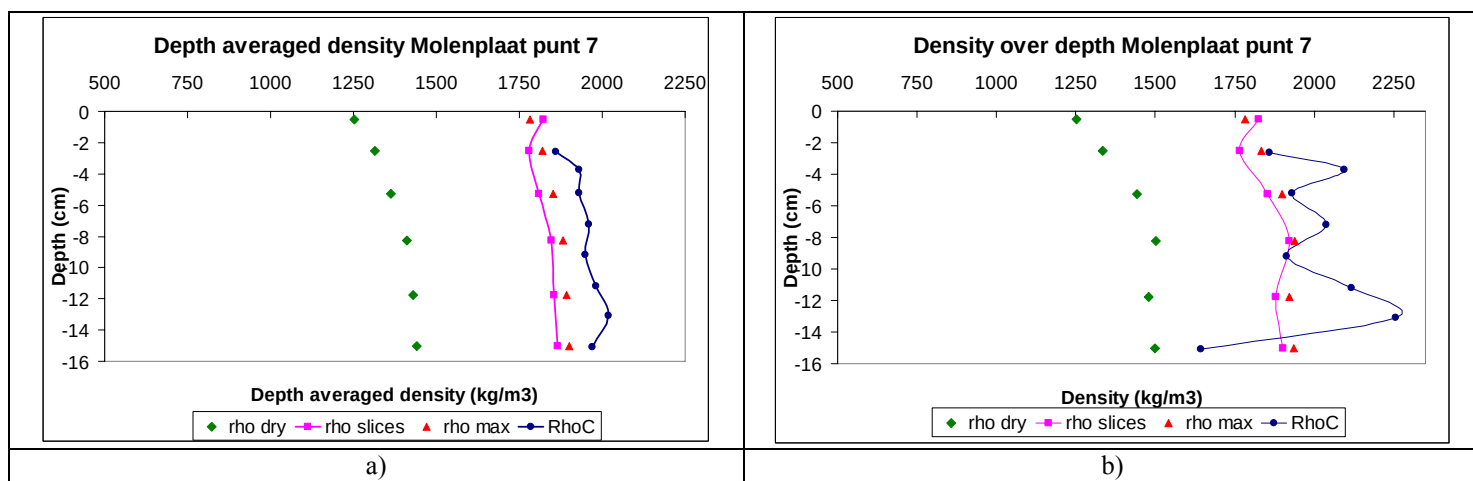


Figure 0.23: Density measurements of RhoC and lab slices, location punt 7: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

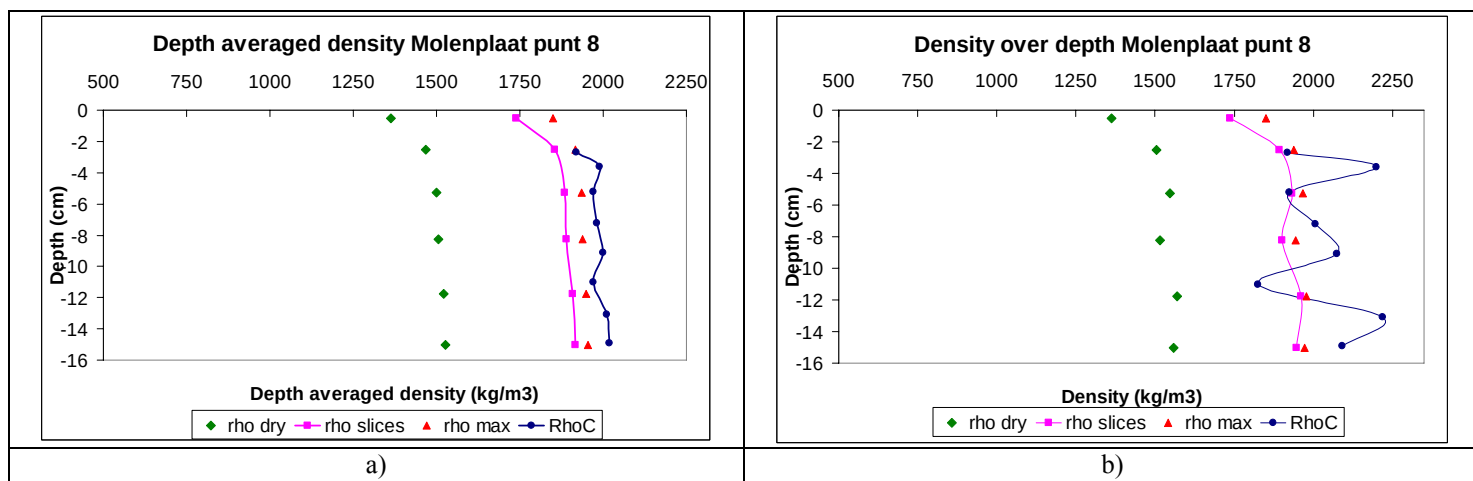


Figure 0.24: Density measurements of RhoC and lab slices, location punt 8: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

C.3 Walsoorden density measurements

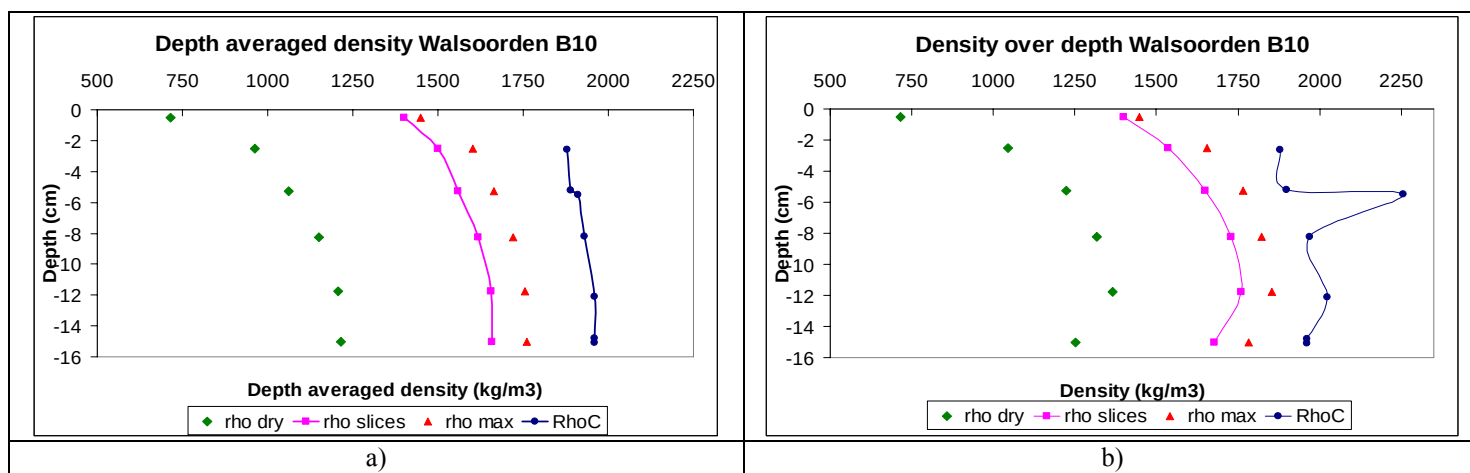


Figure 0.25: Density measurements of RhoC and lab slices, location B-10: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

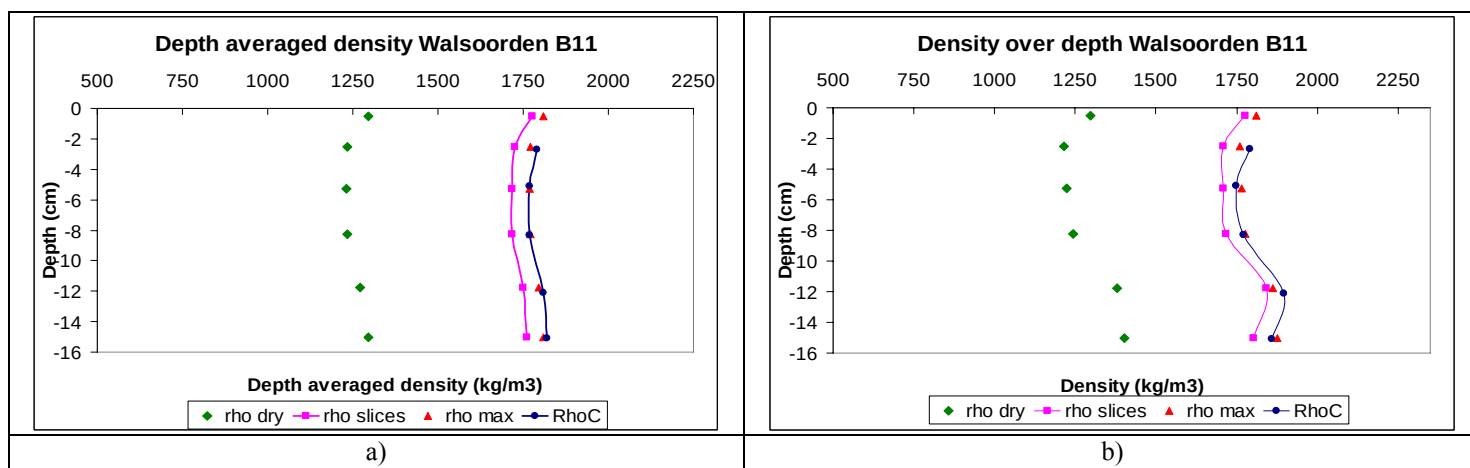
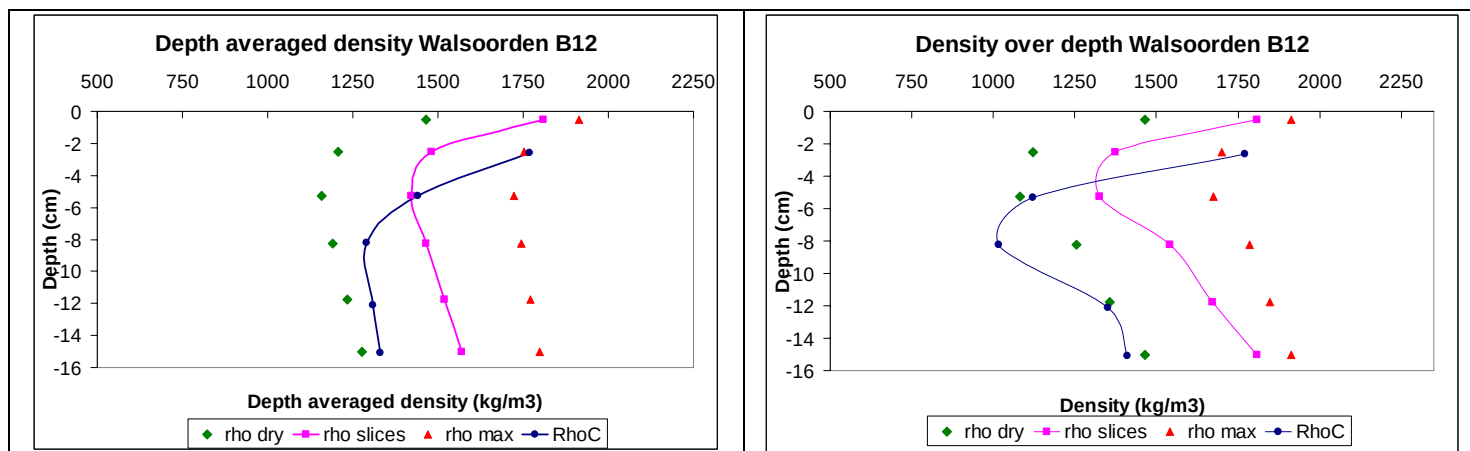


Figure 0.26: Density measurements of RhoC and lab slices, location B-11: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.



a)	b)
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Figure 0.27: Density measurements of RhoC and lab slices, location B-12: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

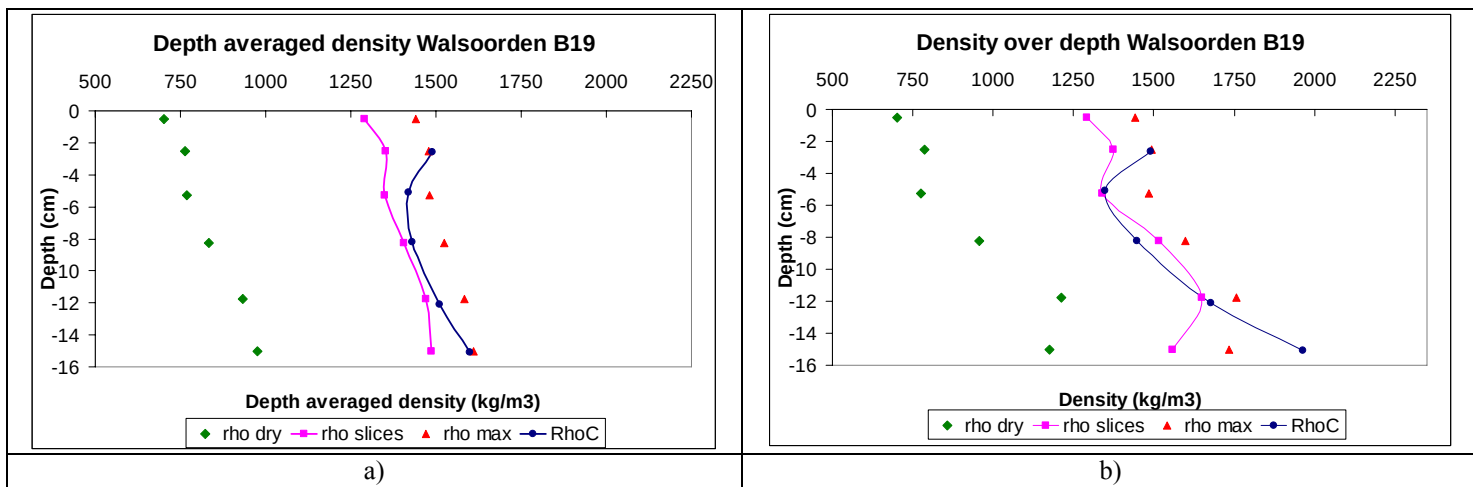


Figure 0.28: Density measurements of RhoC and lab slices, location B-19: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

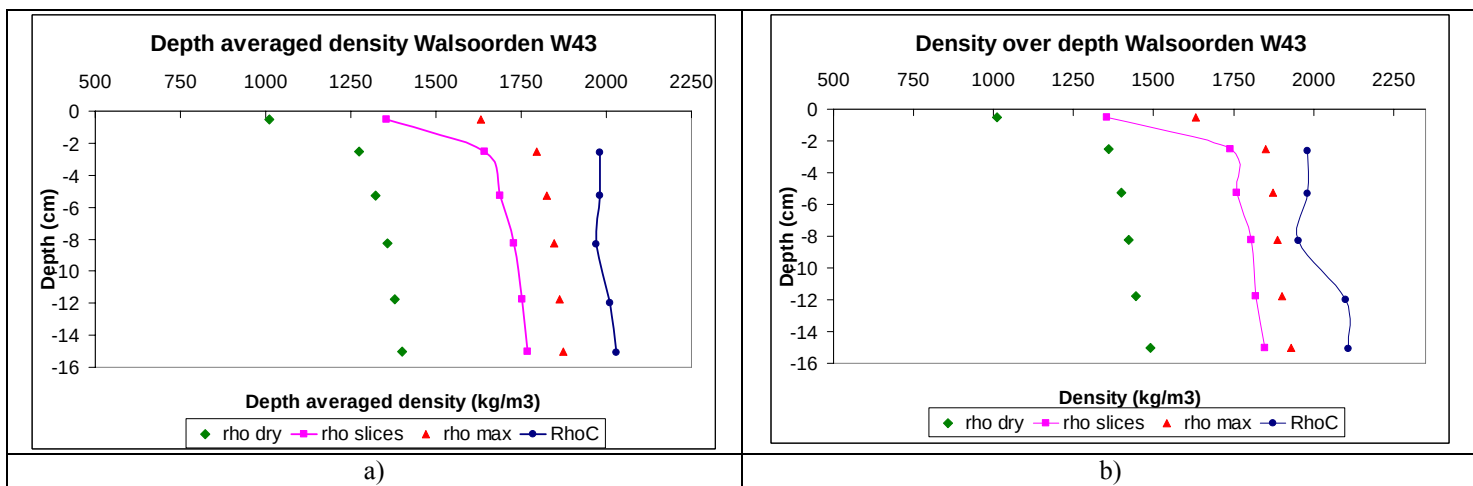
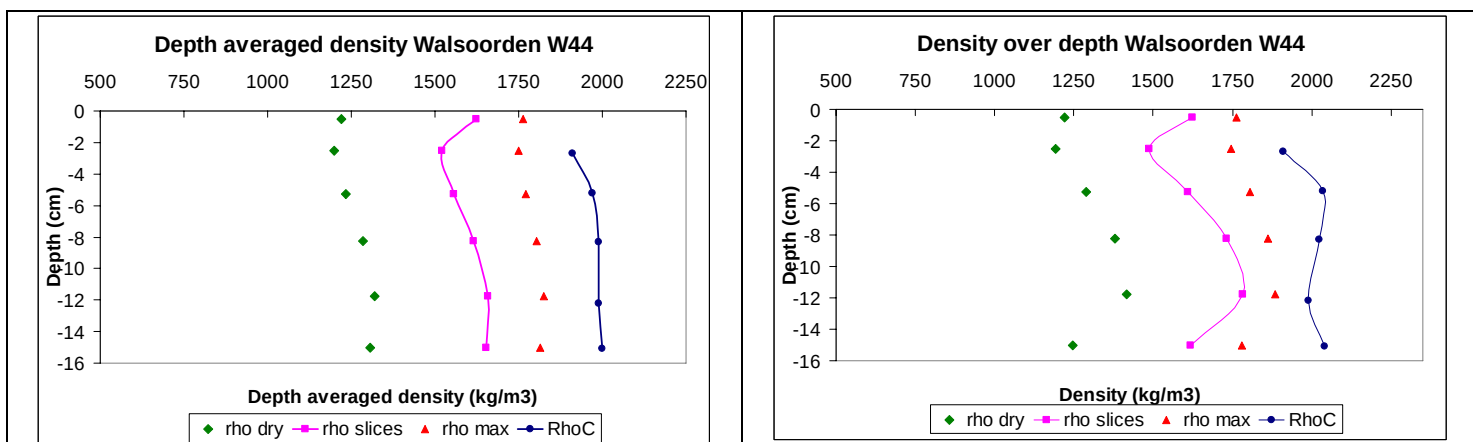


Figure 0.29: Density measurements of RhoC and lab slices, location W-43: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.



a)	b)
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Figure 0.30: Density measurements of RhoC and lab slices, location W-44: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

C.4 Valkenisse density measurements

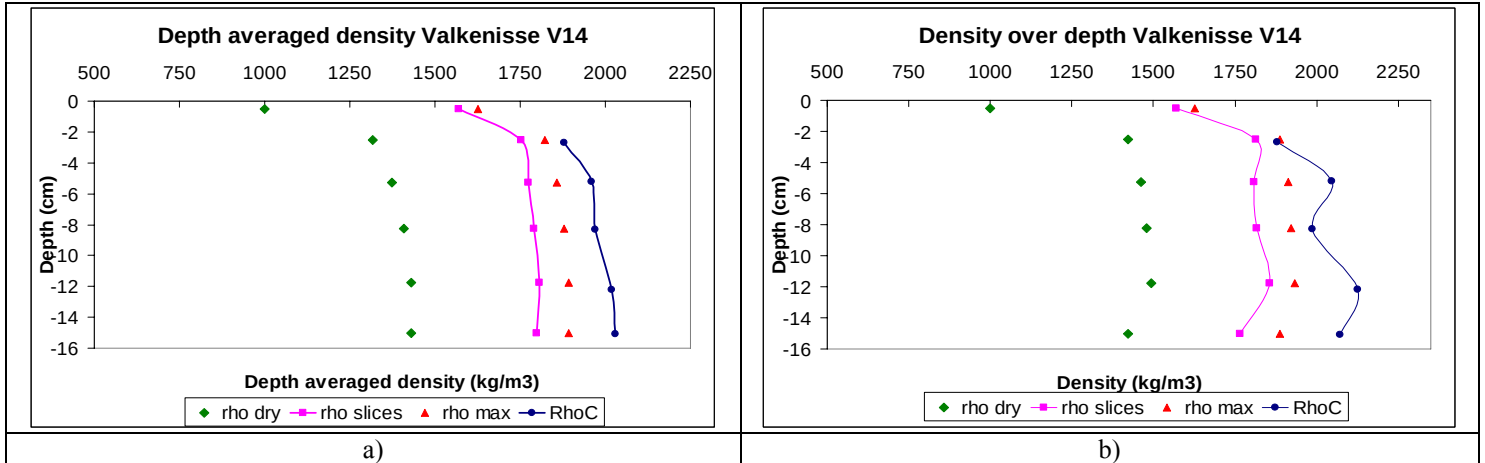


Figure 0.31: Density measurements of RhoC and lab slices, location V-14: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

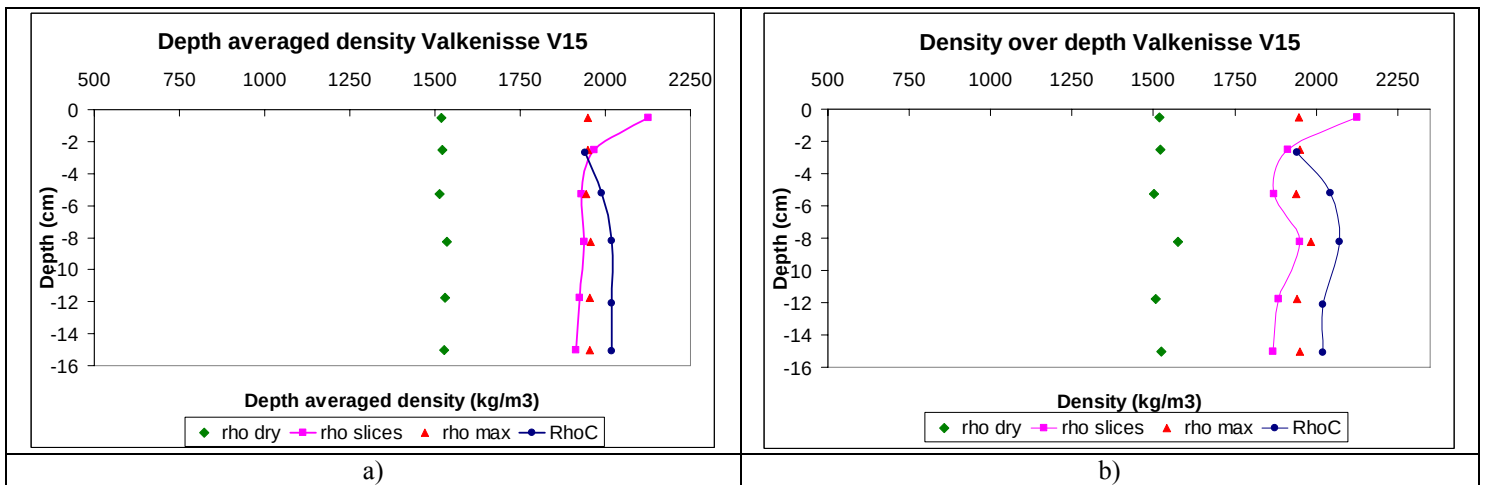


Figure 0.32: Density measurements of RhoC and lab slices, location V-15: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

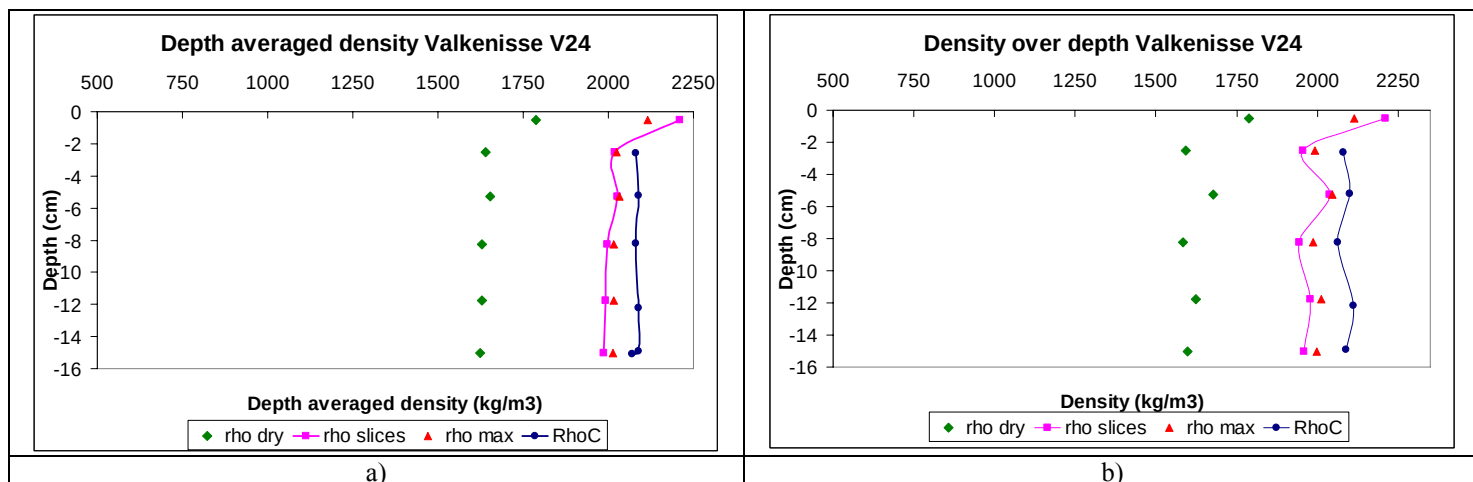


Figure 0.33: Density measurements of RhoC and lab slices, location V-24: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

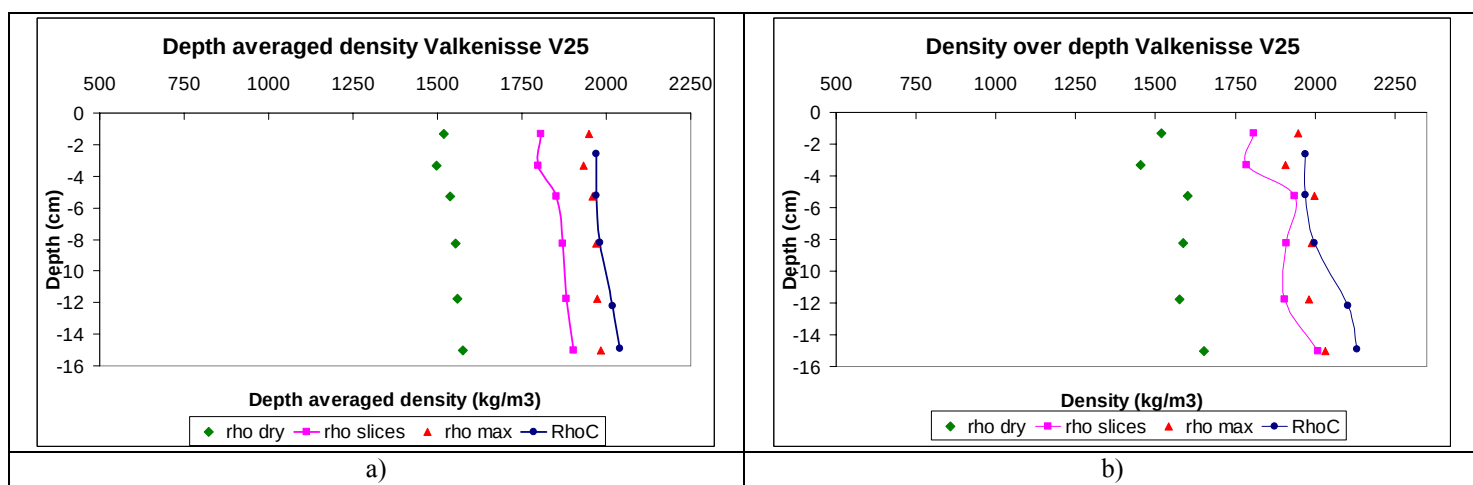


Figure 0.34: Density measurements of RhoC and lab slices, location V-25: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

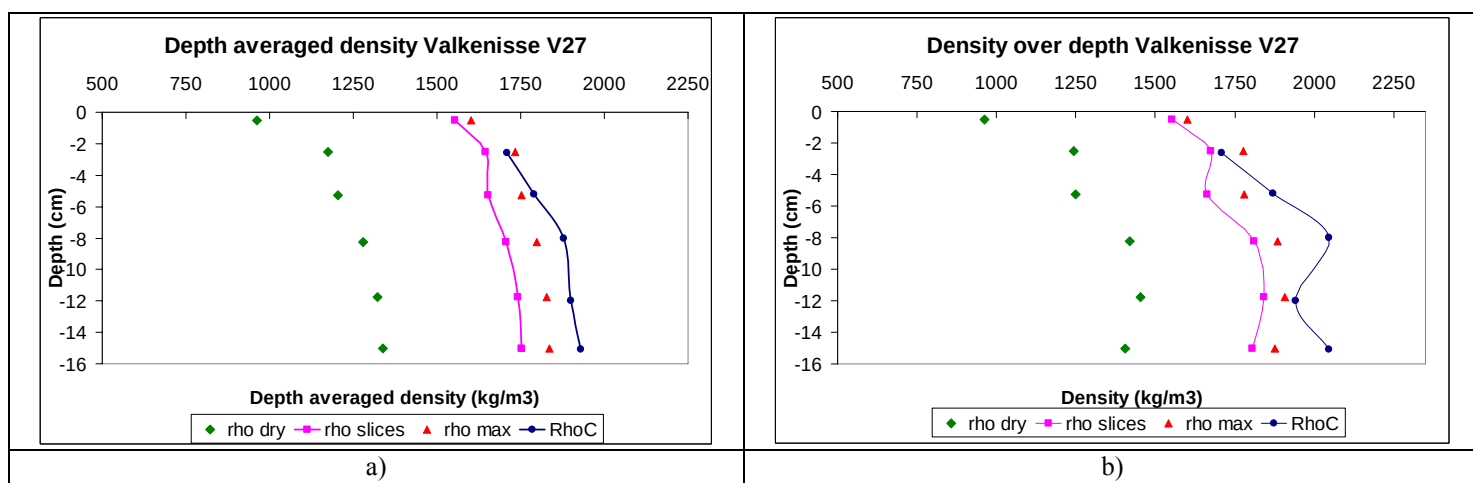


Figure 0.35: Density measurements of RhoC and lab slices, location V-27: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

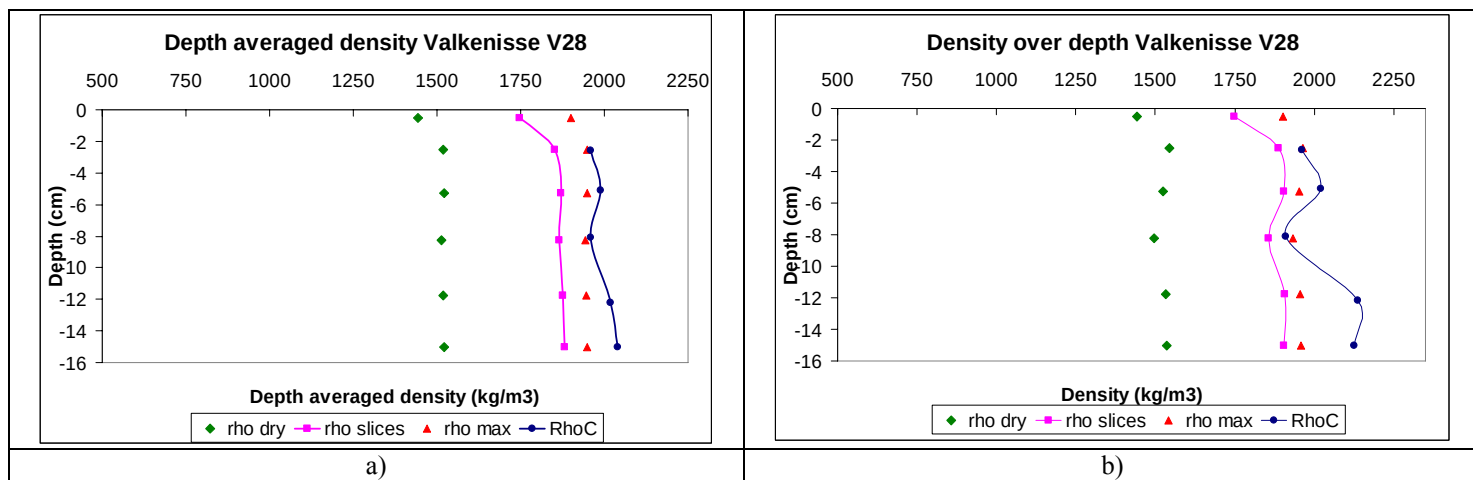


Figure 0.36: Density measurements of RhoC and lab slices, location V-28: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

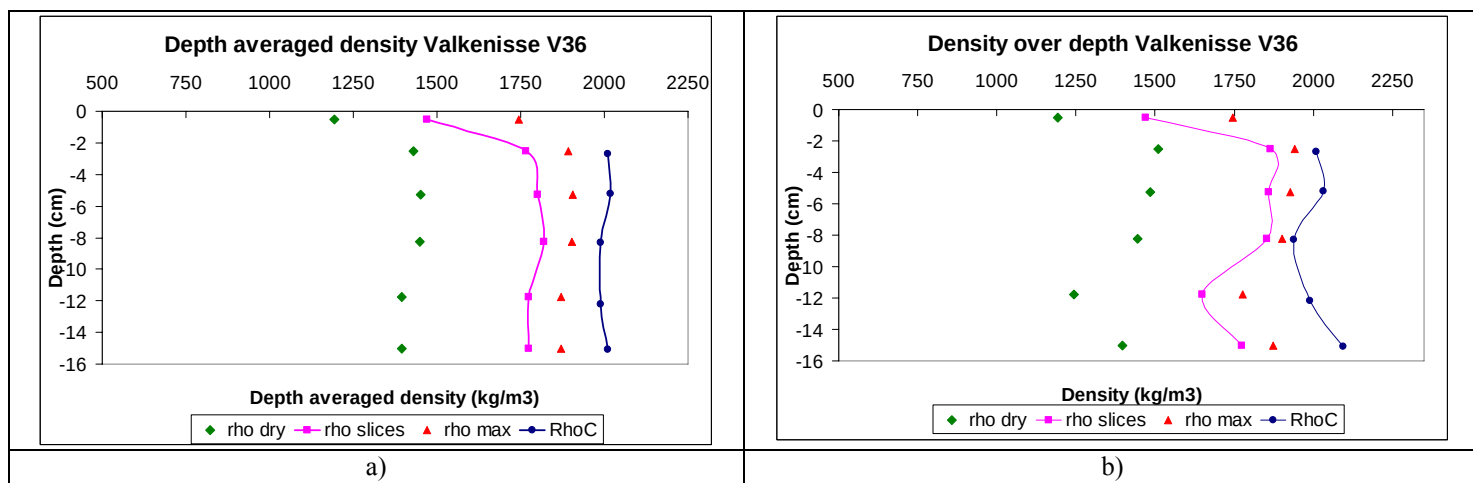


Figure 0.37: Density measurements of RhoC and lab slices, location V-36: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is without correction.

Appendix D Data field locations

D.1 Data Saeftinghe

D.1.1 General overview

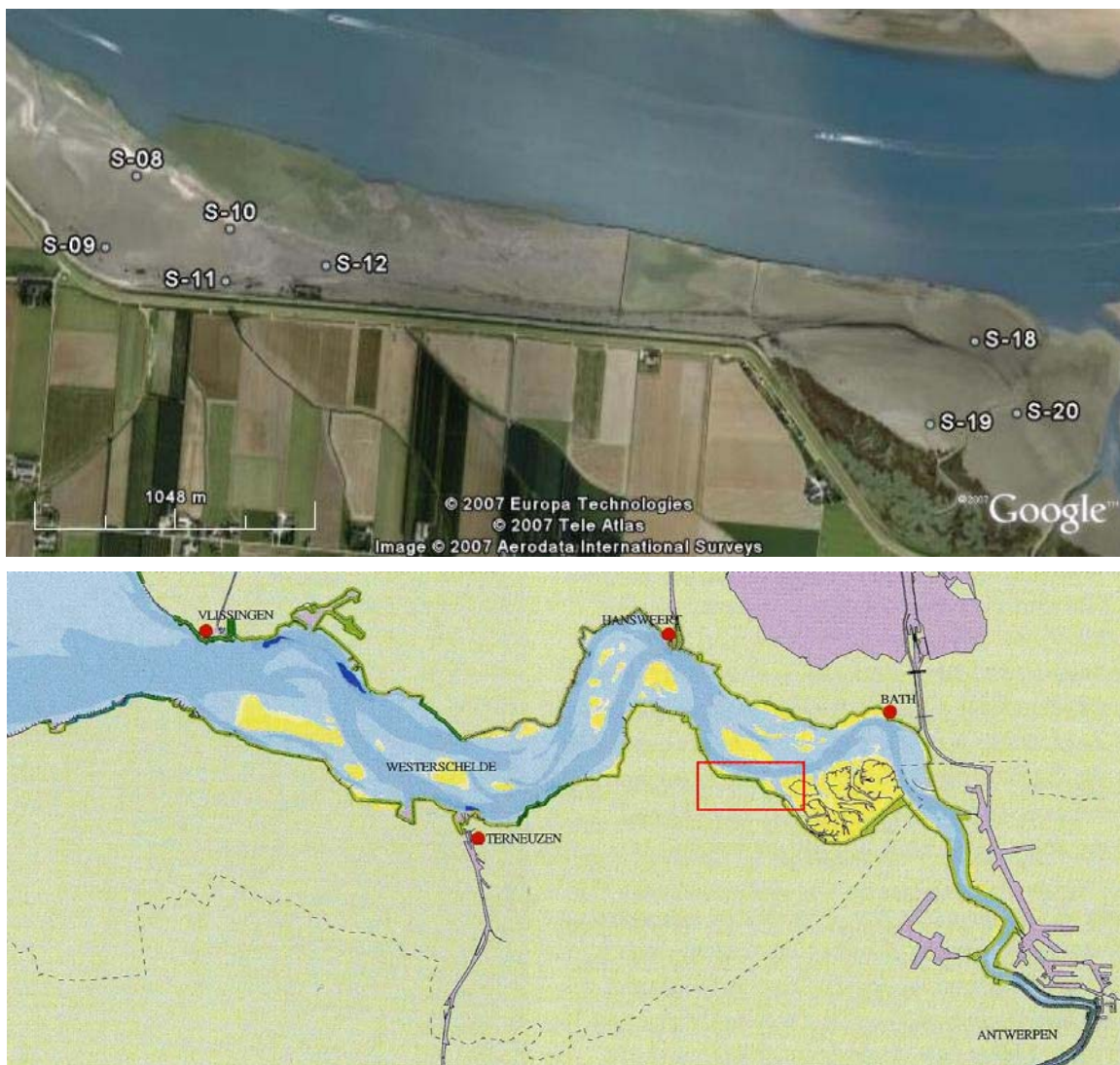


Figure 0.38: Map of Western Scheldt with sample locations at Saeftinghe.

D.1.2 Radiometric measurements

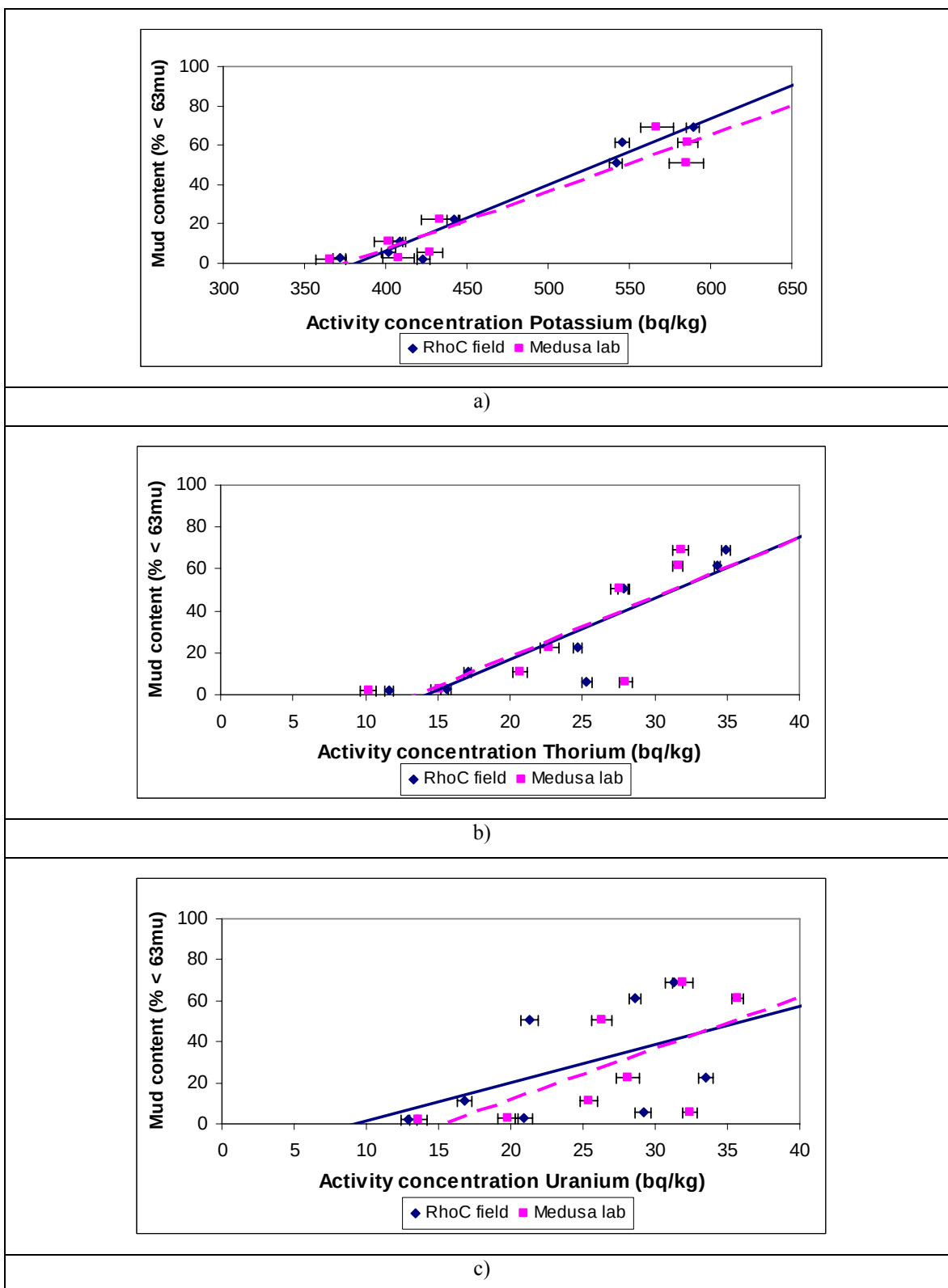


Figure 0.39: Radiometric measurements and mud content. Lines indicate linear best fit. a) Potassium activity concentrations. b) Thorium activity concentrations. c) Uranium activity concentrations.

D.1.3 Density measurements of RhoC and lab analysis

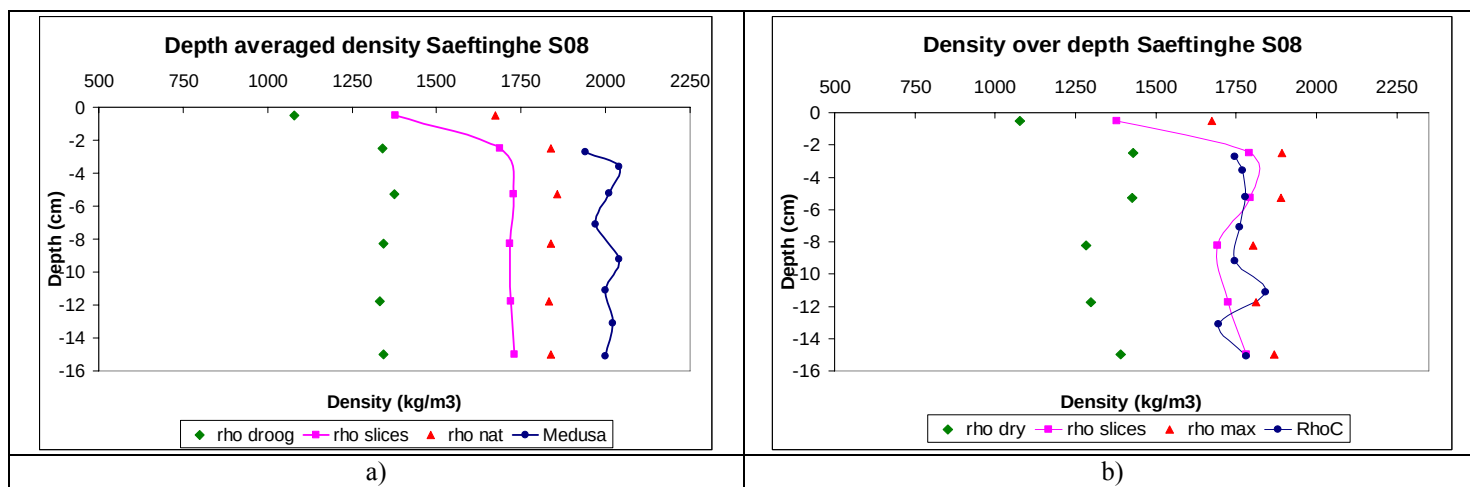


Figure 0.40: Density measurements of RhoC and lab slices, location S-08: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

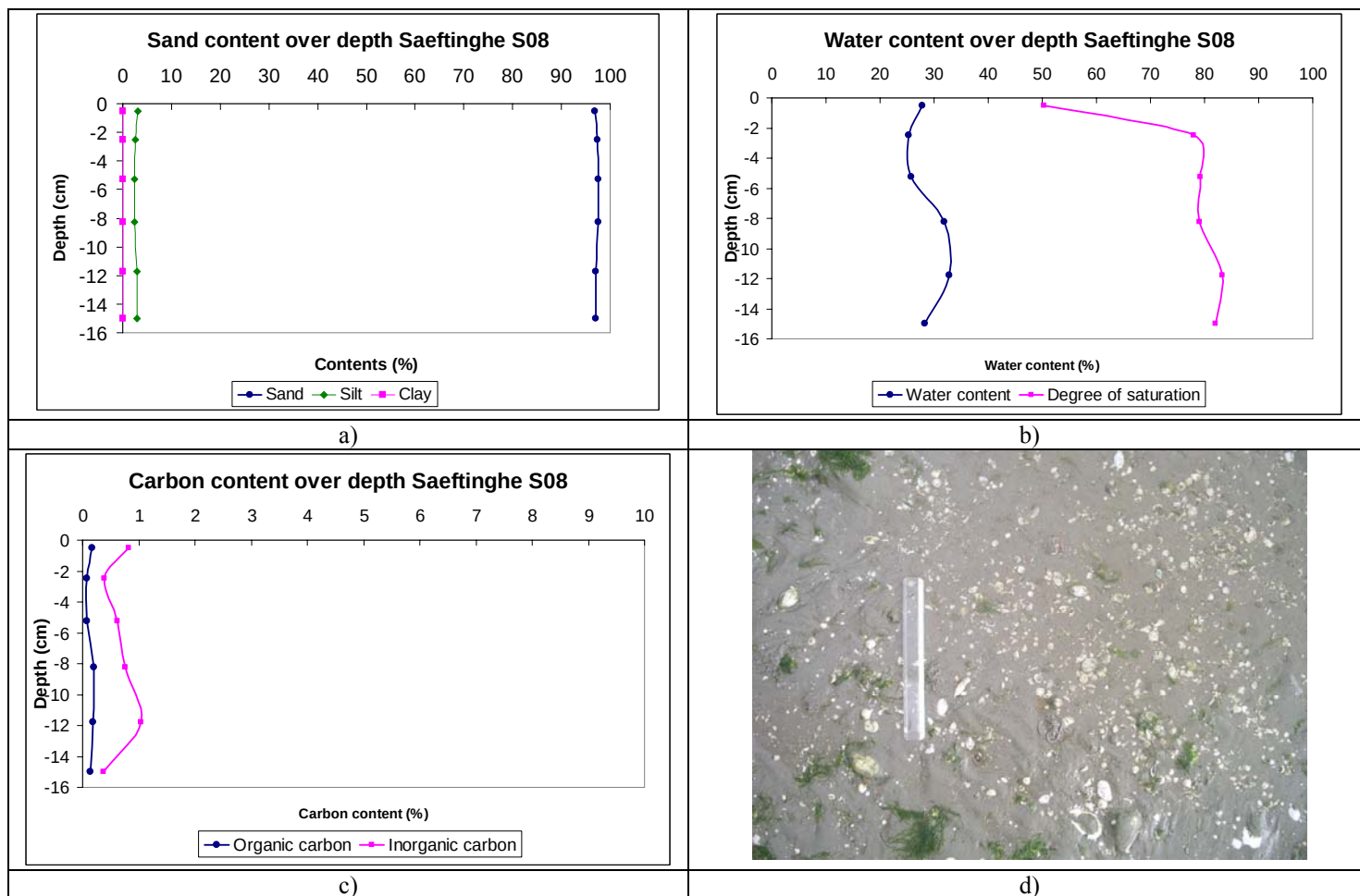


Figure 0.41: Results of lab analysis, location S-08: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

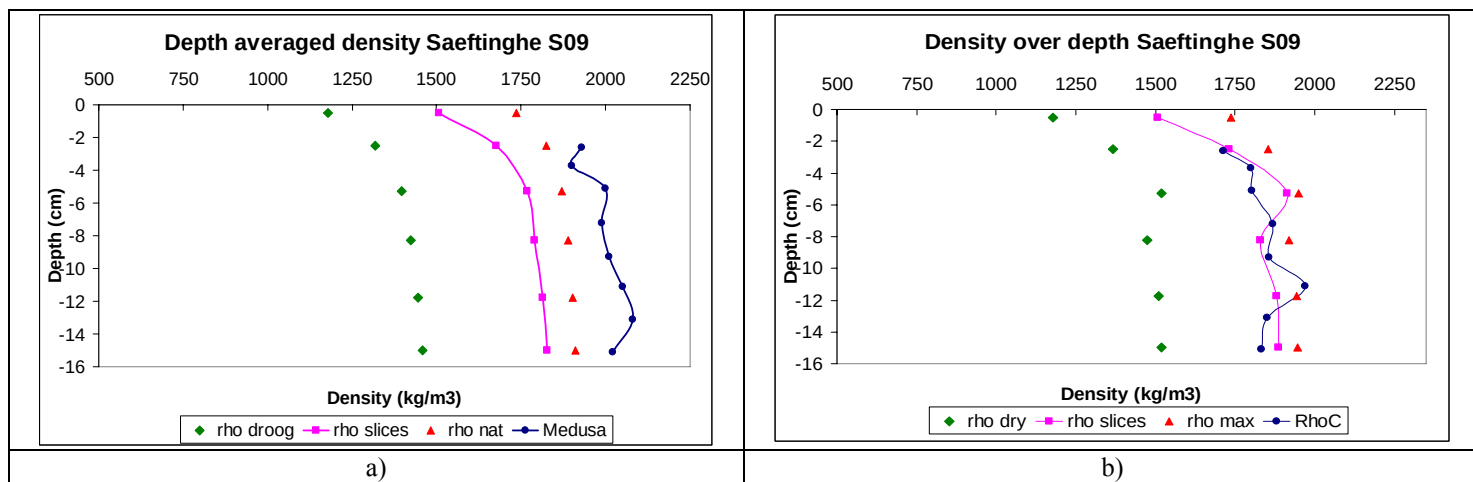


Figure 0.42: Density measurements of RhoC and lab slices, location S-09: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

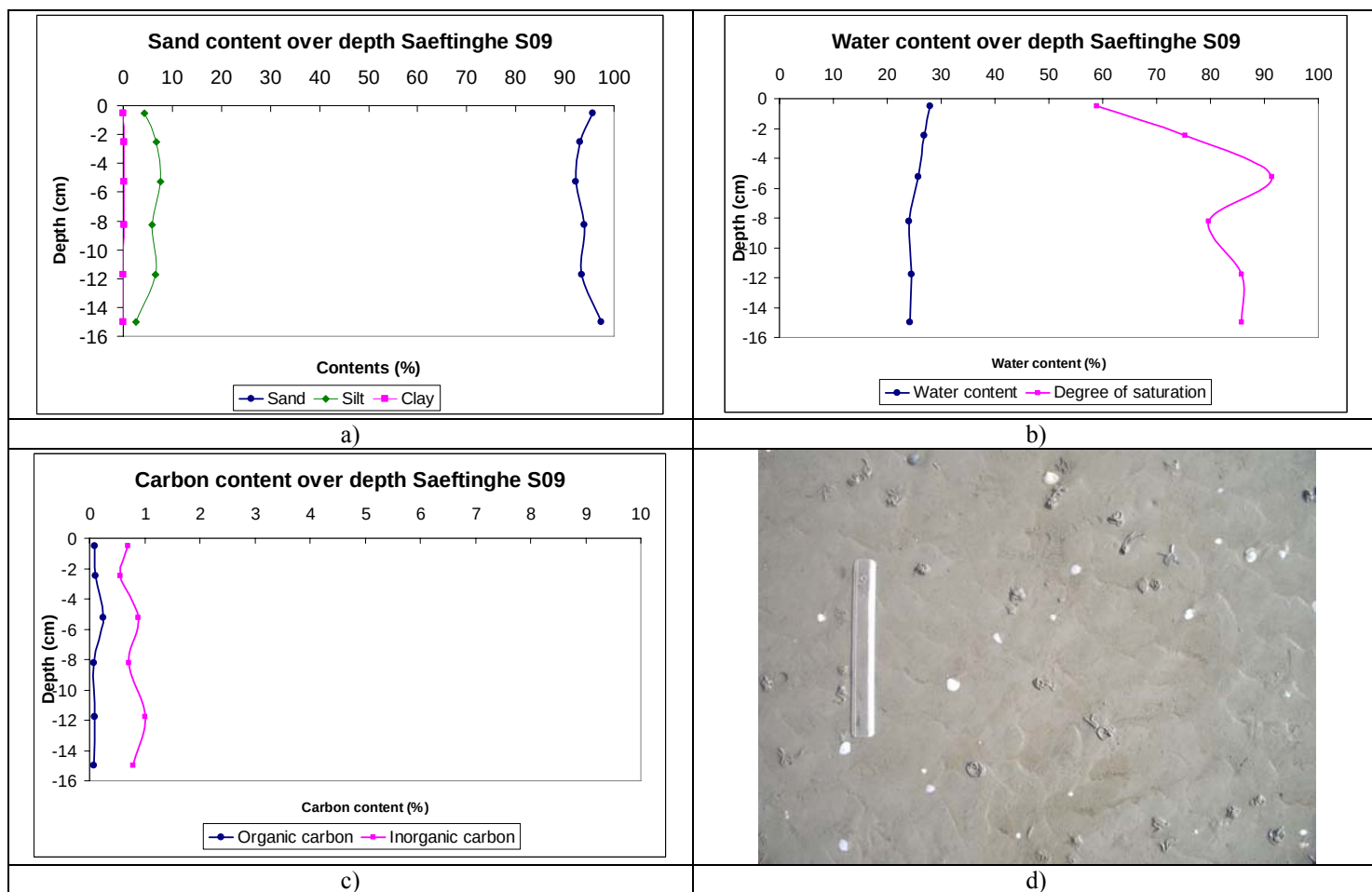


Figure 0.43: Results of lab analysis, location S-09: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

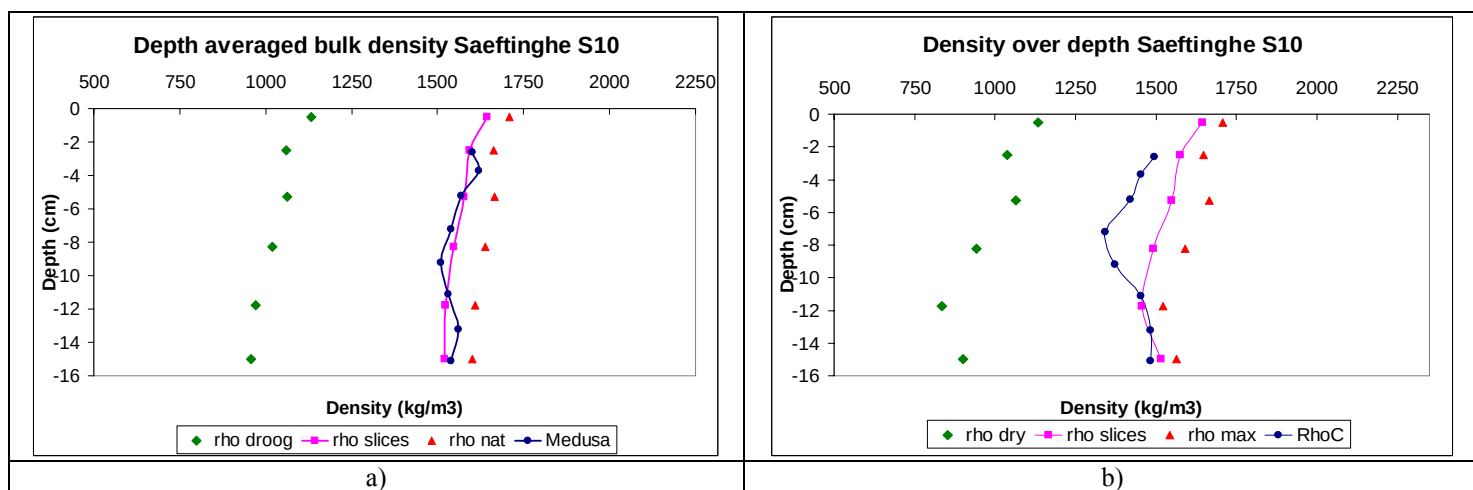


Figure 0.44: Density measurements of RhoC and lab slices, location S-10: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

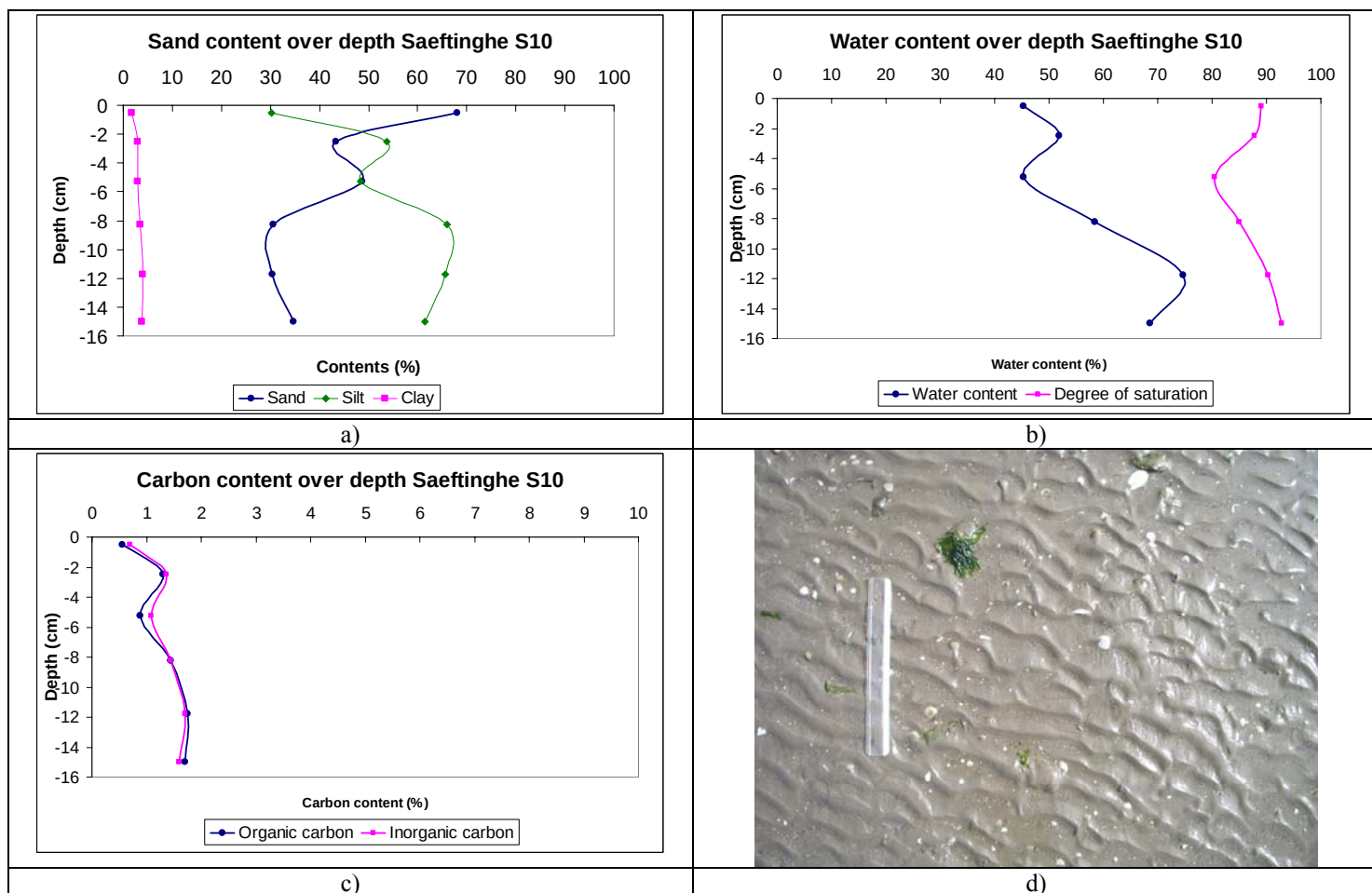


Figure 0.45: Results of lab analysis, location S-10: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

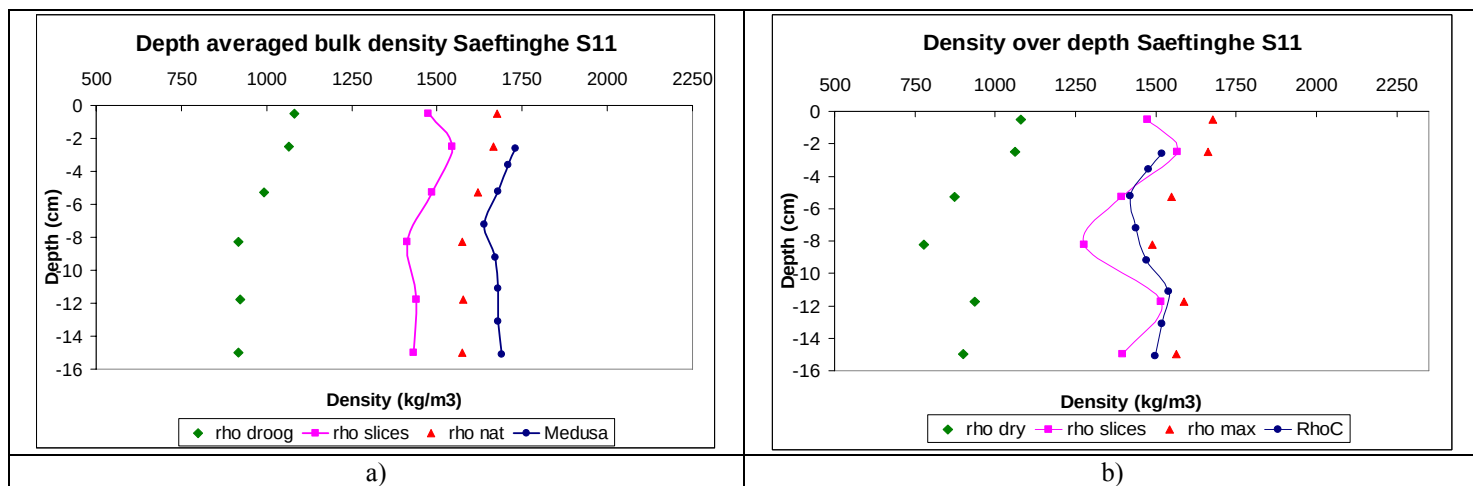


Figure 0.46: Density measurements of RhoC and lab slices, location S-11: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

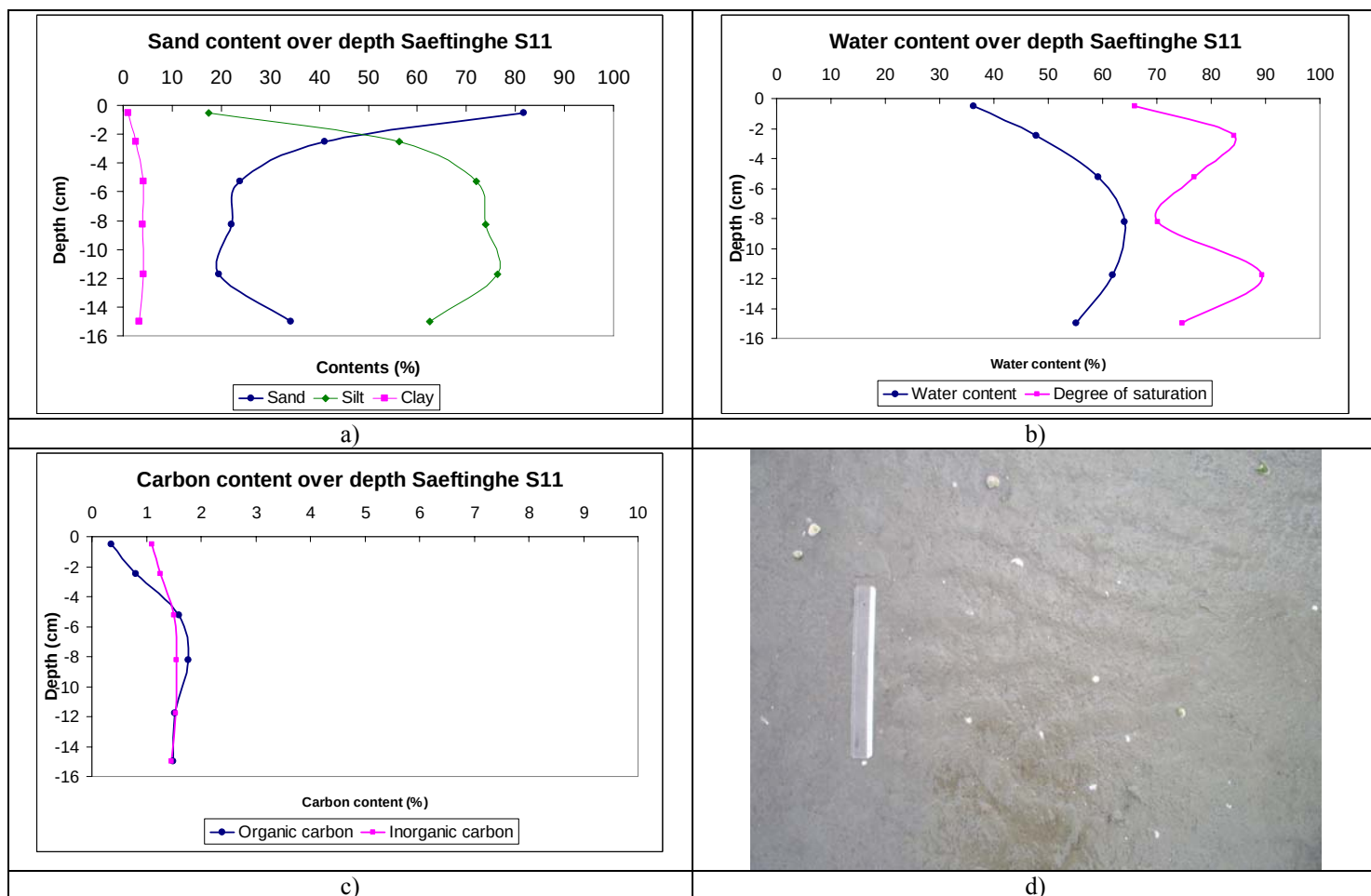


Figure 0.47: Results of lab analysis, location S-11: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

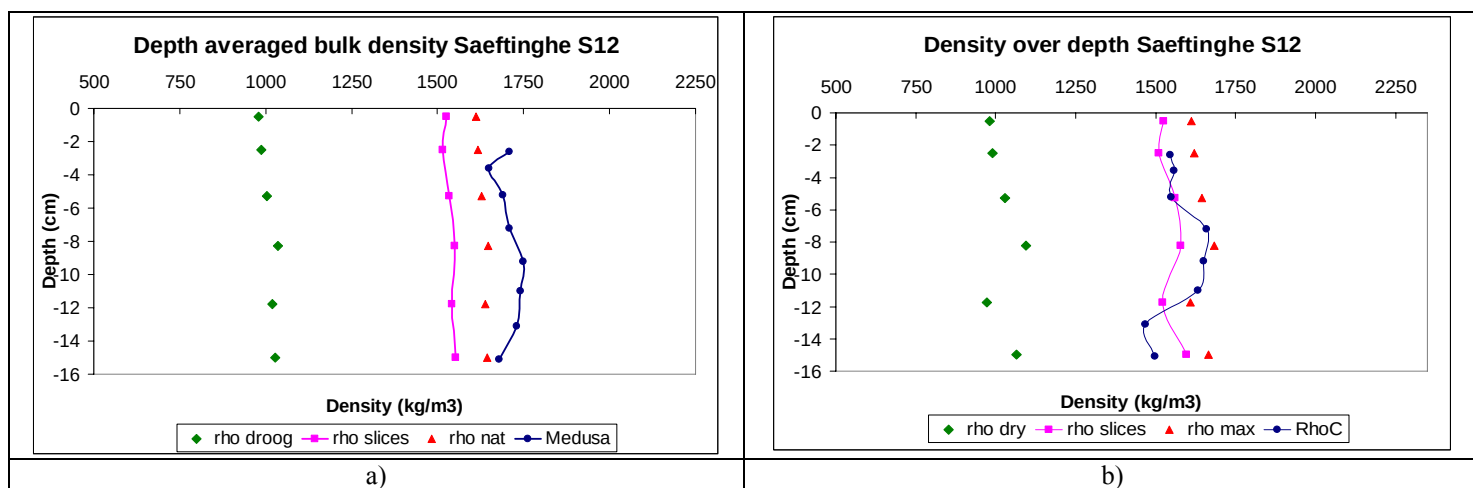


Figure 0.48: Density measurements of RhoC and lab slices, location S-12: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

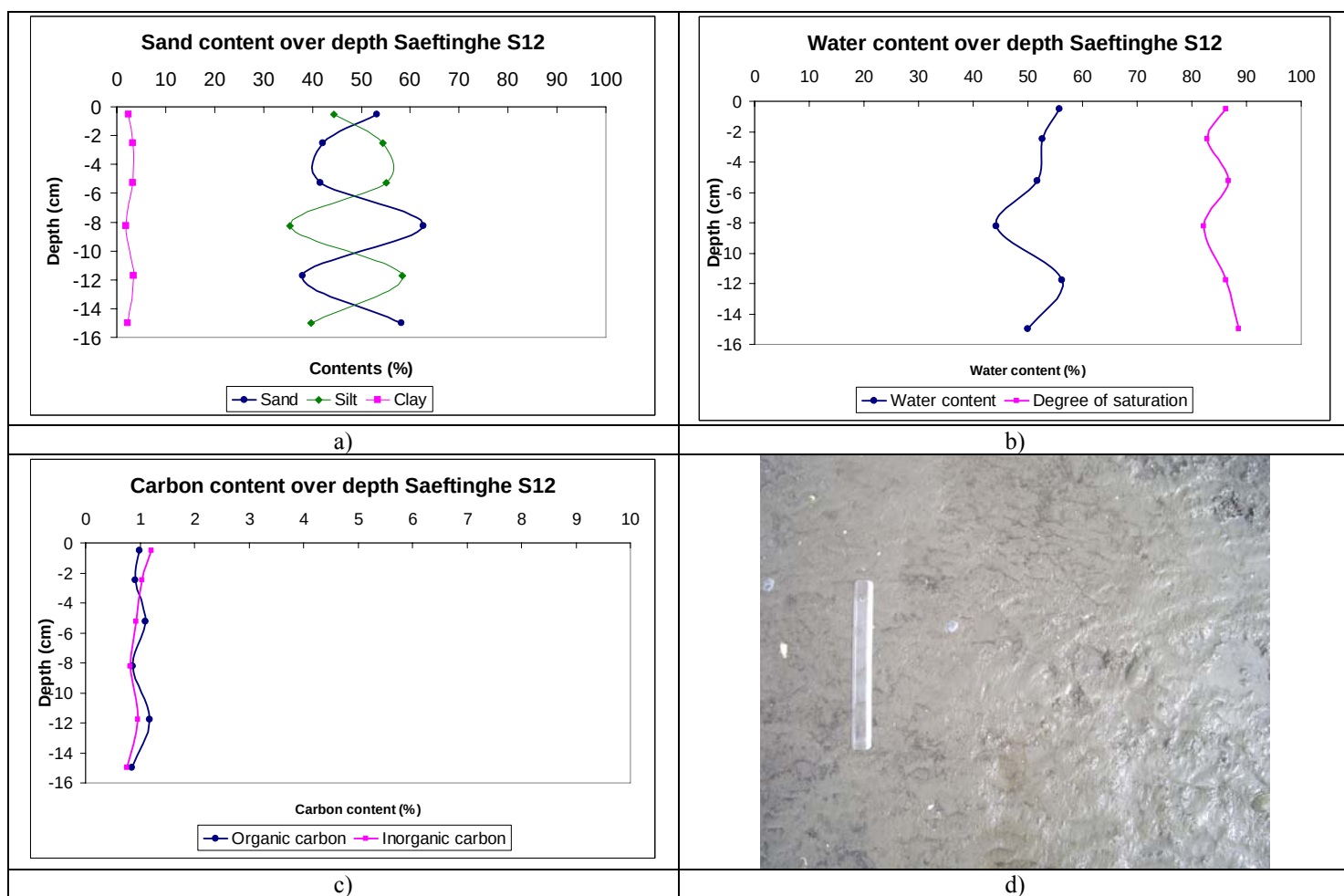


Figure 0.49: Results of lab analysis, location S-12: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

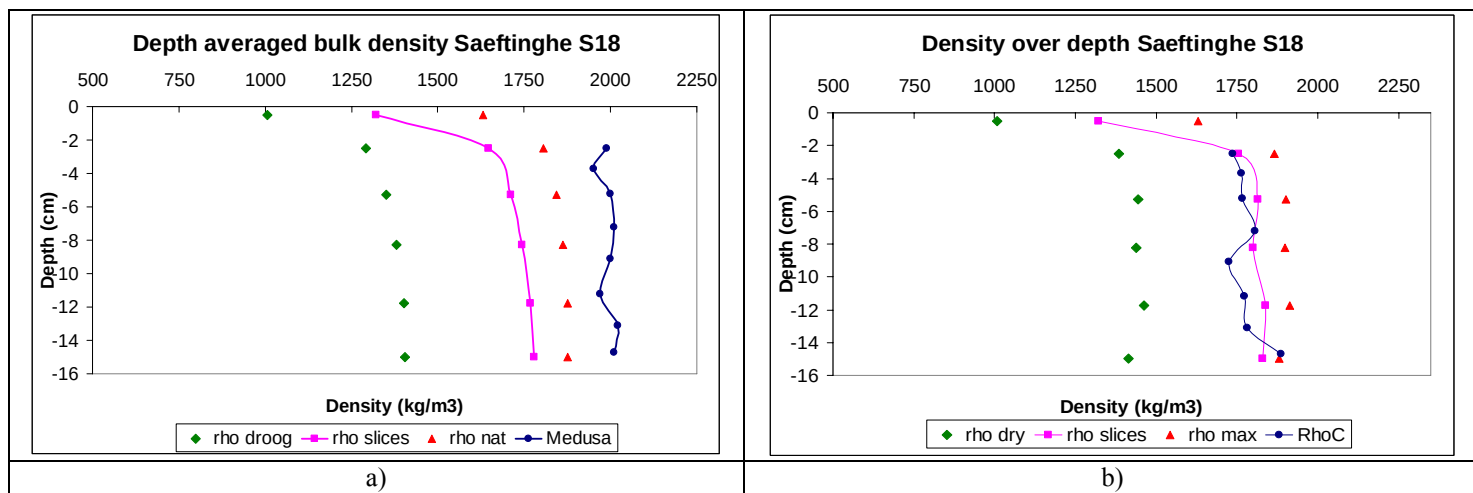


Figure 0.50: Density measurements of RhoC and lab slices, location S-18: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

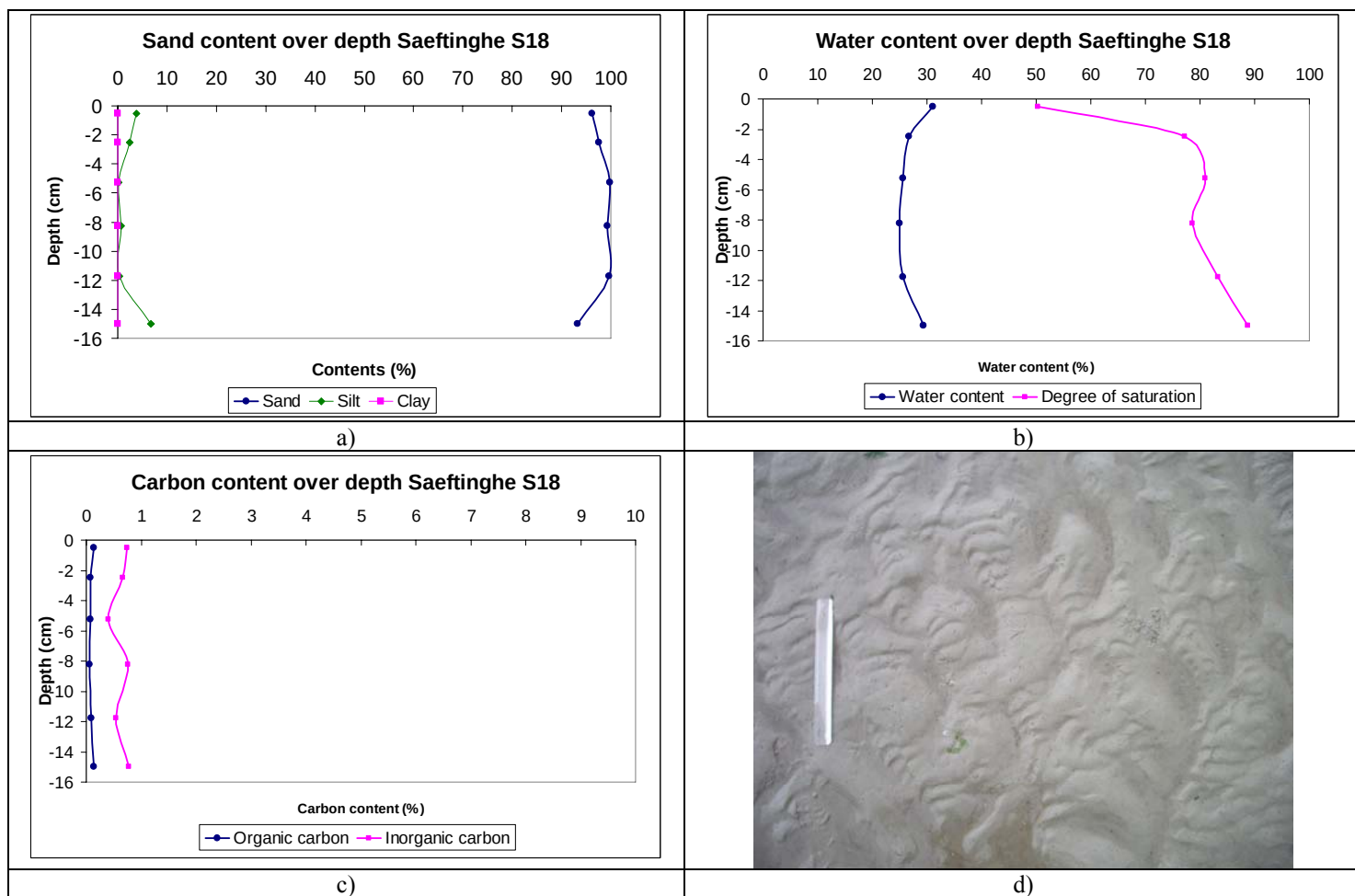


Figure 0.51: Results of lab analysis, location S-18: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

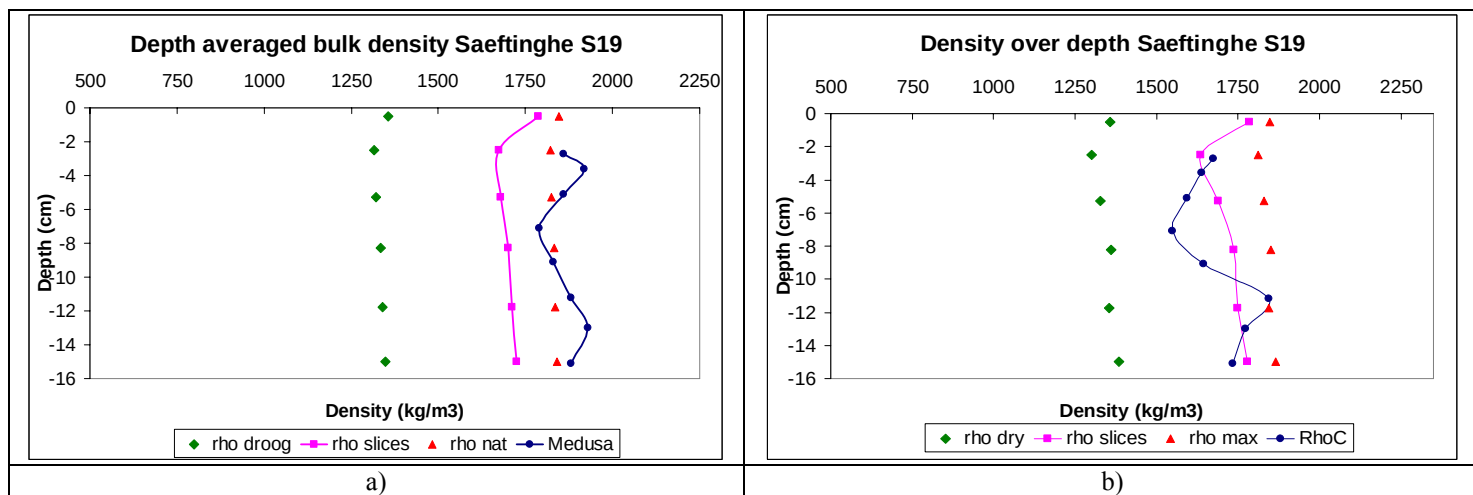


Figure 0.52: Density measurements of RhoC and lab slices, location S-19: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

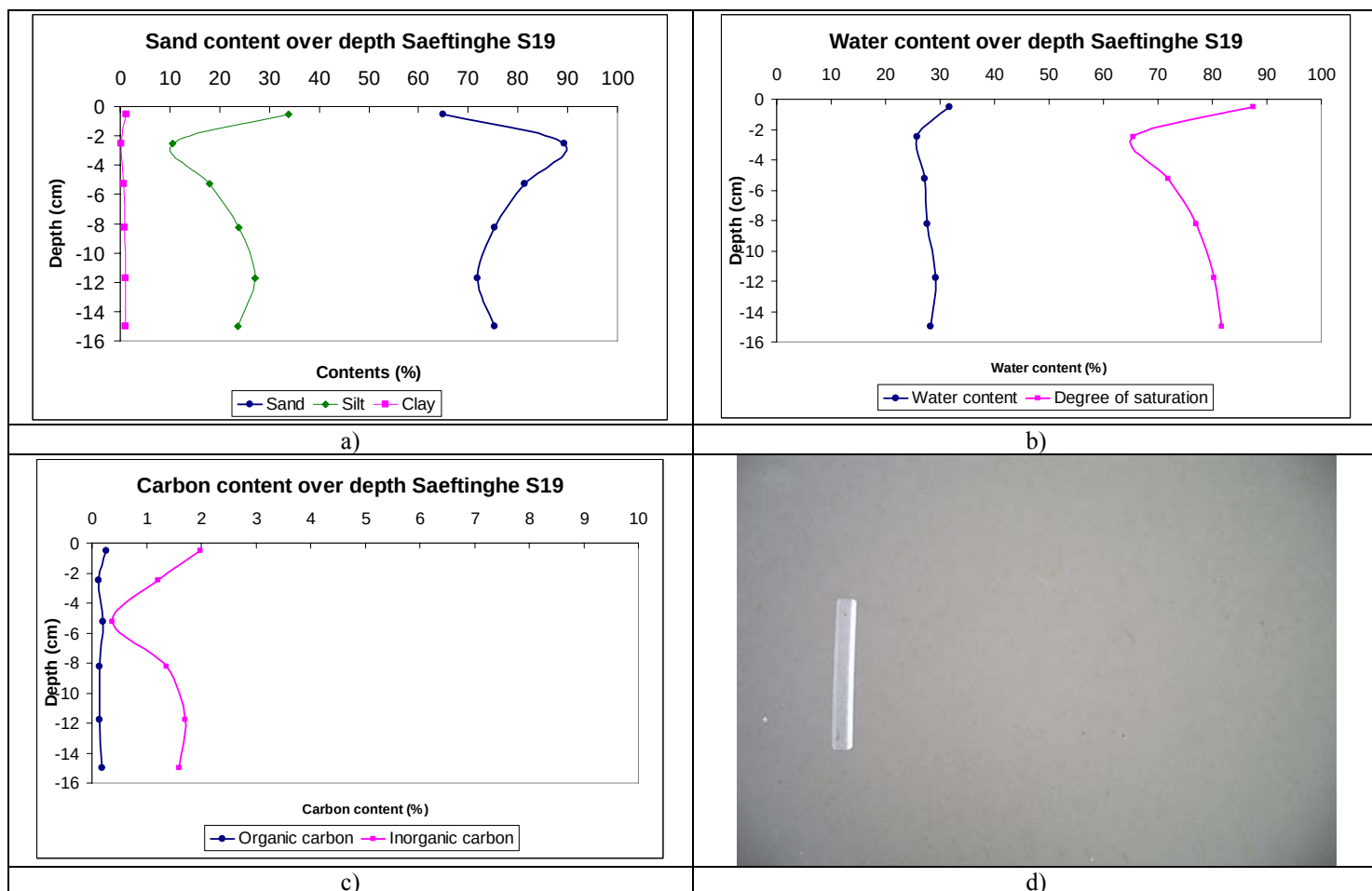


Figure 0.53: Results of lab analysis, location S-19: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

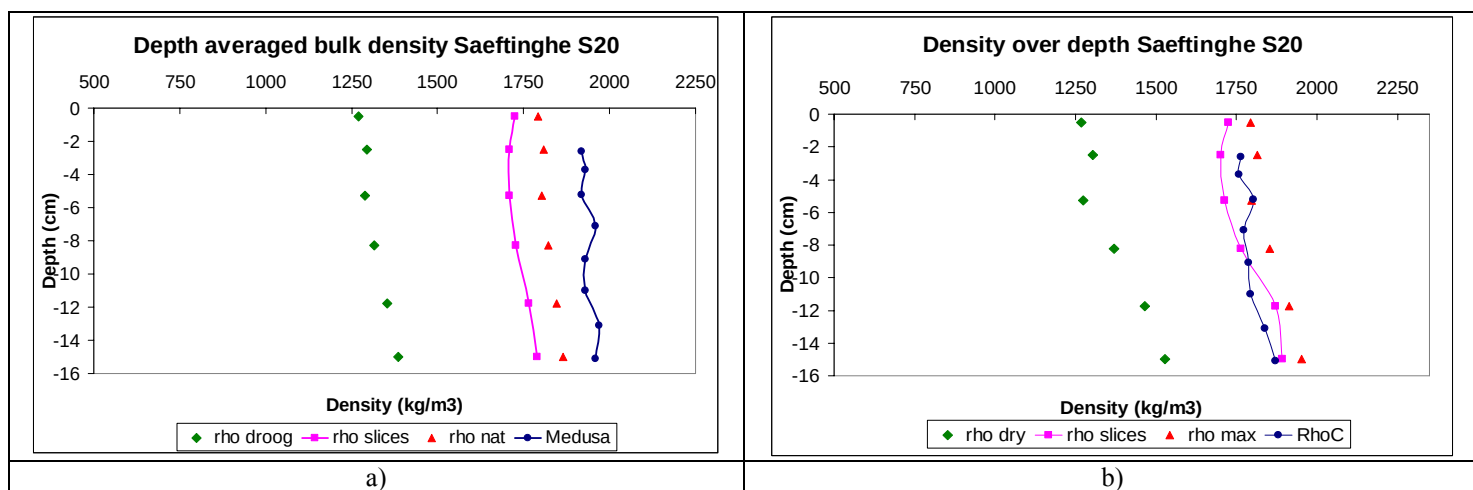


Figure 0.54: Density measurements of RhoC and lab slices, location S-20: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

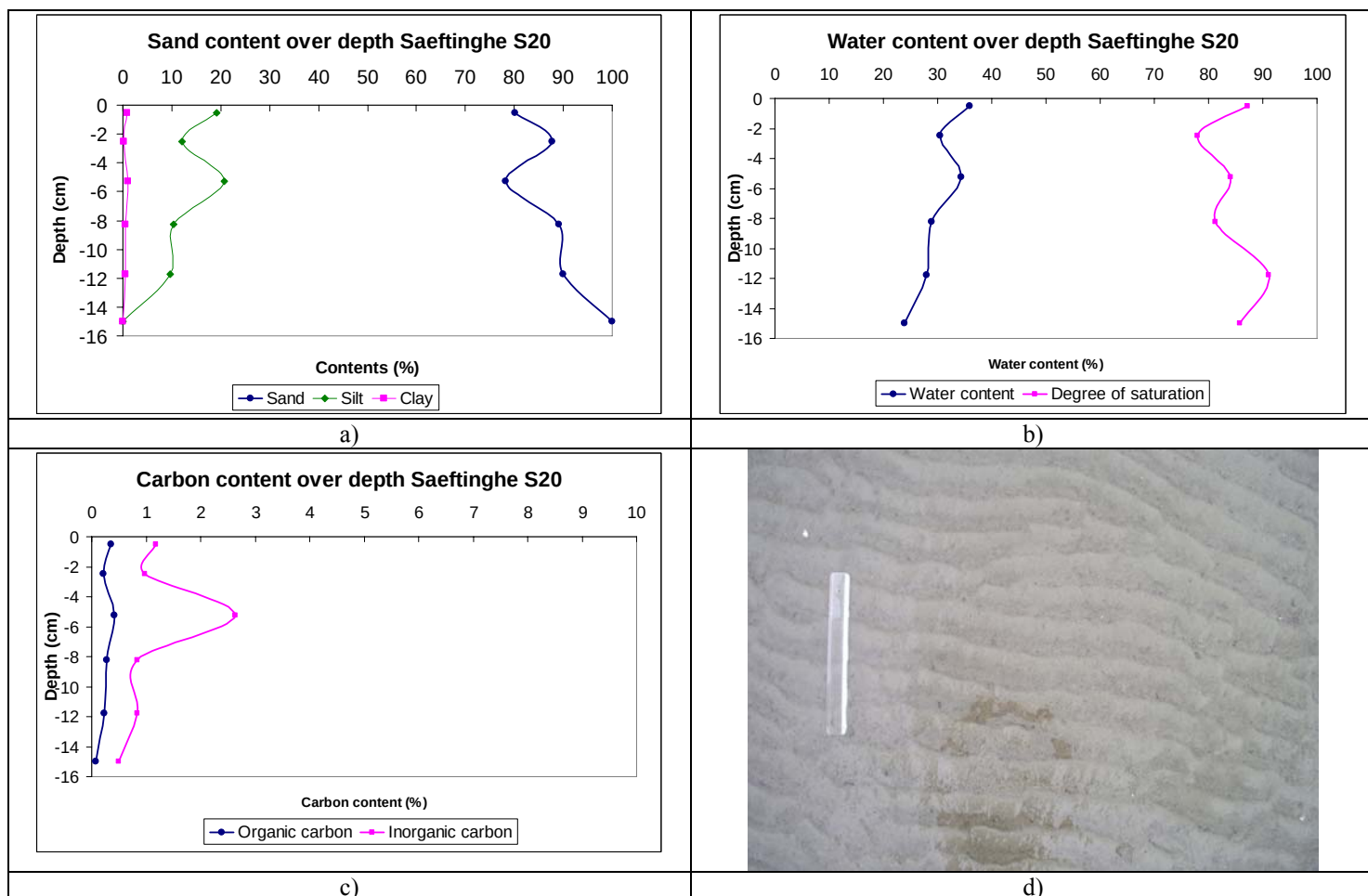


Figure 0.55: Results of lab analysis, location S-20: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

D.2 Data Molenplaat

D.2.1 General overview

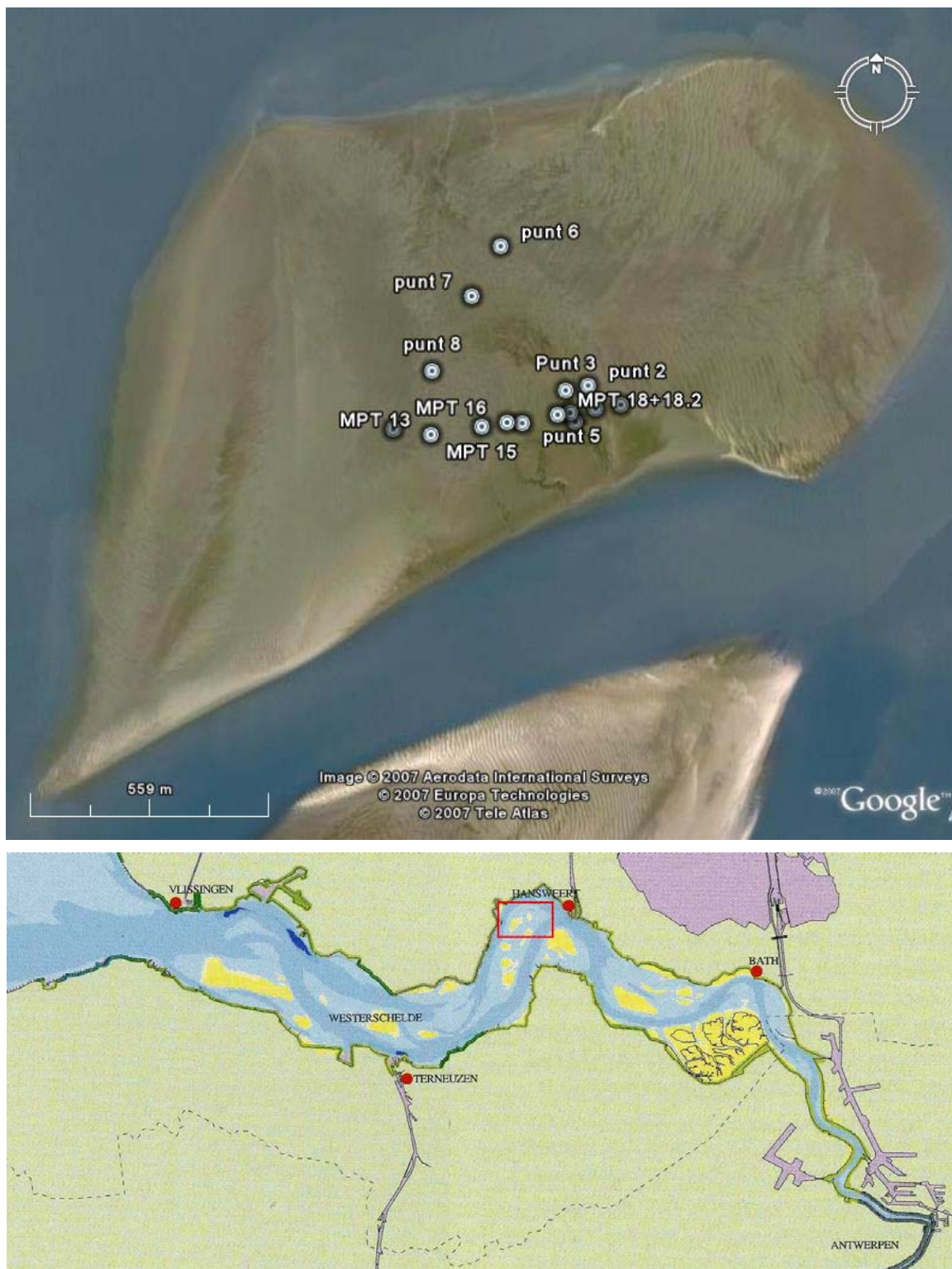


Figure 0.56: Map of Western Scheldt with sample location on Molenplaat.

D.2.2 Radiometric measurements

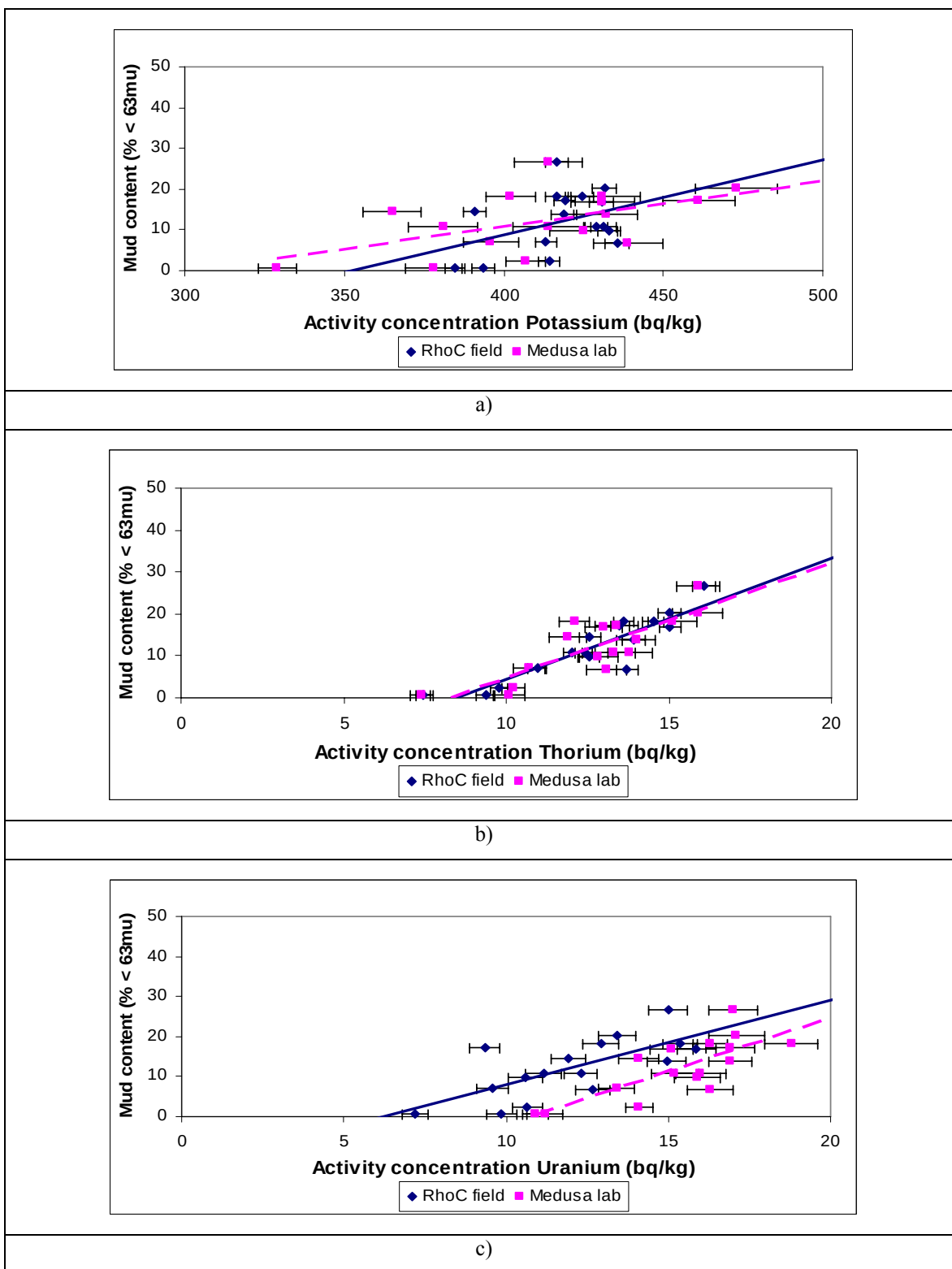


Figure 0.57: Radiometric measurements and mud content. Lines indicate linear best fit. a) Potassium activity concentrations. b) Thorium activity concentrations. c) Uranium activity concentrations.

D.2.3 Density measurements of RhoC and lab analysis

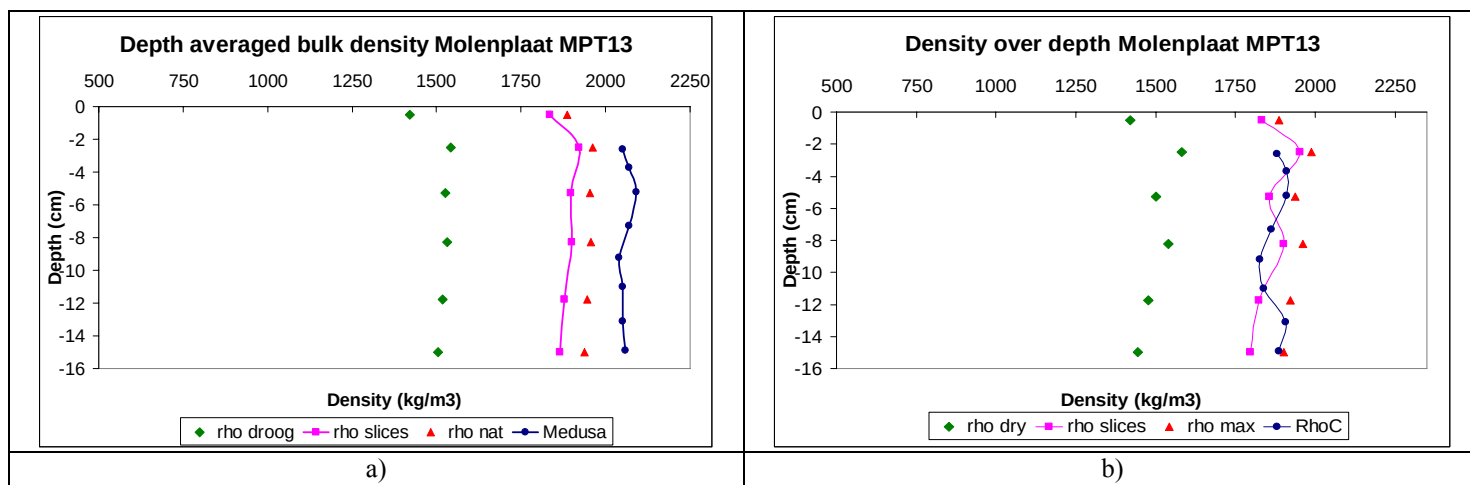


Figure 0.58: Density measurements of RhoC and lab slices, location MPT-13: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

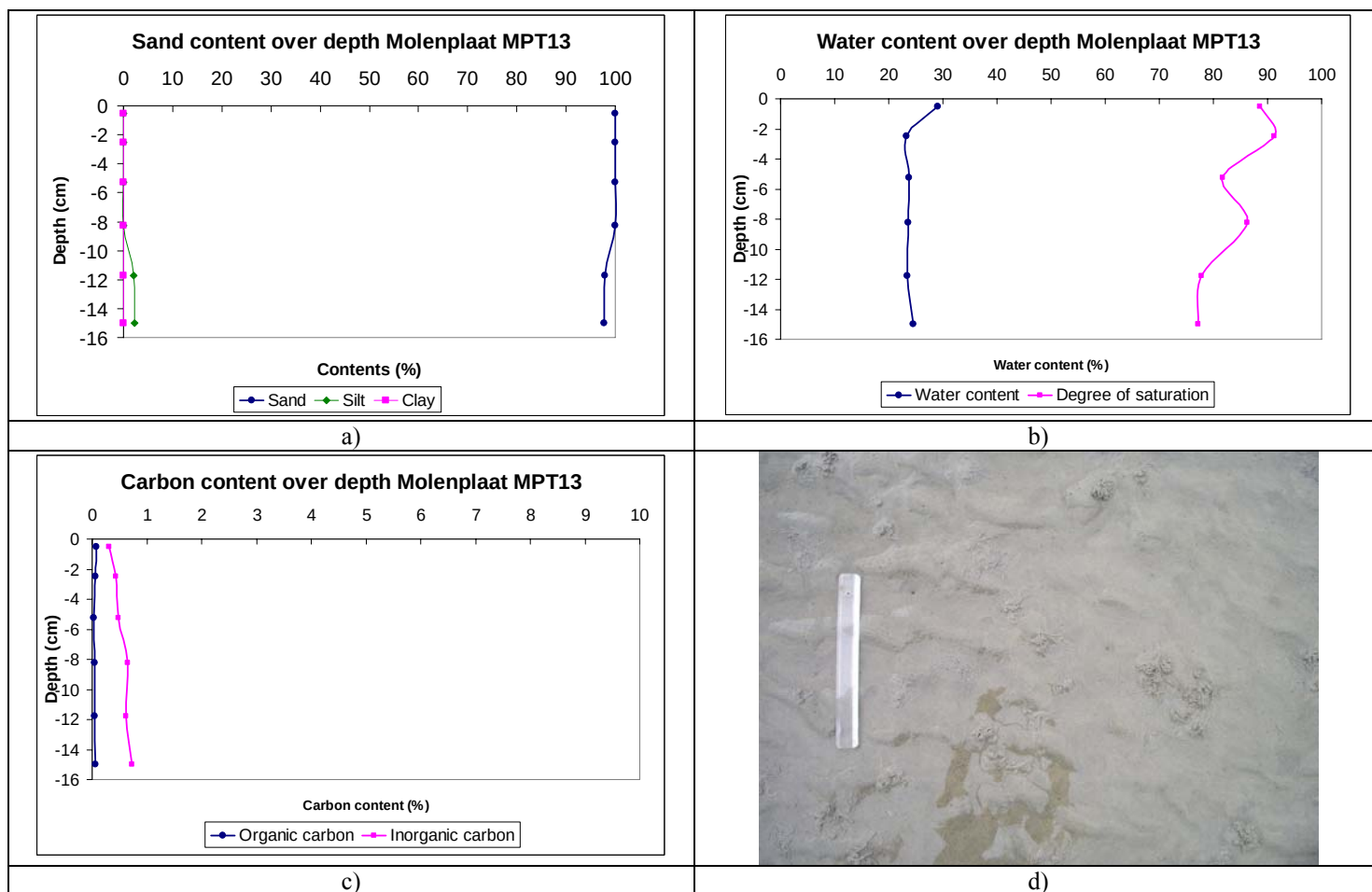


Figure 0.59: Results of lab analysis, location MPT-13: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

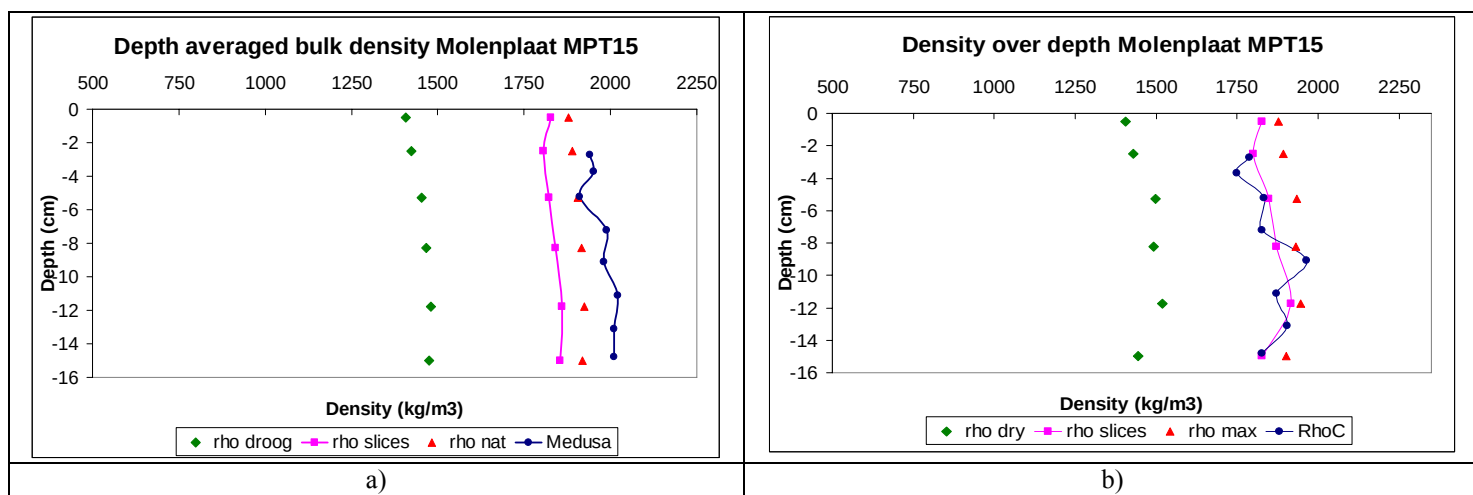


Figure 0.60: Density measurements of RhoC and lab slices, location MPT-15: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

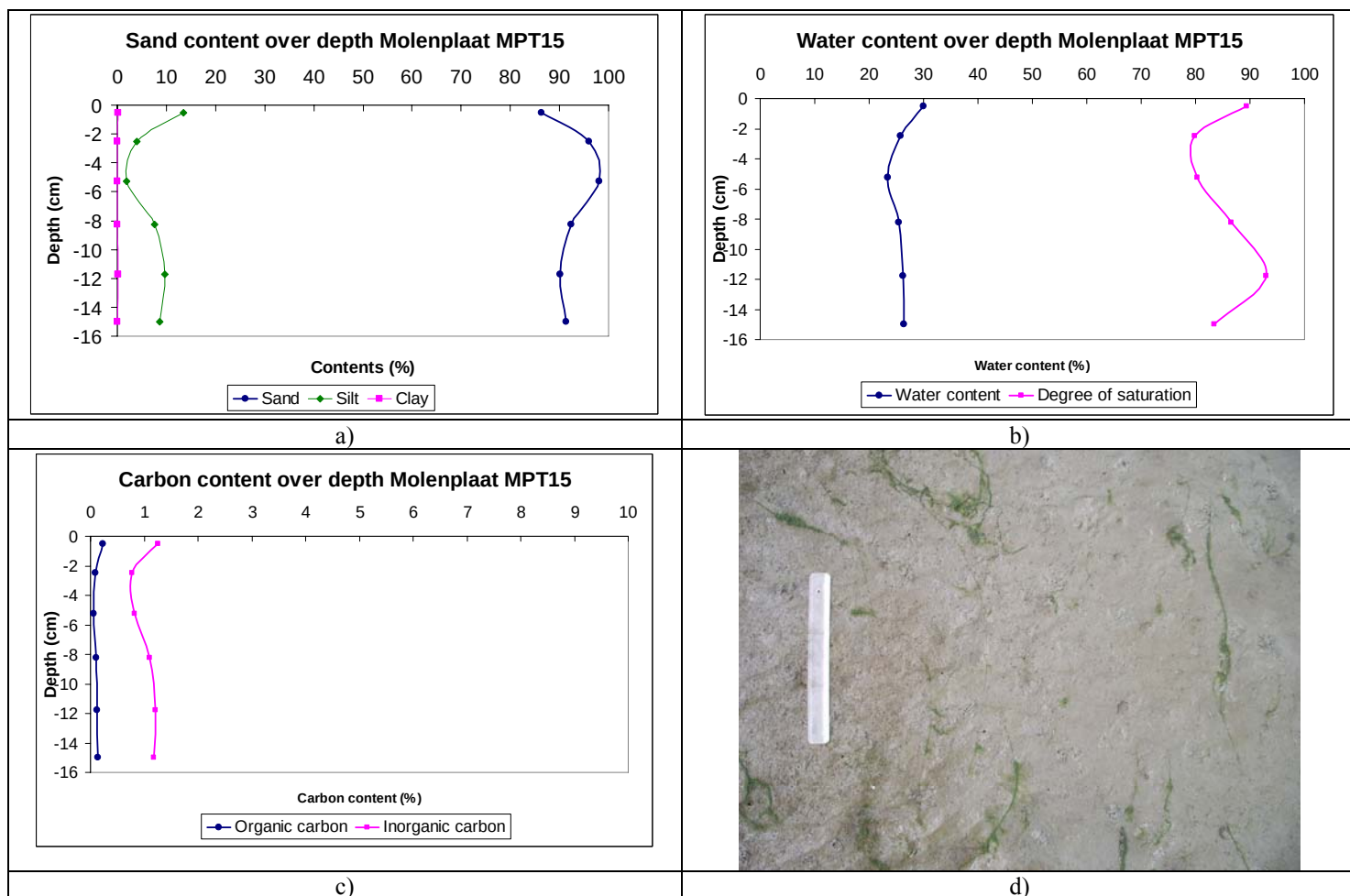


Figure 0.61: Results of lab analysis, location MPT-15: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

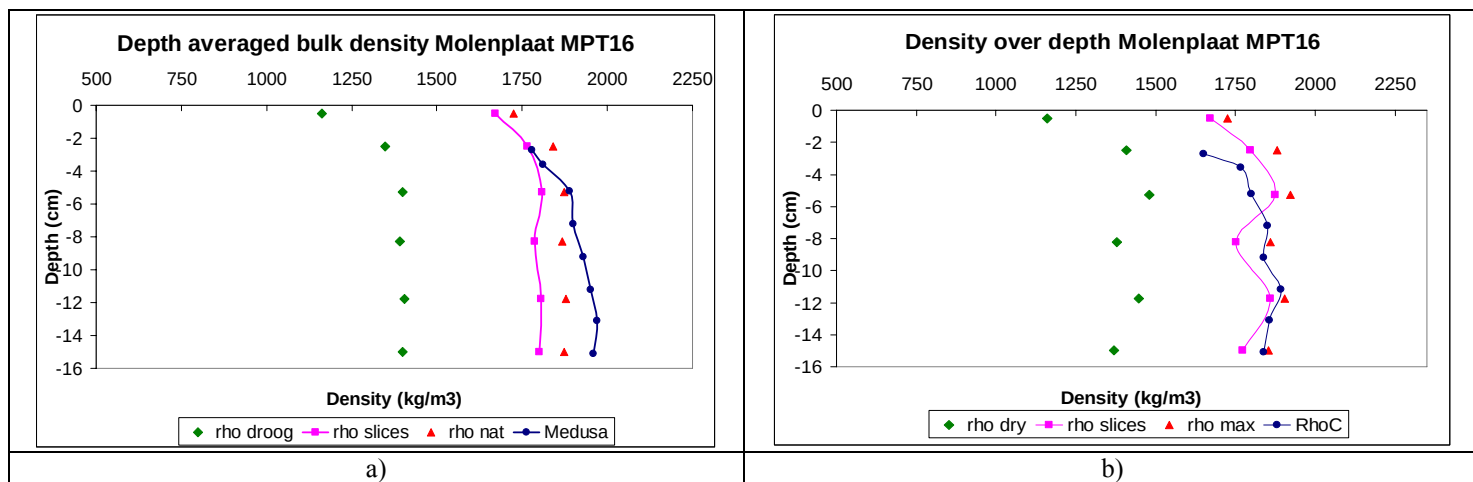


Figure 0.62: Density measurements of RhoC and lab slices, location MPT-16: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

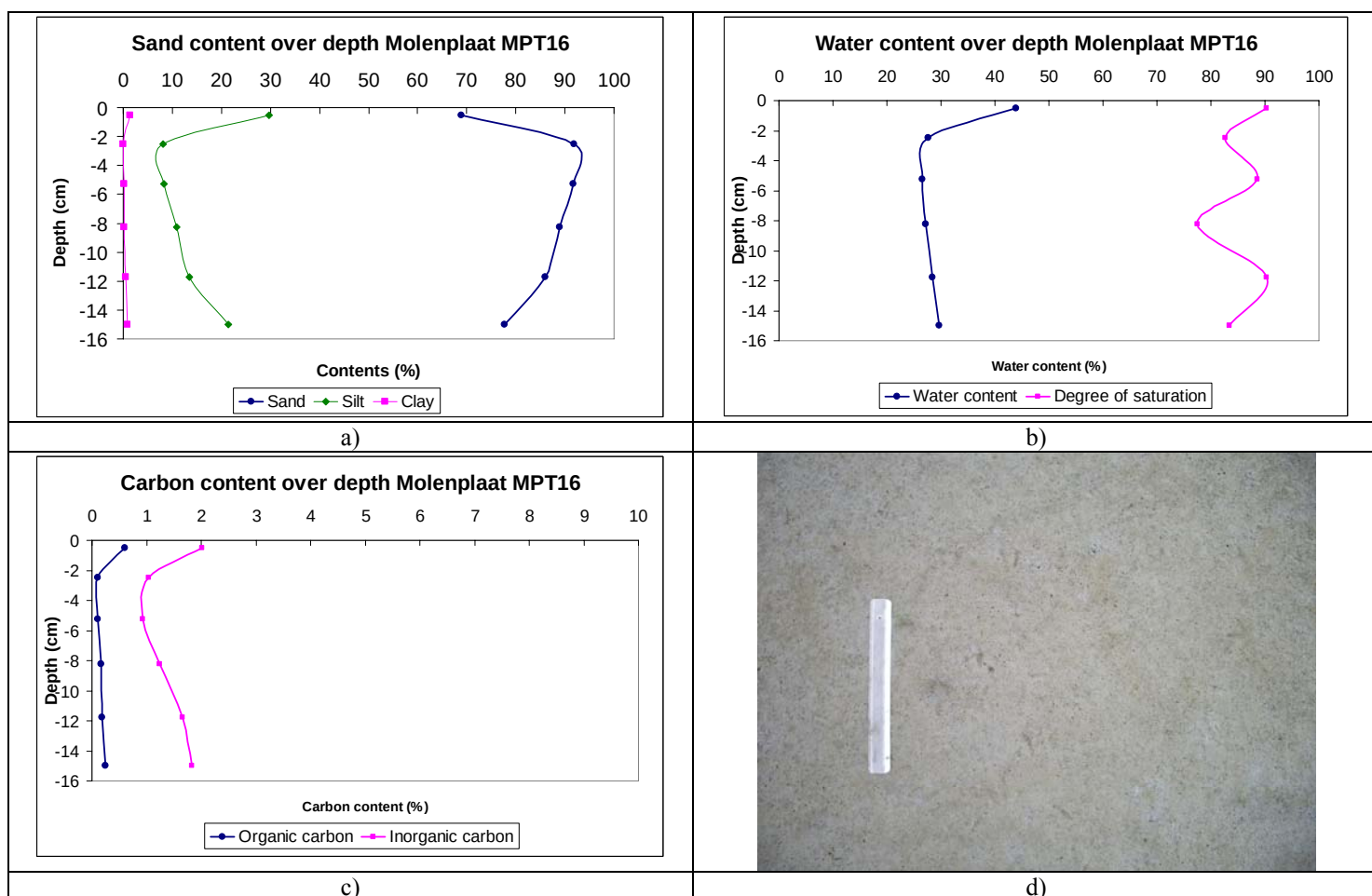


Figure 0.63: Results of lab analysis, location MPT-16: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

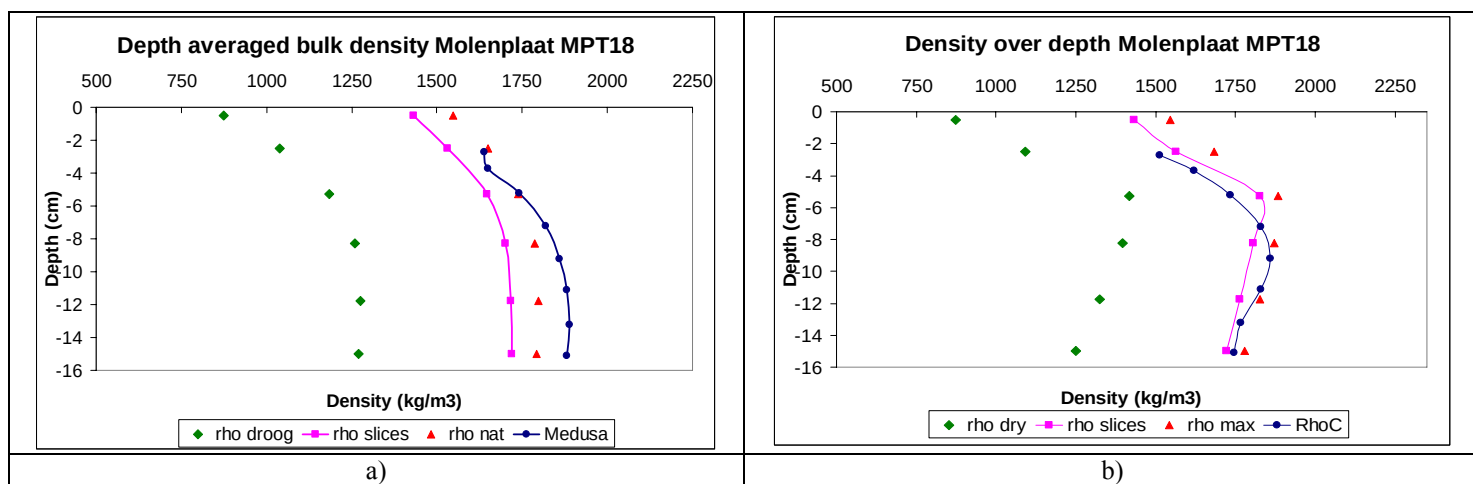


Figure 0.64: Density measurements of RhoC and lab slices, location MPT-18: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

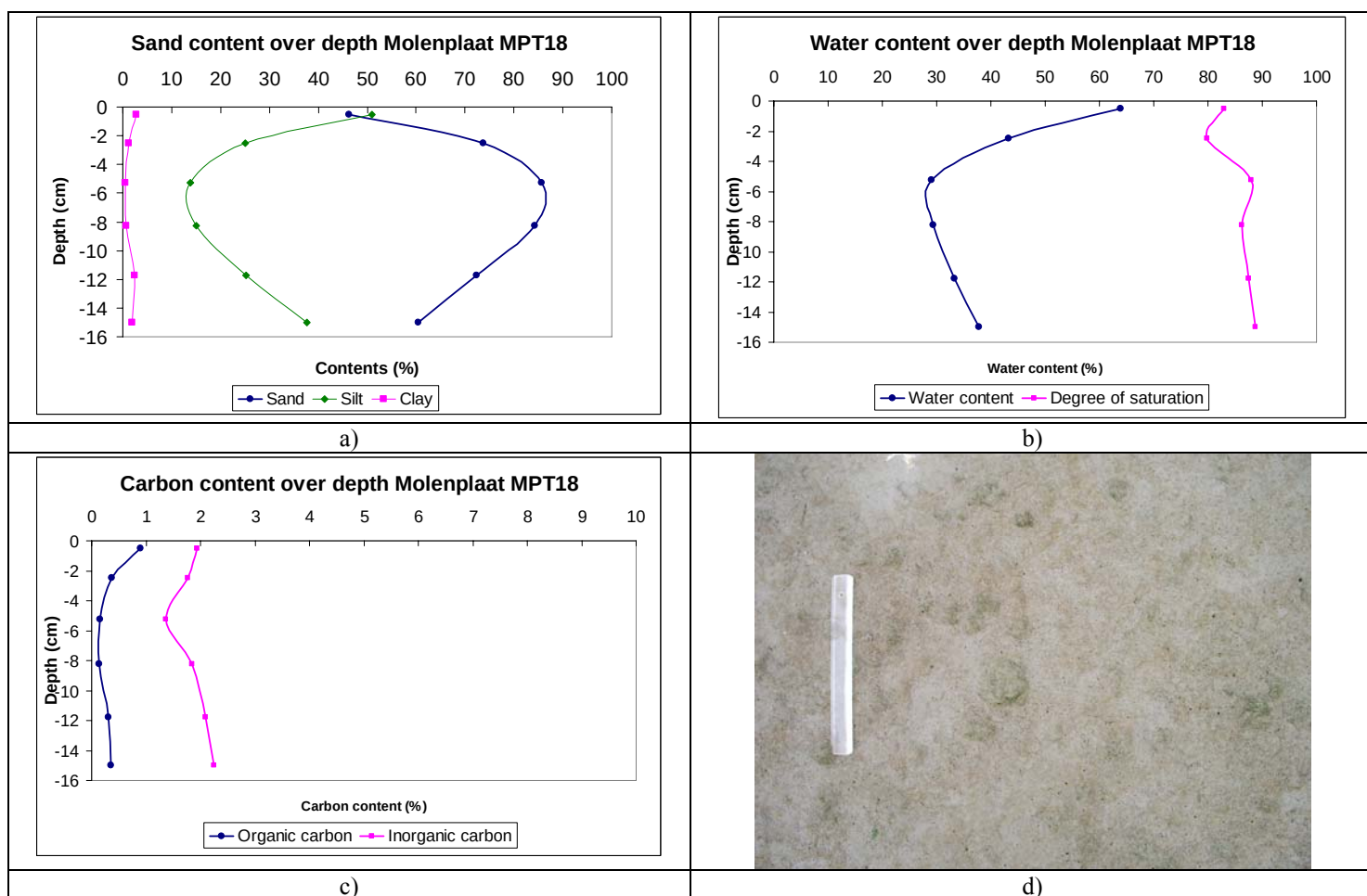


Figure 0.65: Results of lab analysis, location MPT-18: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

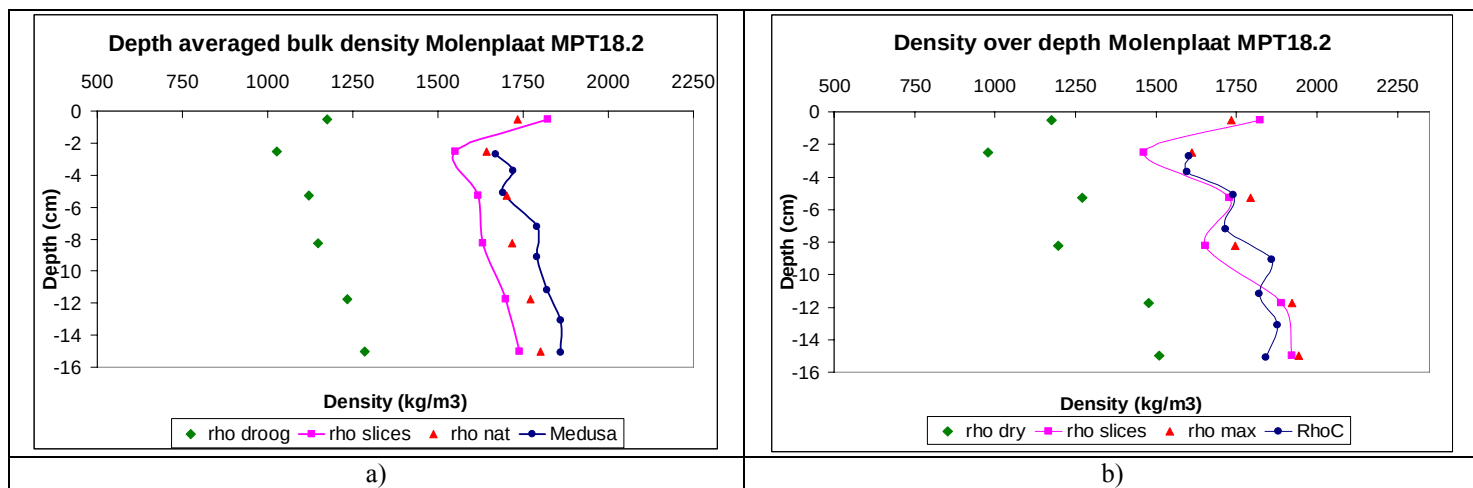


Figure 0.66: Density measurements of RhoC and lab slices, location MPT-18.2: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

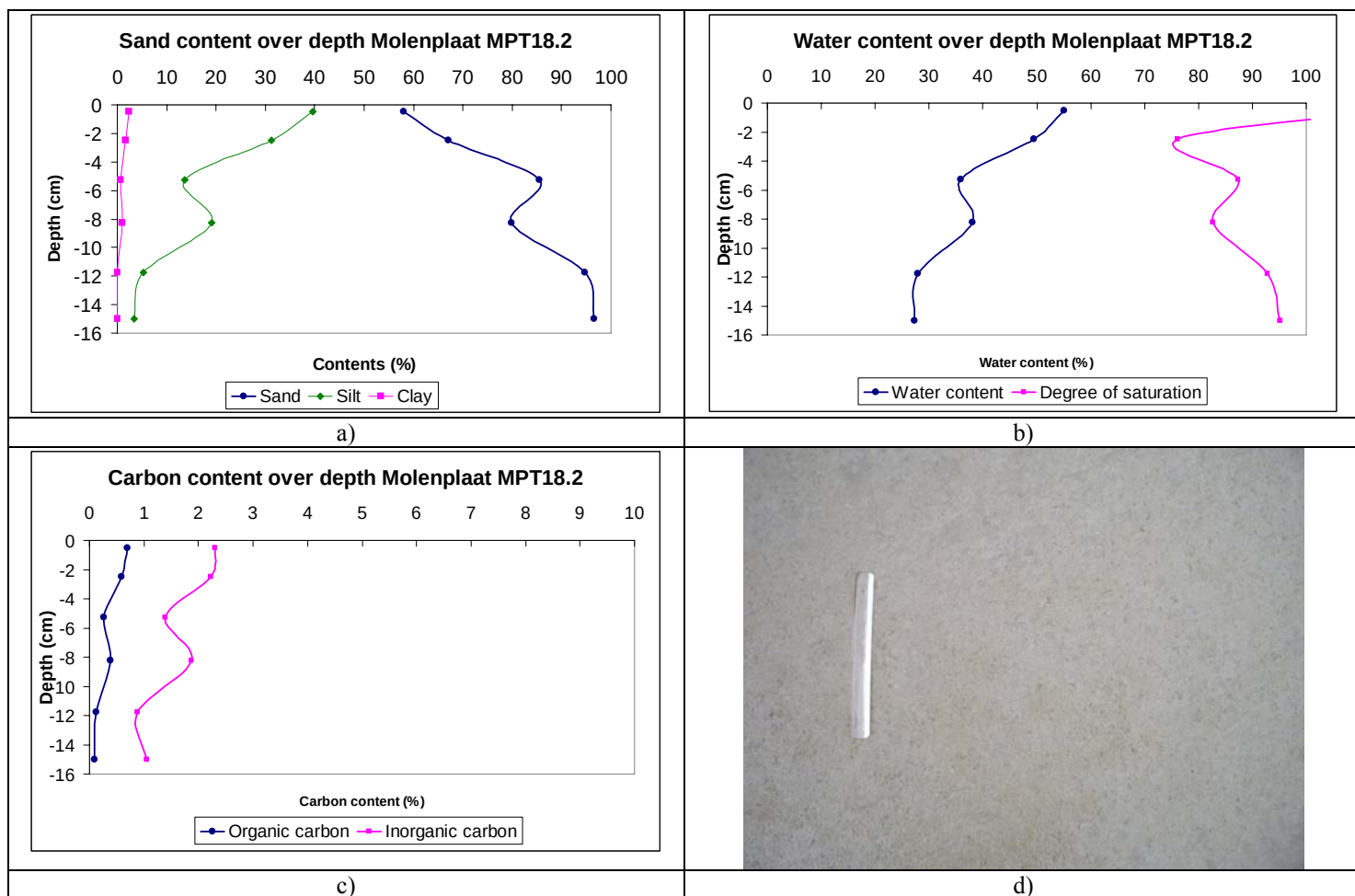


Figure 0.67: Results of lab analysis, location MPT-18.2: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

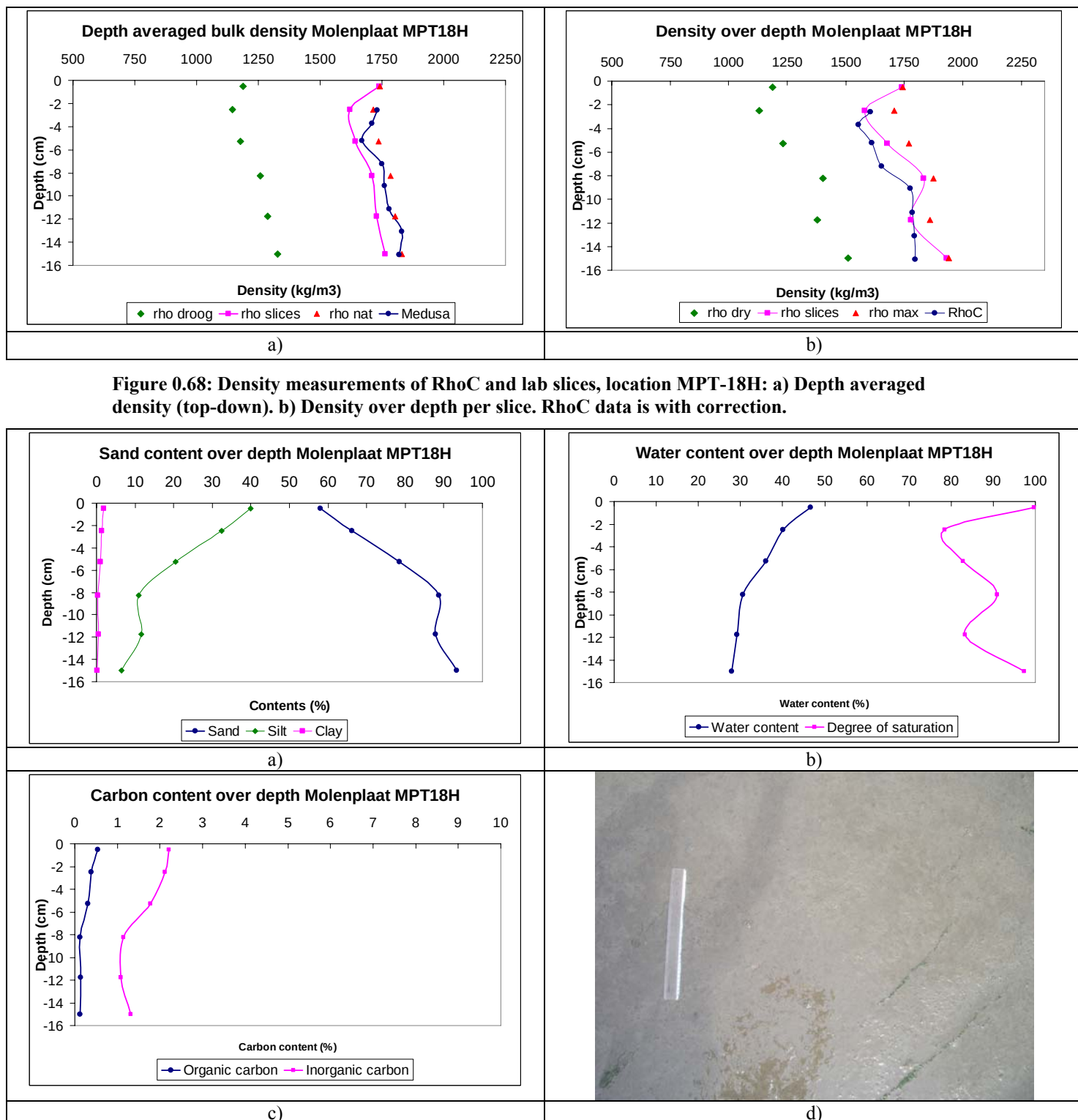


Figure 0.69: Results of lab analysis, location MPT-18H: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

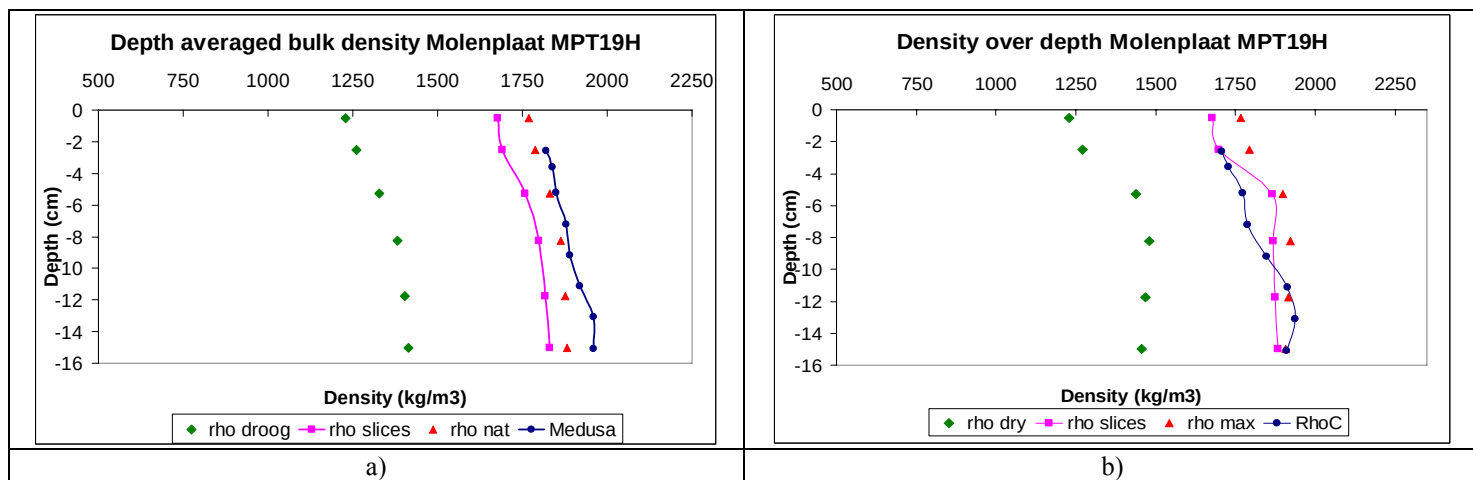


Figure 0.70: Density measurements of RhoC and lab slices, location MPT-19H: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

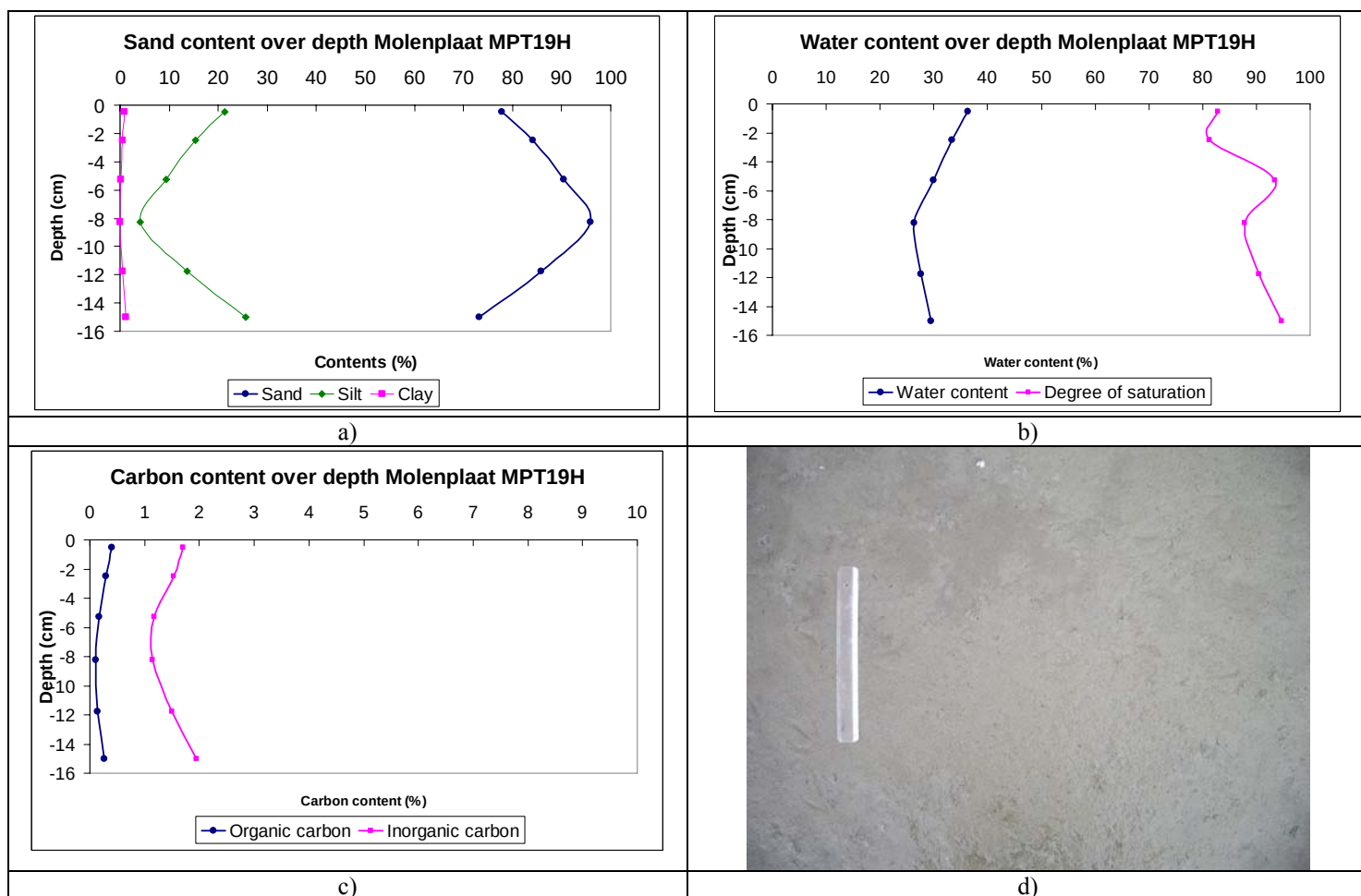


Figure 0.71: Results of lab analysis, location MPT-19H: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

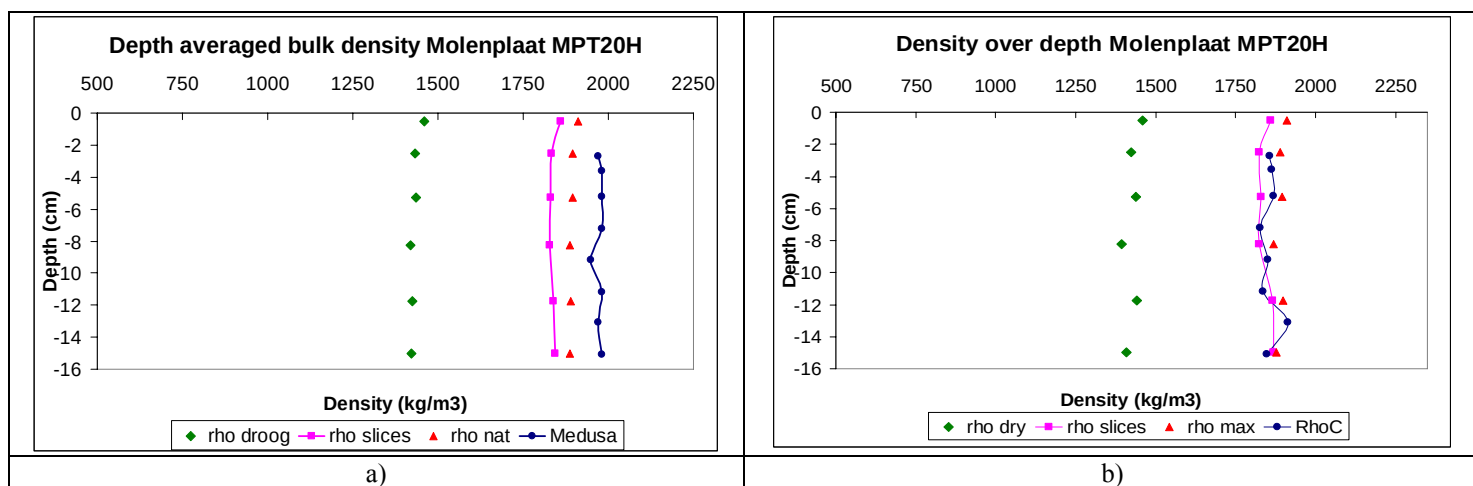


Figure 0.72: Density measurements of RhoC and lab slices, location MPT-20H: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

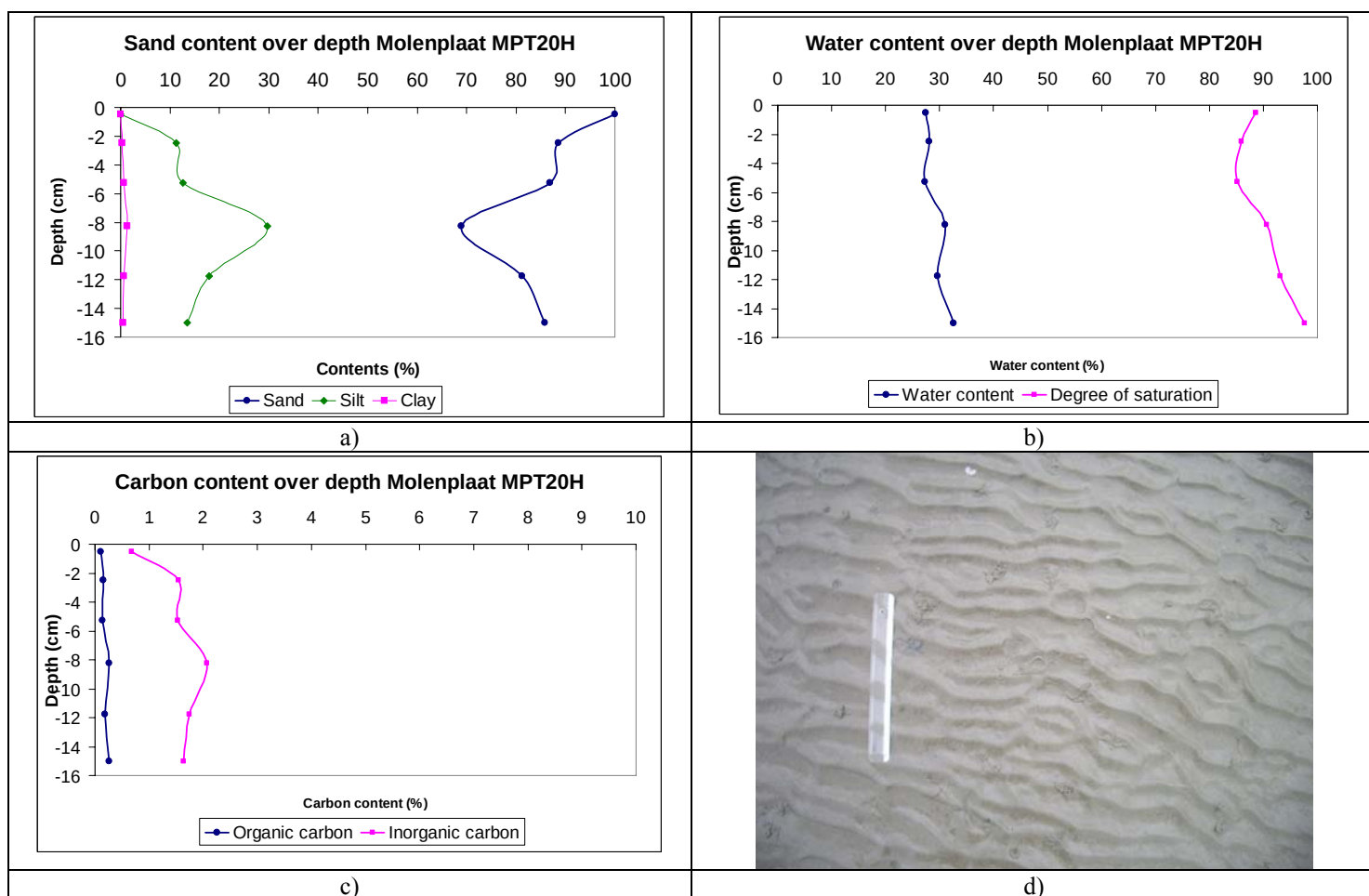
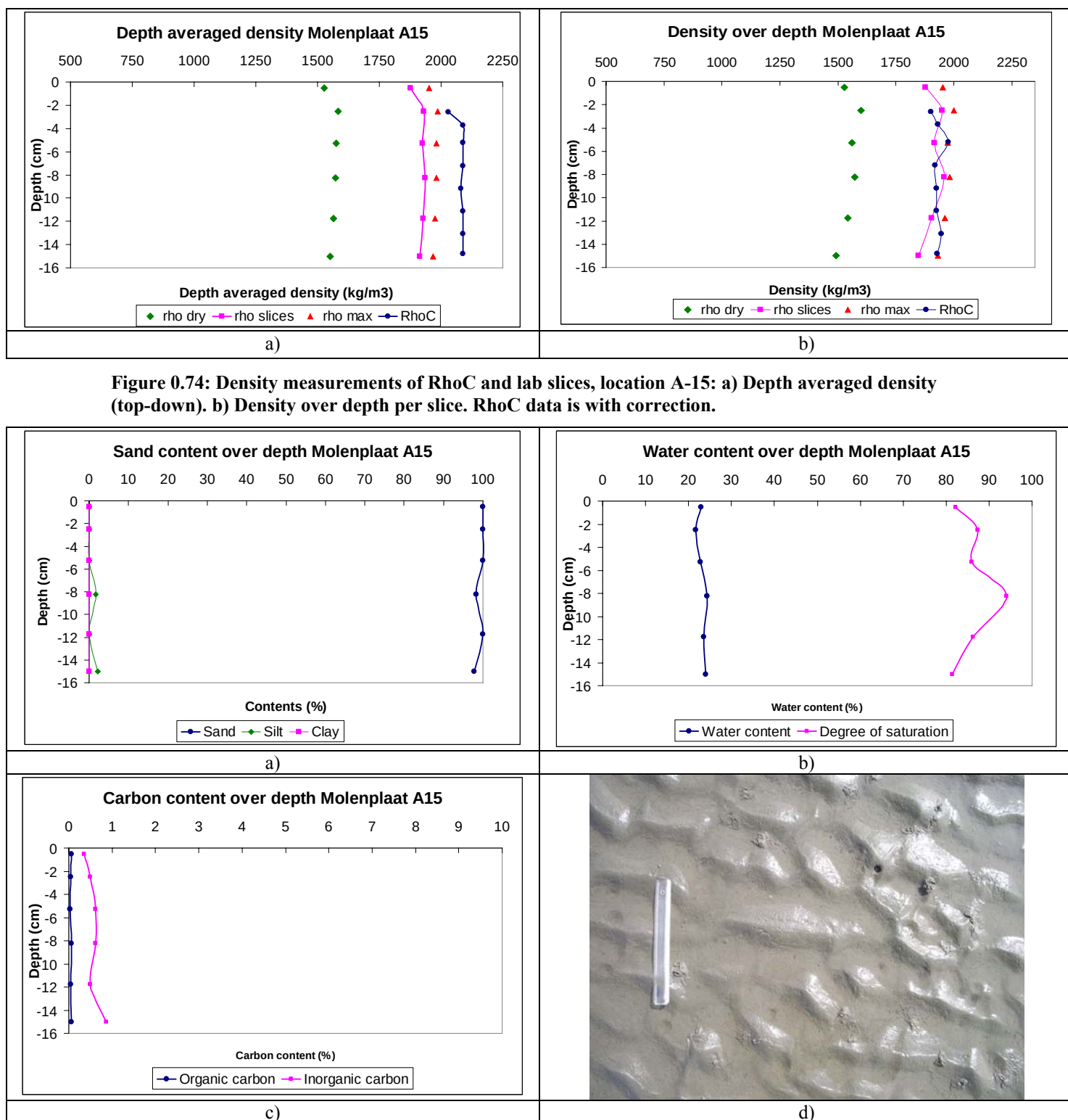


Figure 0.73: Results of lab analysis, location MPT-20H: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).



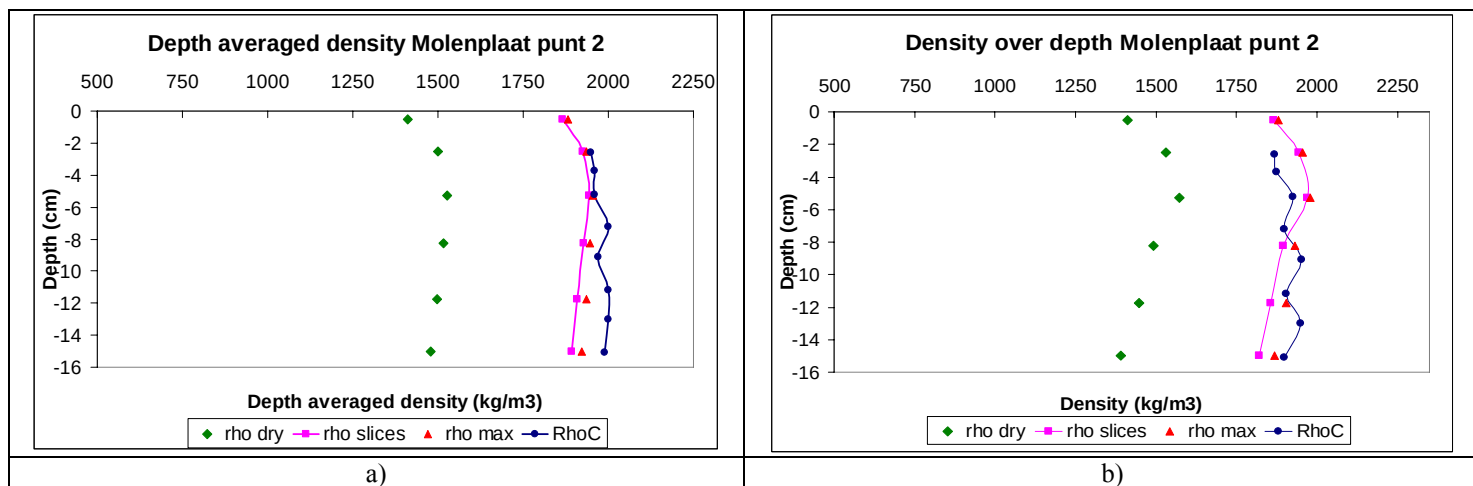


Figure 0.76: Density measurements of RhoC and lab slices, location punt 2: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

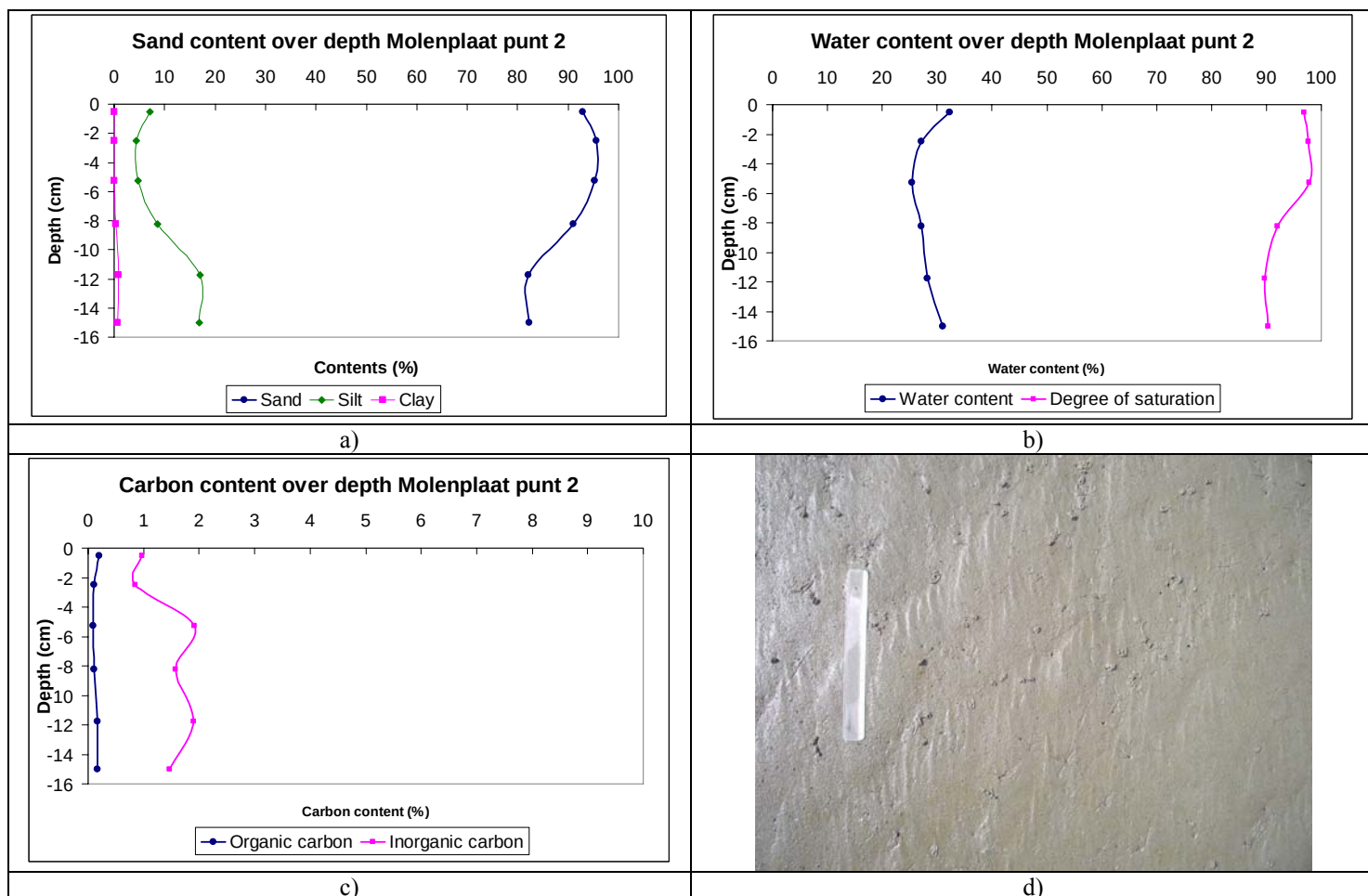


Figure 0.77: Results of lab analysis, location punt 2: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

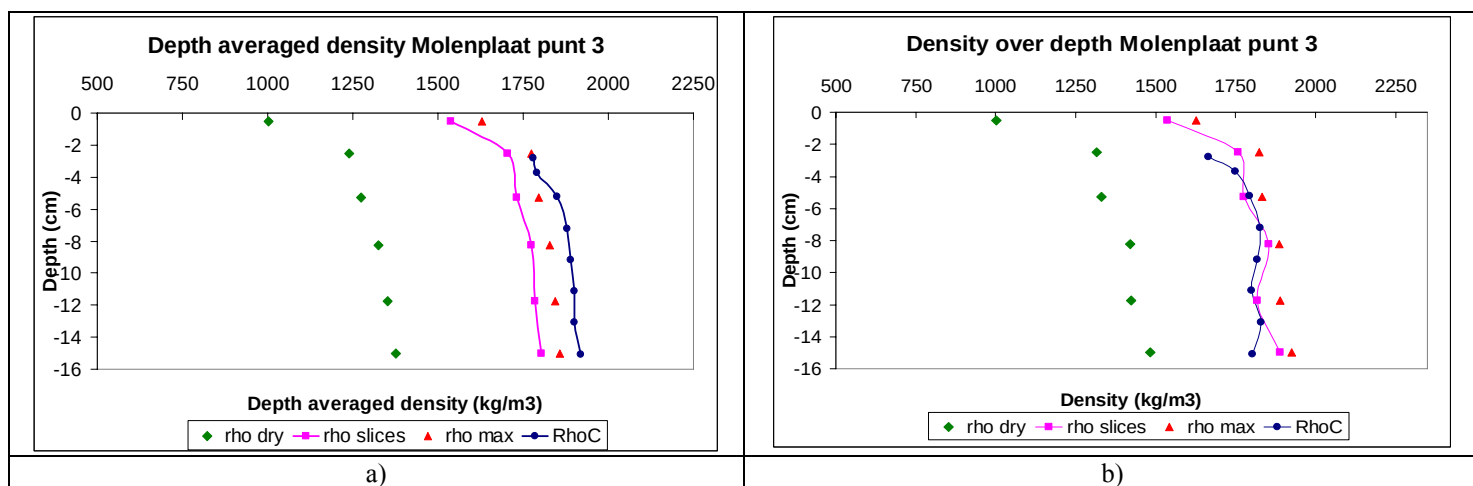


Figure 0.78: Density measurements of RhoC and lab slices, location punt 3: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

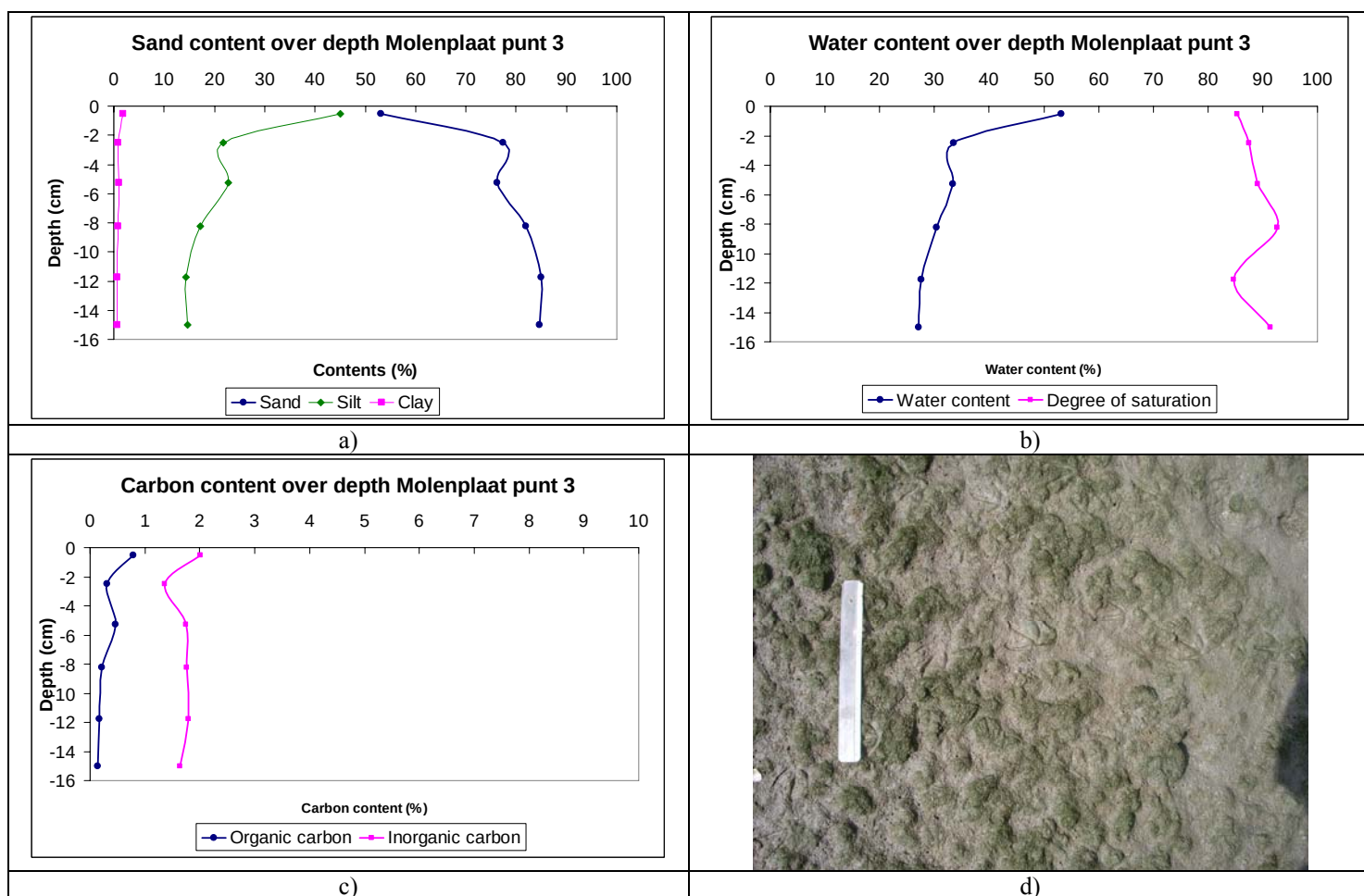


Figure 0.79: Results of lab analysis, location punt 3: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

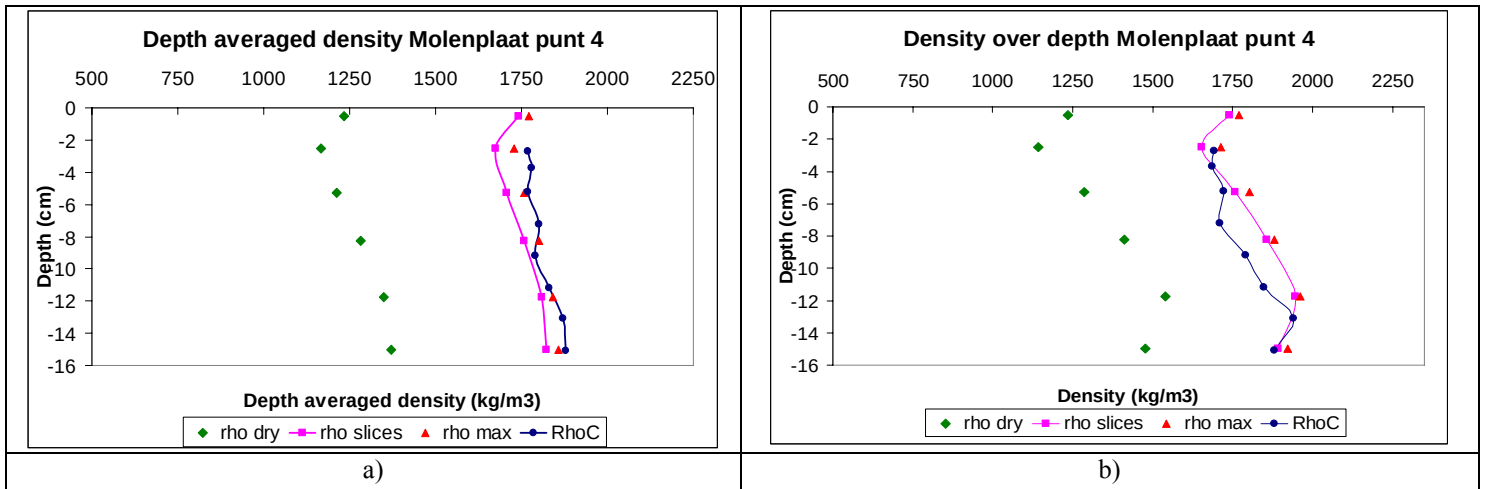


Figure 0.80: Density measurements of RhoC and lab slices, location punt 4: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

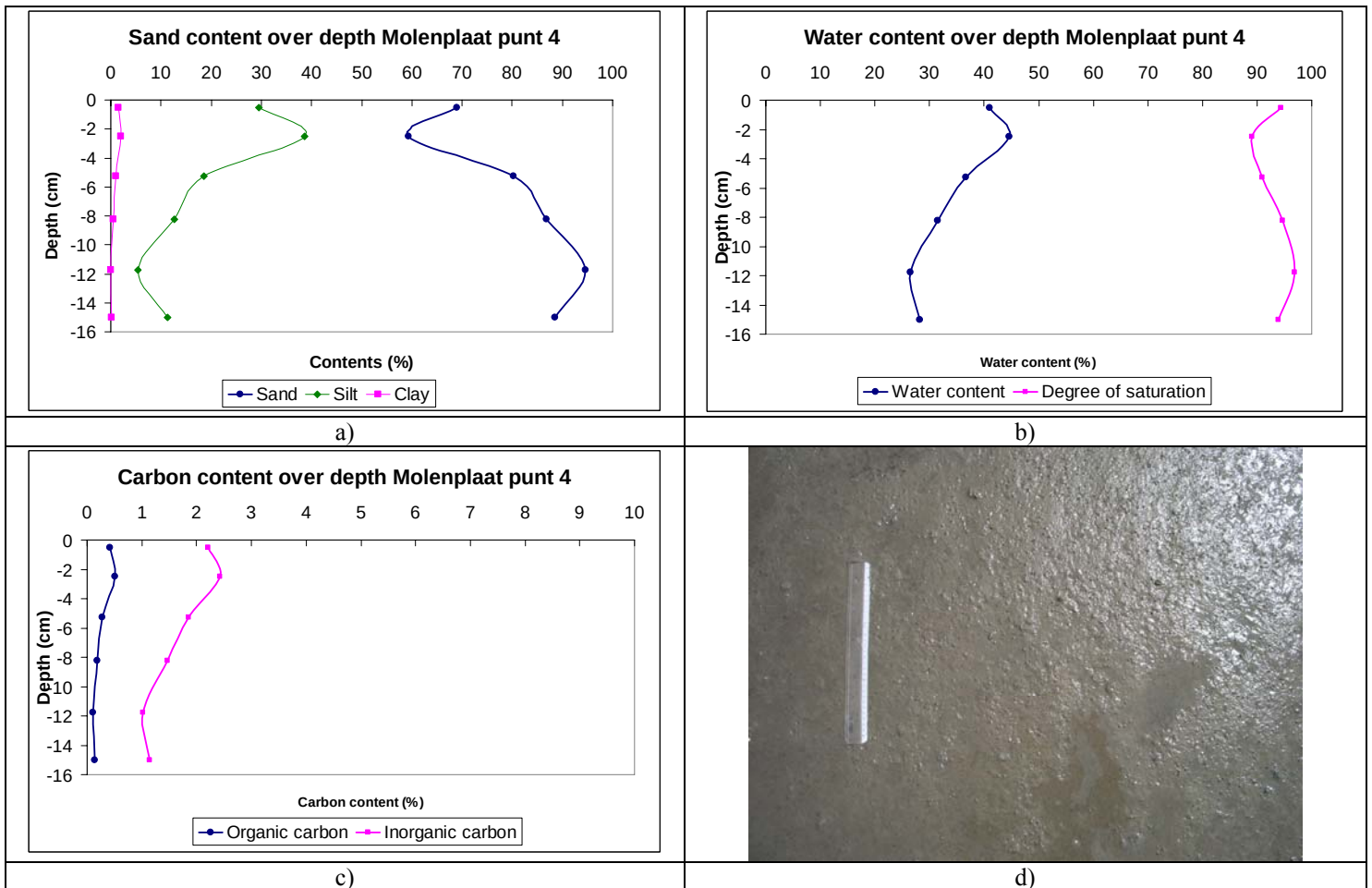


Figure 0.81: Results of lab analysis, location punt 4: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

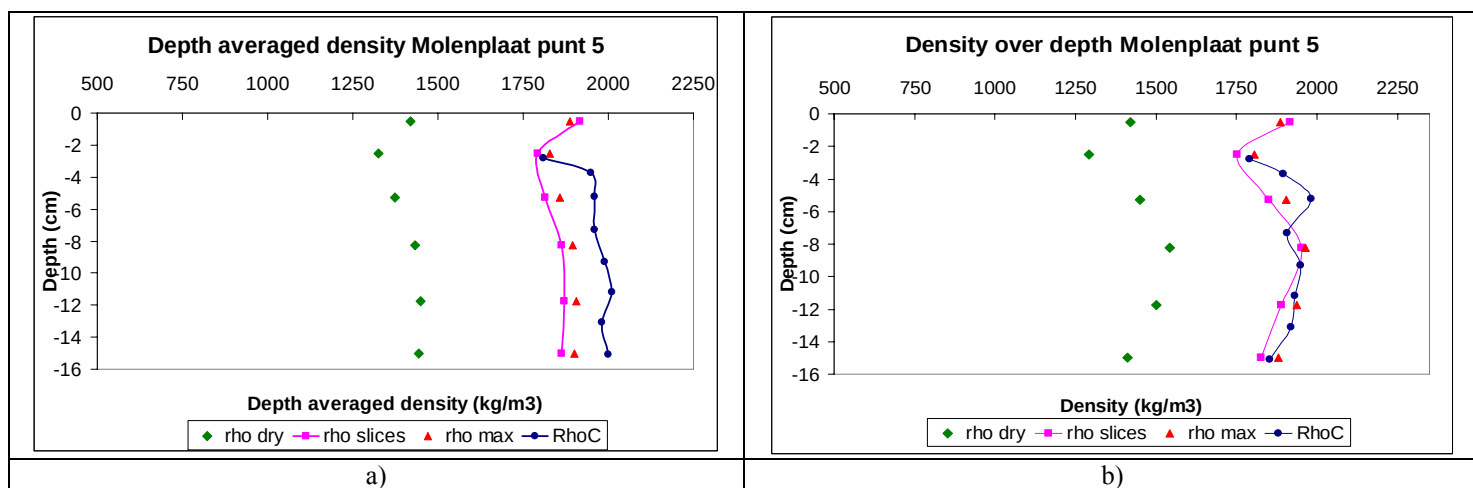


Figure 0.82: Density measurements of RhoC and lab slices, location punt 5: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

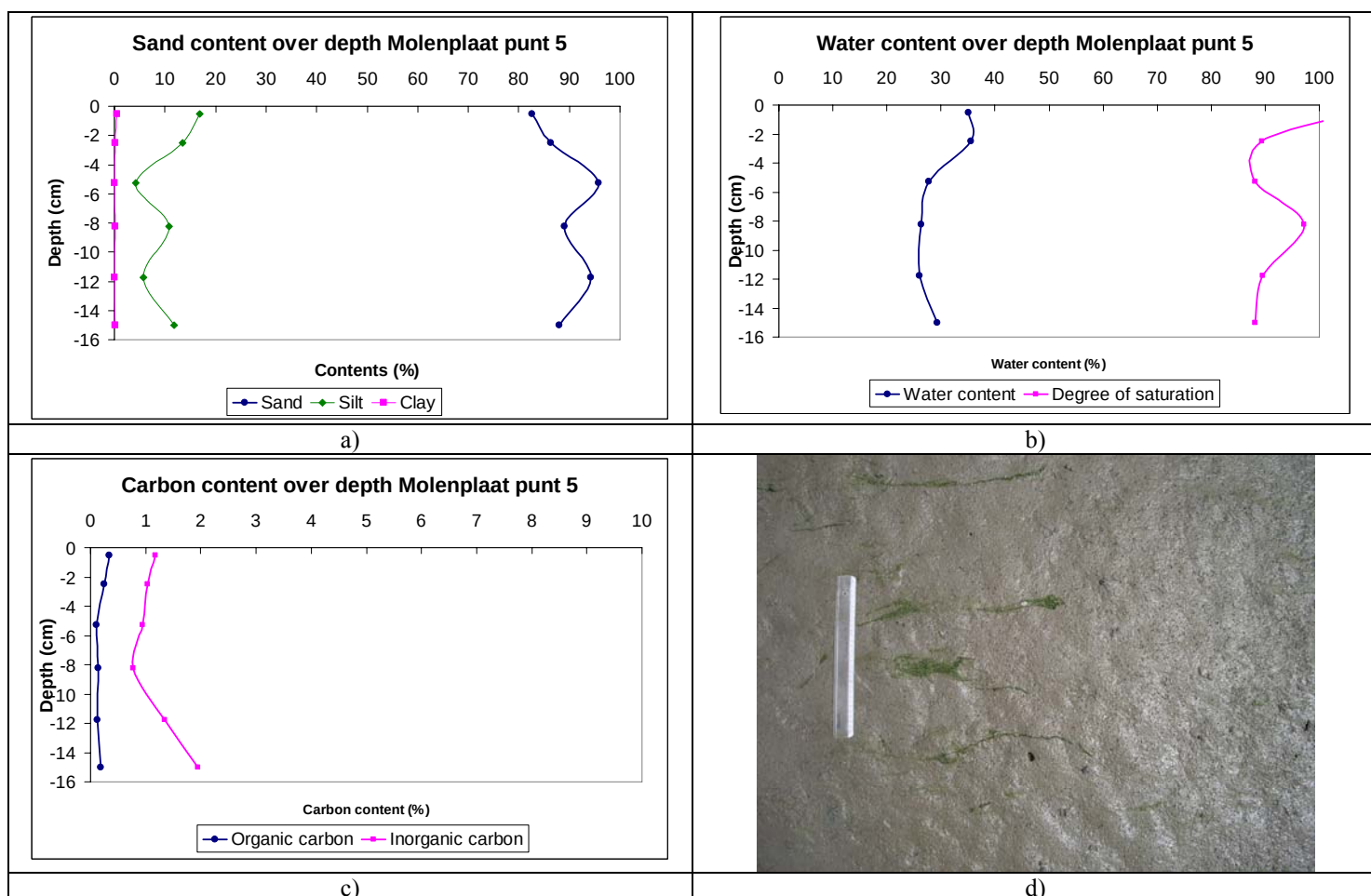


Figure 0.83: Results of lab analysis, location punt 5: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

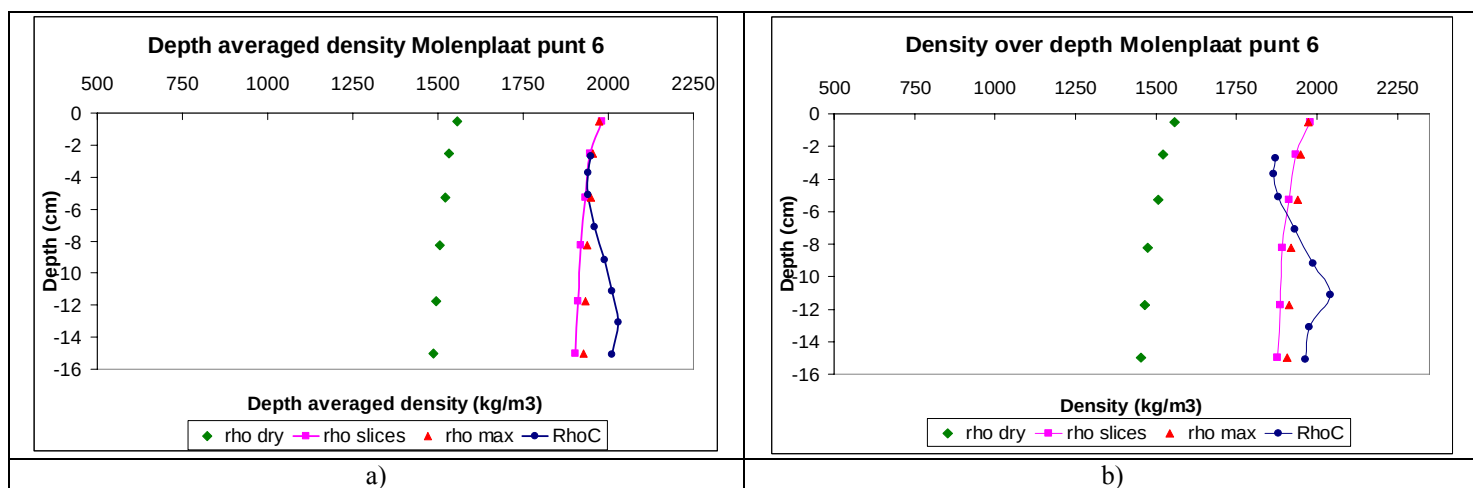


Figure 0.84: Density measurements of RhoC and lab slices, location punt 6: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

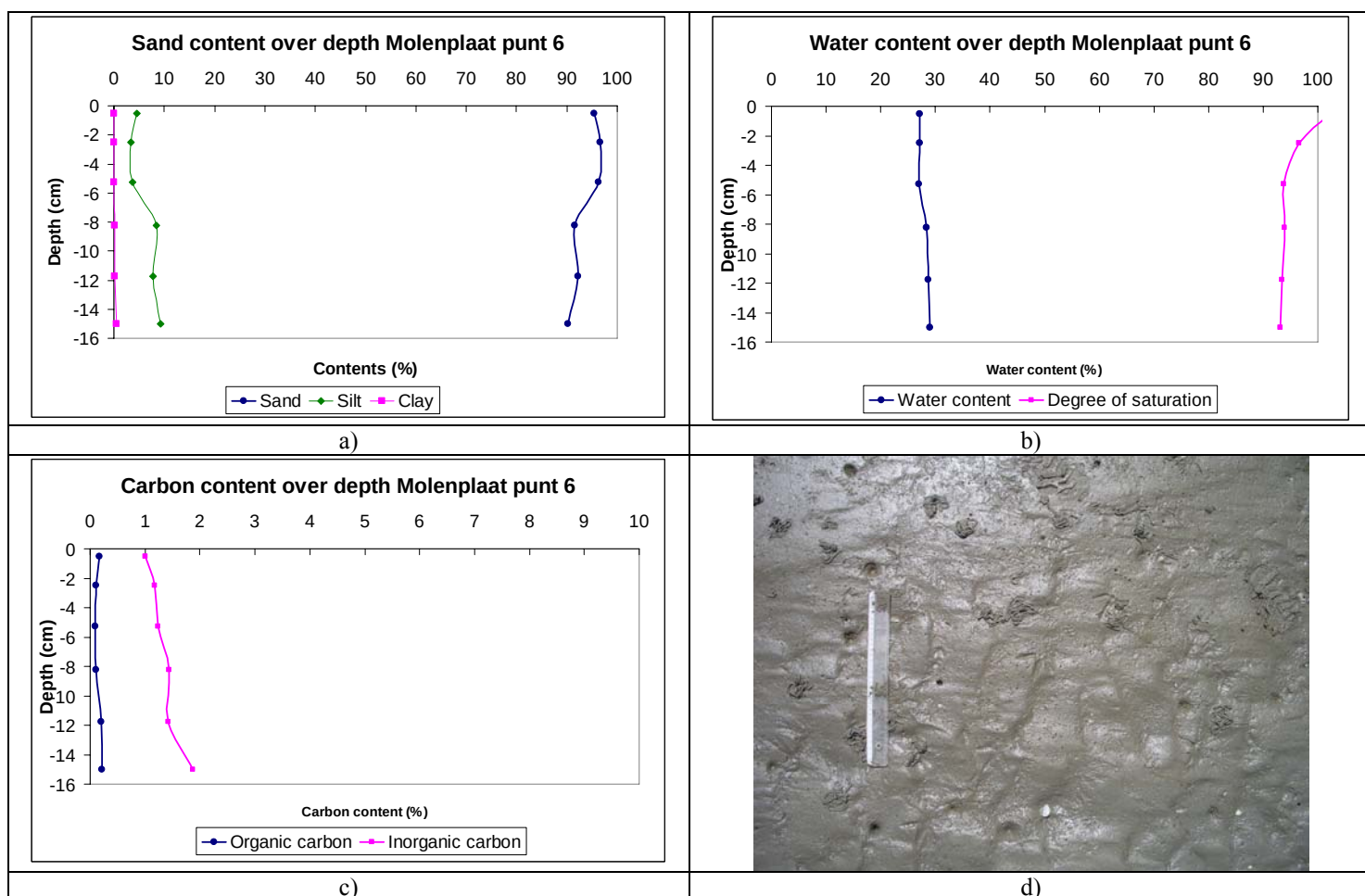


Figure 0.85: Results of lab analysis, location punt 6: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

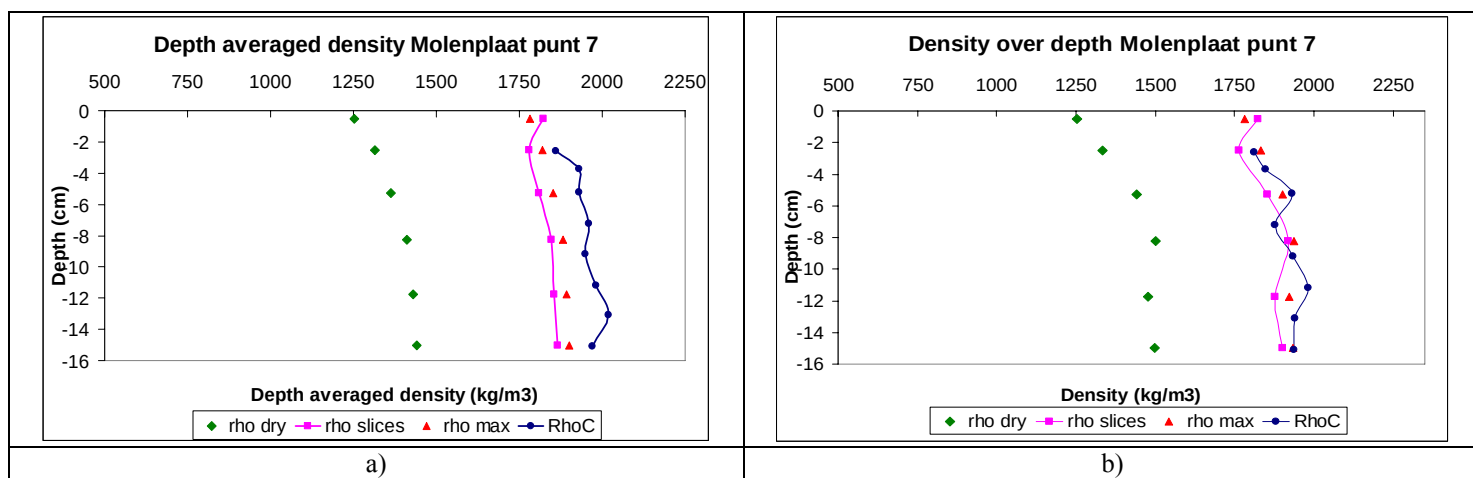


Figure 0.86: Density measurements of RhoC and lab slices, location punt 7: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

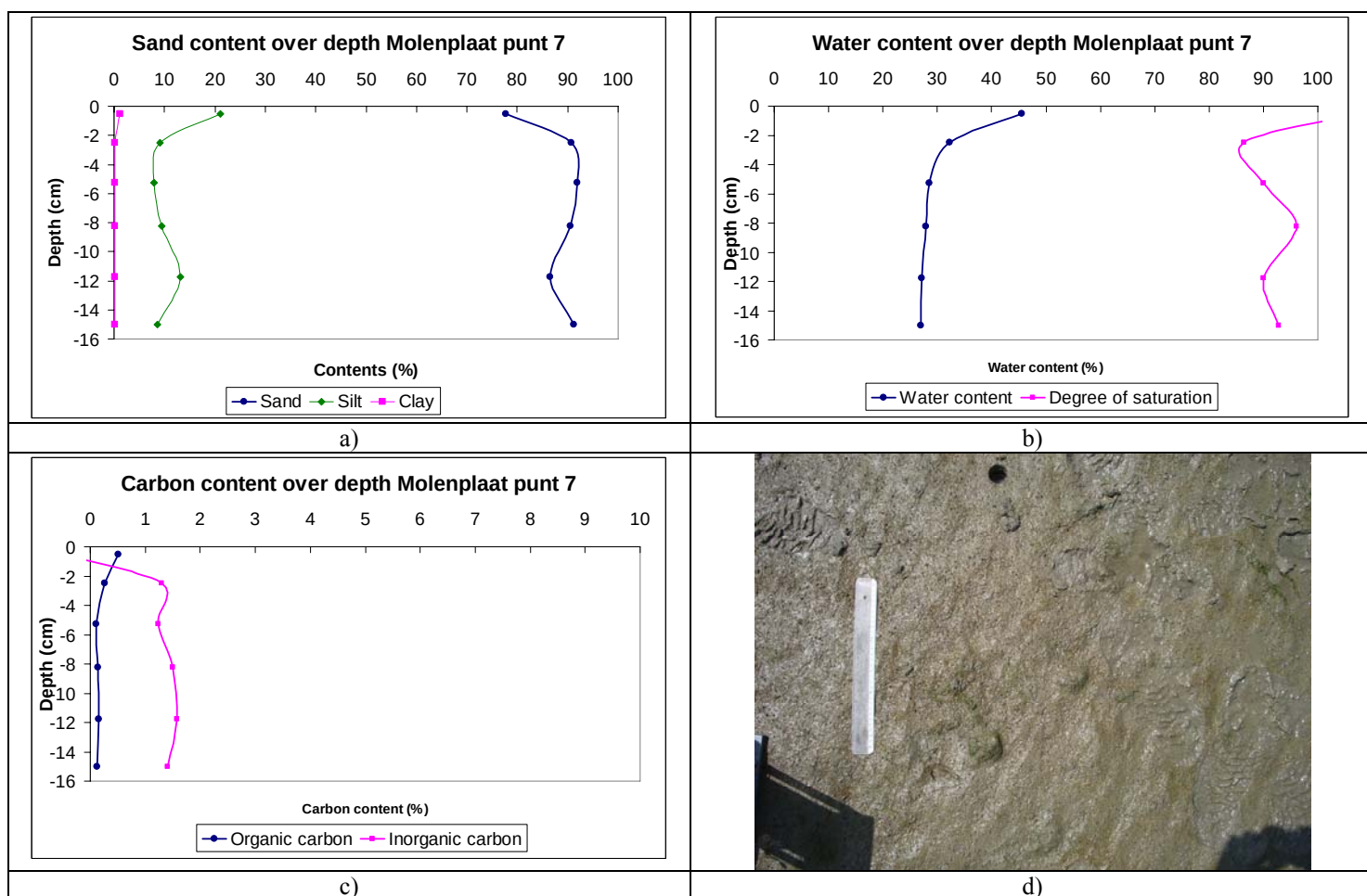


Figure 0.87: Results of lab analysis, location punt 7: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

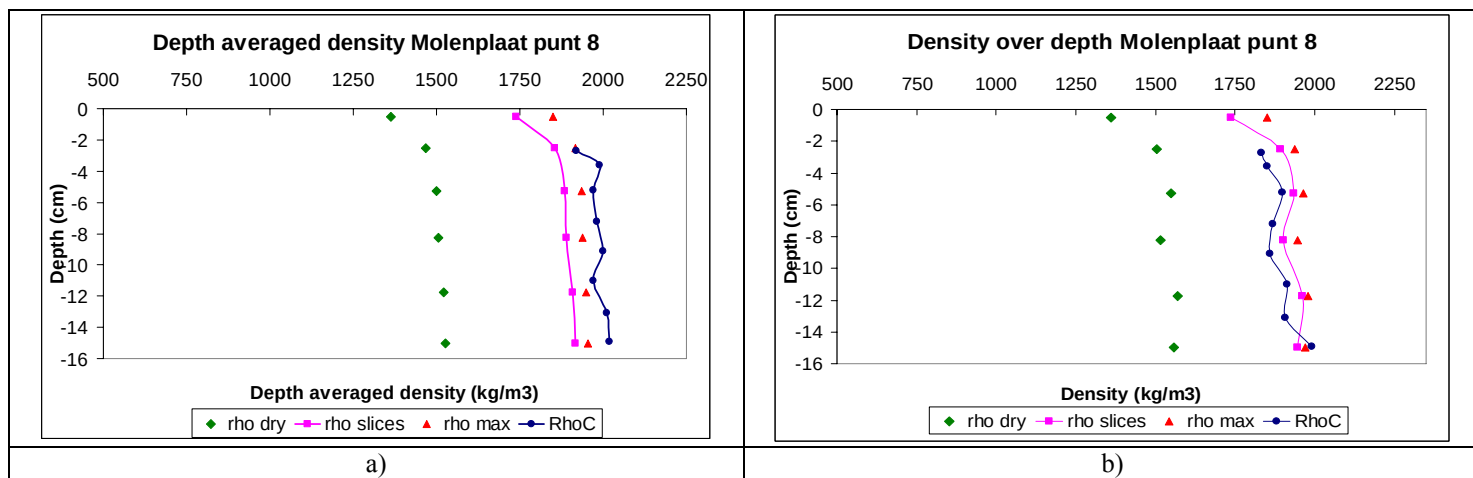


Figure 0.88: Density measurements of RhoC and lab slices, location punt 8: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

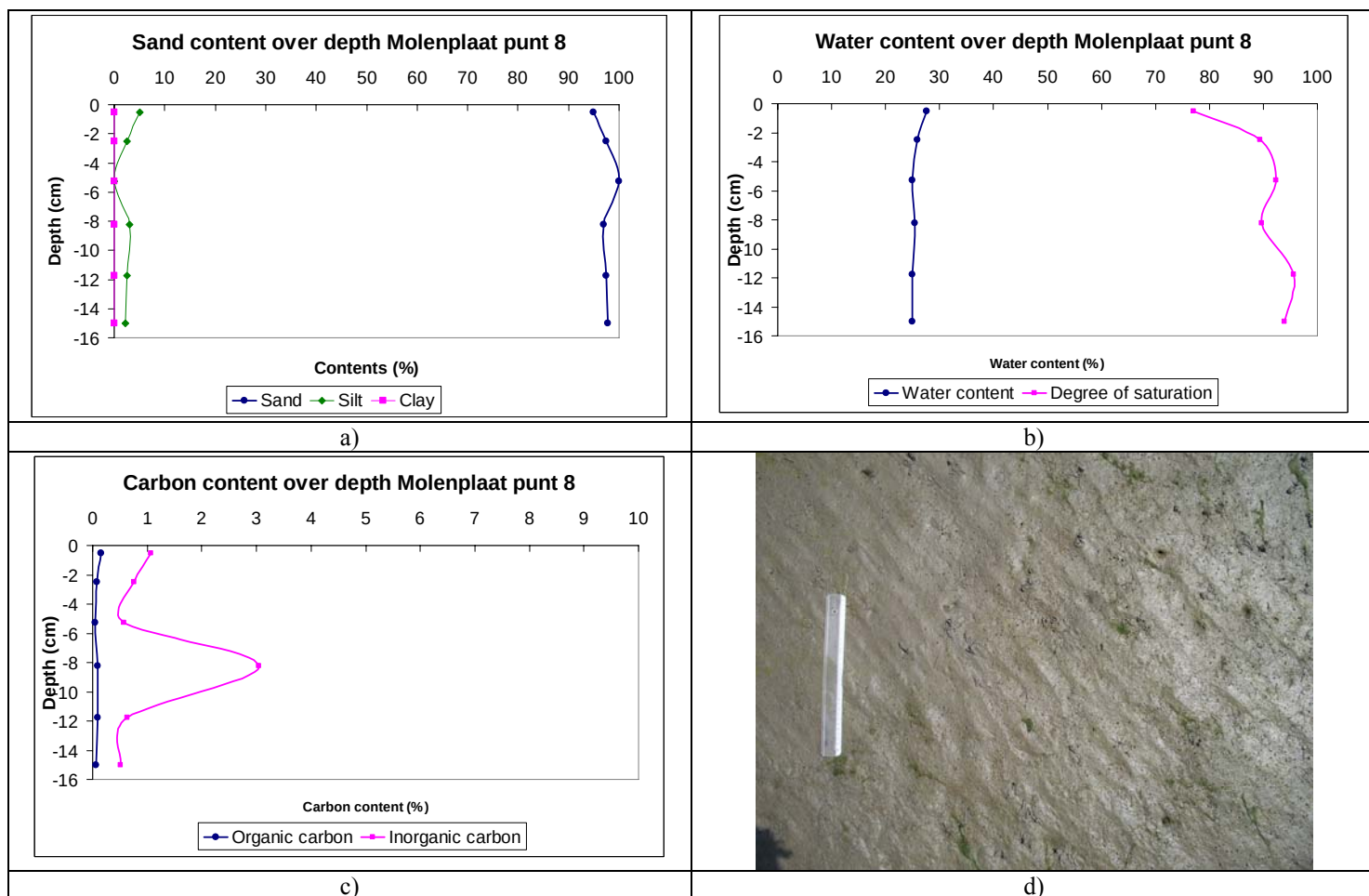


Figure 0.89: Results of lab analysis, location punt 8: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

D.3 Data Plaat van Walsoorden

D.3.1 General overview

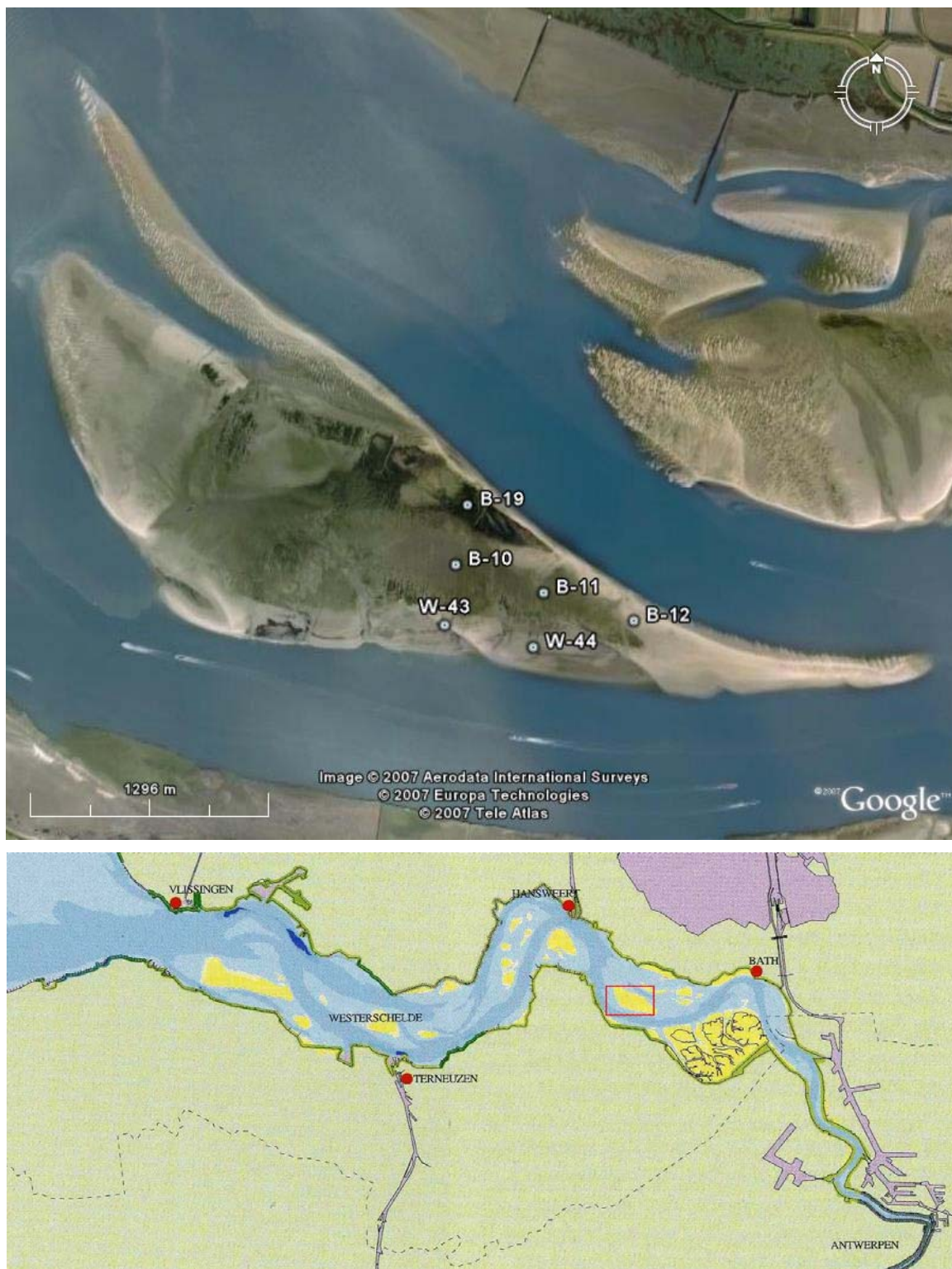


Figure 0.90: Map of Western Scheldt with sample locations on Plaat van Walsoorden.

D.3.2 Radiometric measurements

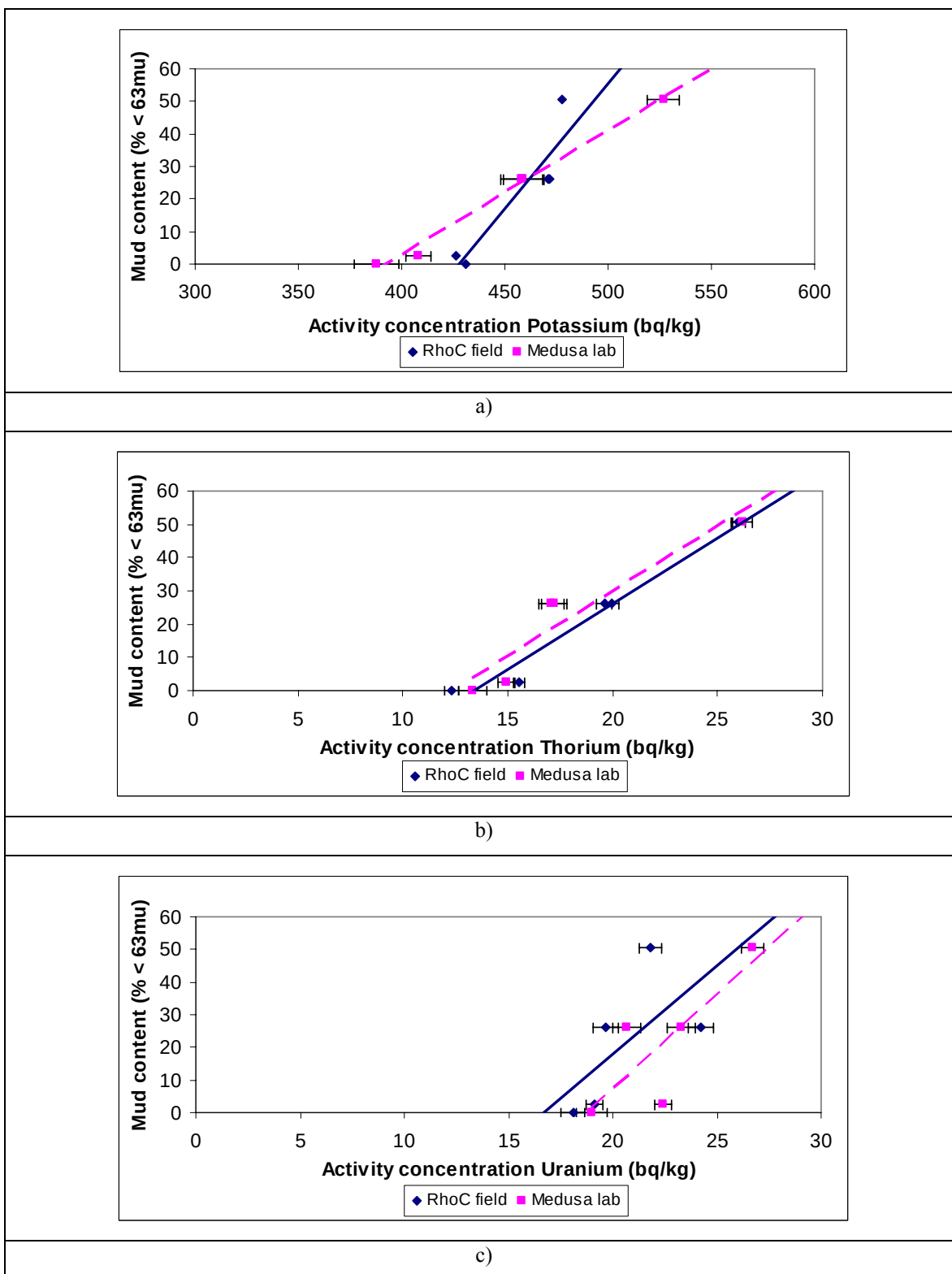


Figure 0.91: Radiometric measurements and mud content. Lines indicate linear best fit. a) Potassium activity concentrations. b) Thorium activity concentrations. c) Uranium activity concentrations.

D.3.3 Density measurements of RhoC and lab analysis

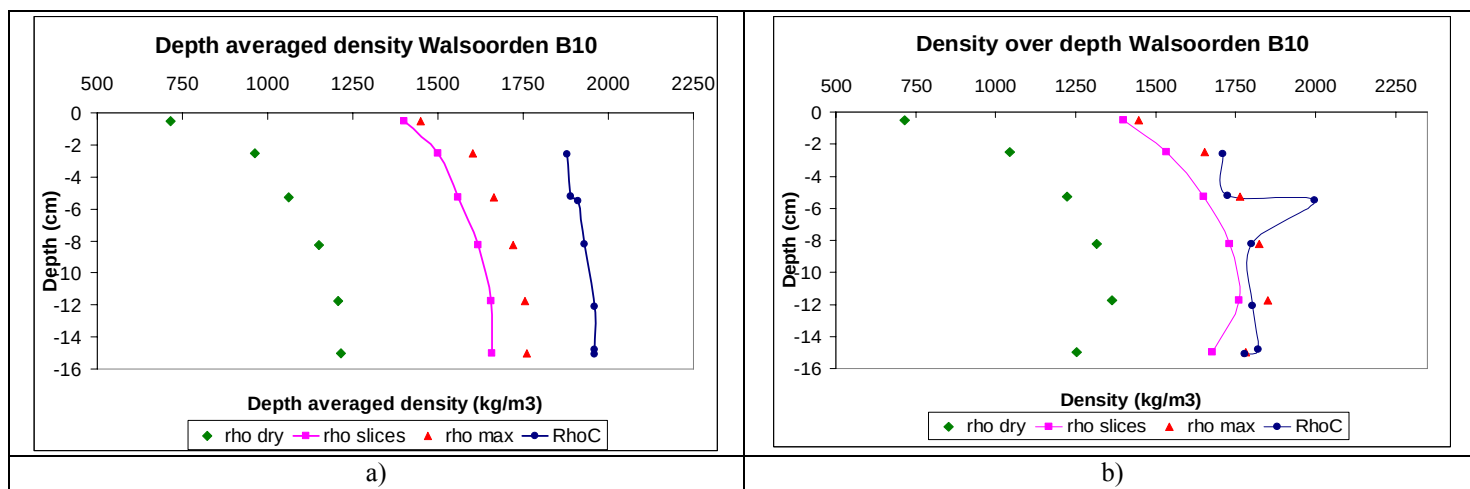


Figure 0.92: Density measurements of RhoC and lab slices, location B-10: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

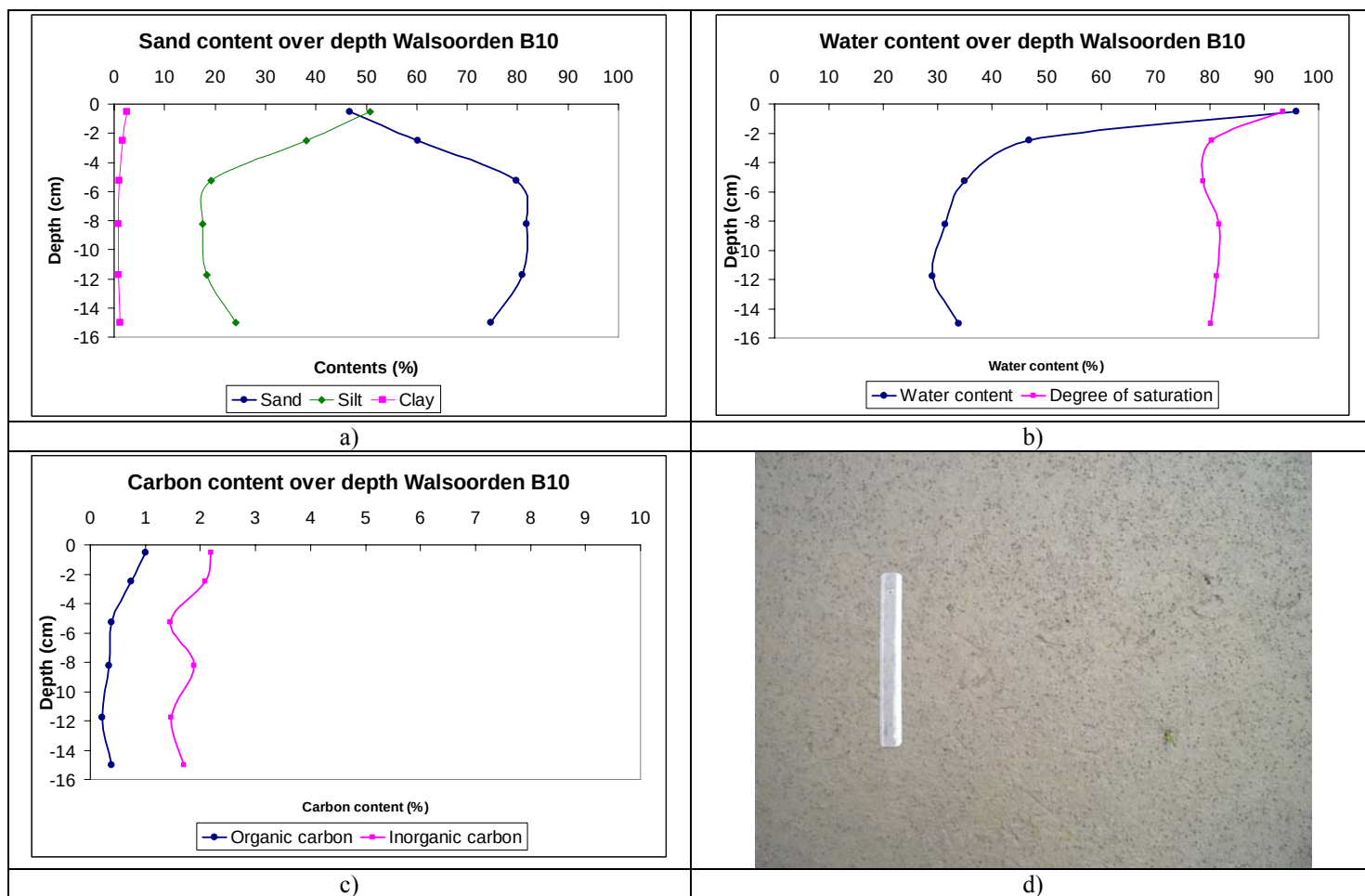


Figure 0.93: Results of lab analysis, location B-10: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

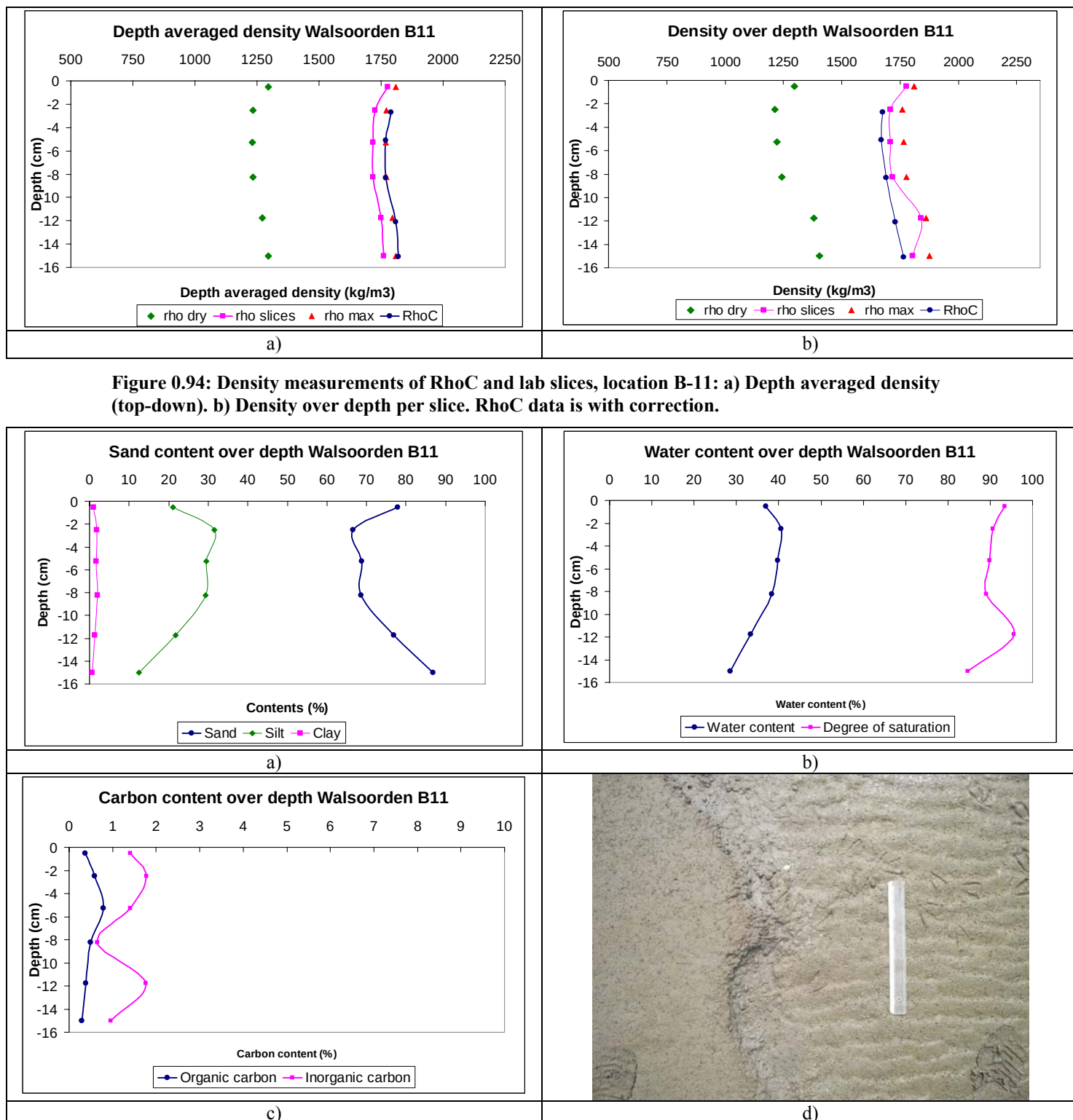


Figure 0.94: Density measurements of RhoC and lab slices, location B-11: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

Figure 0.95: Results of lab analysis, location B-11: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

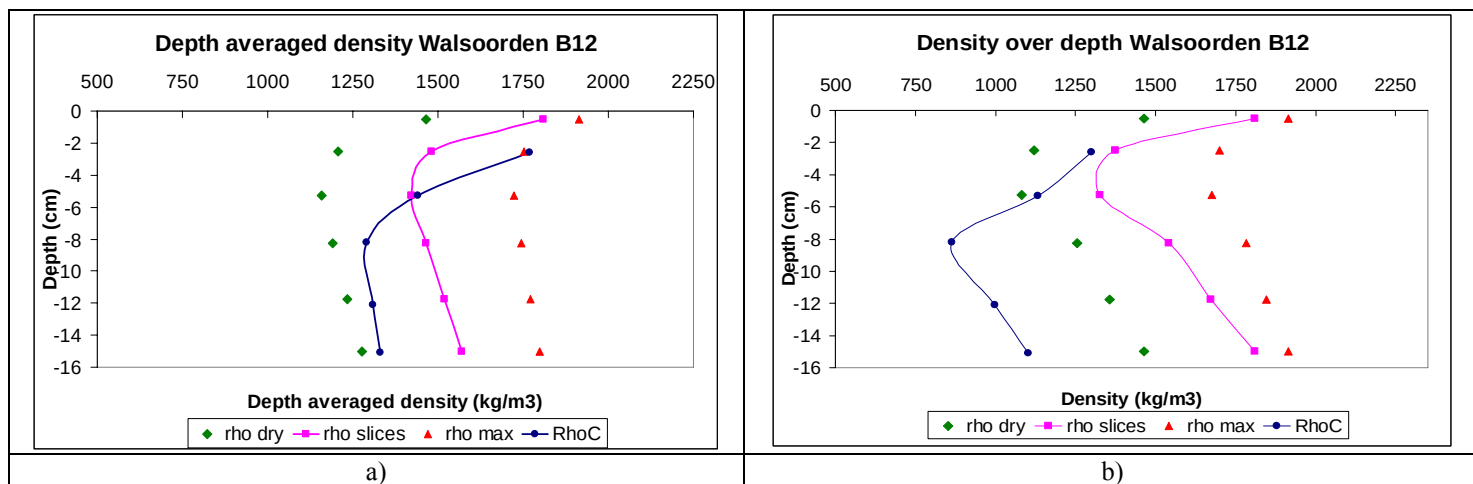


Figure 0.96: Density measurements of RhoC and lab slices, location B-12: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

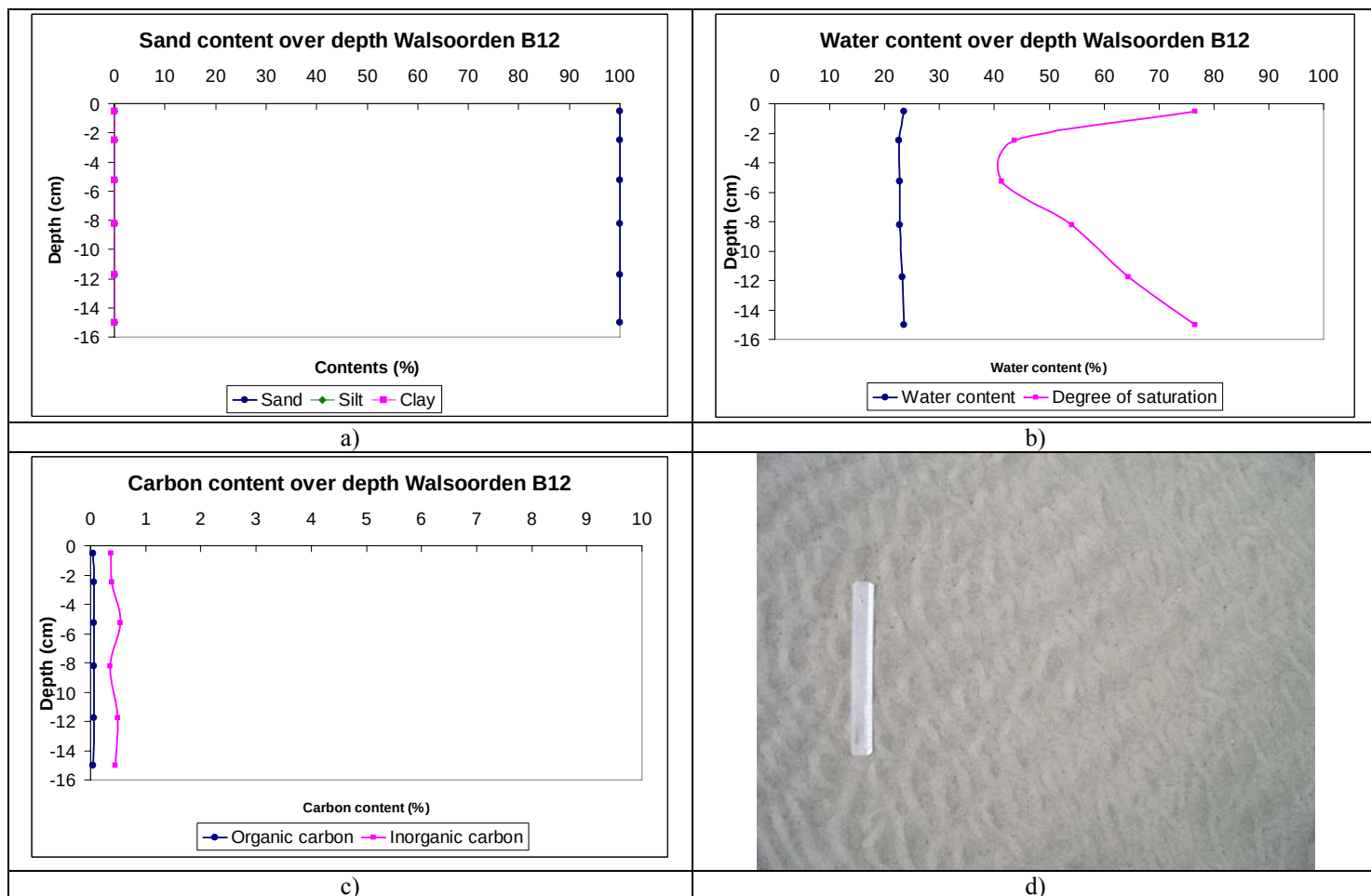


Figure 0.97: Results of lab analysis, location B-12: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

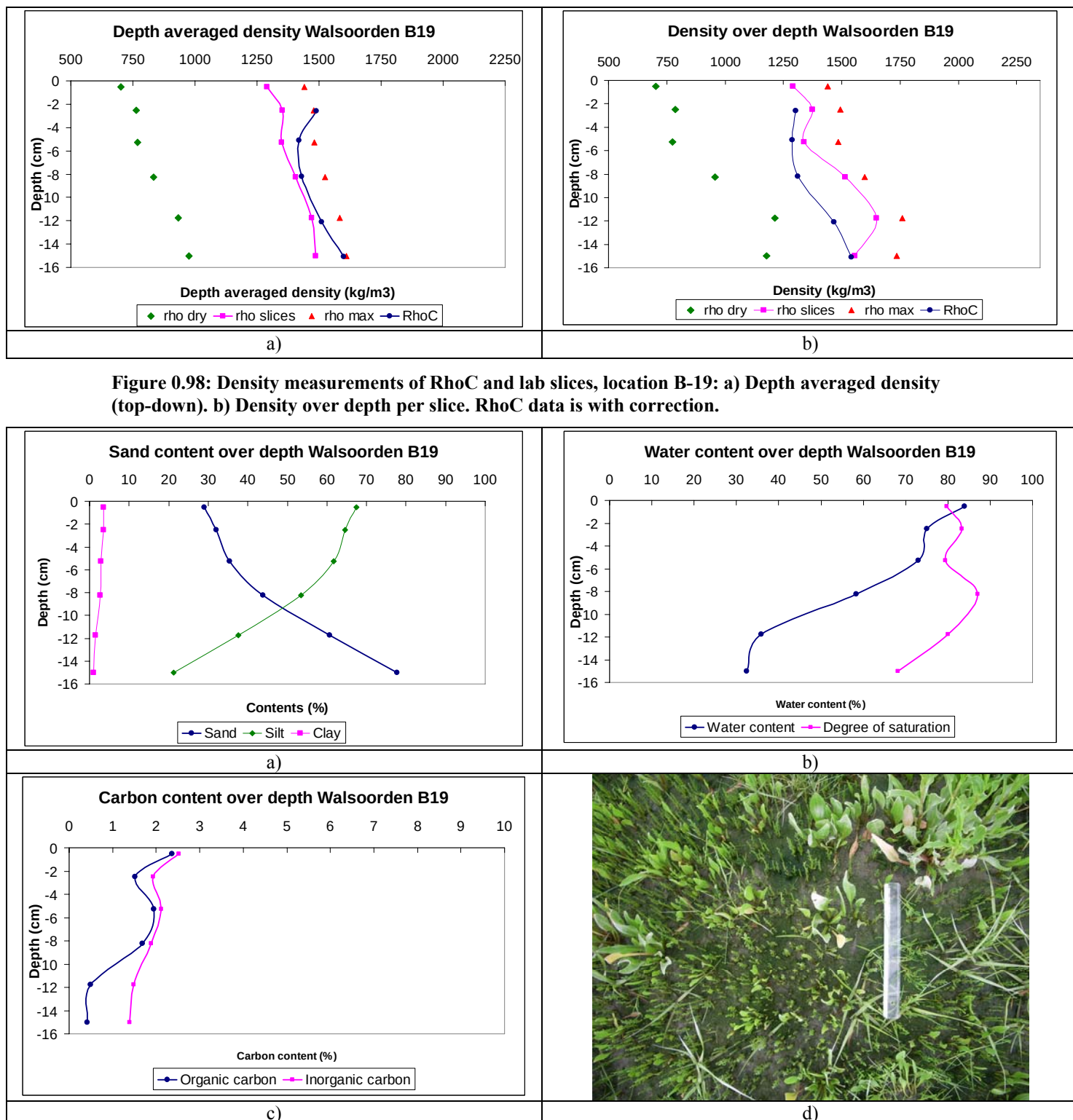


Figure 0.98: Density measurements of RhoC and lab slices, location B-19: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

Figure 0.99: Results of lab analysis, location B-19: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

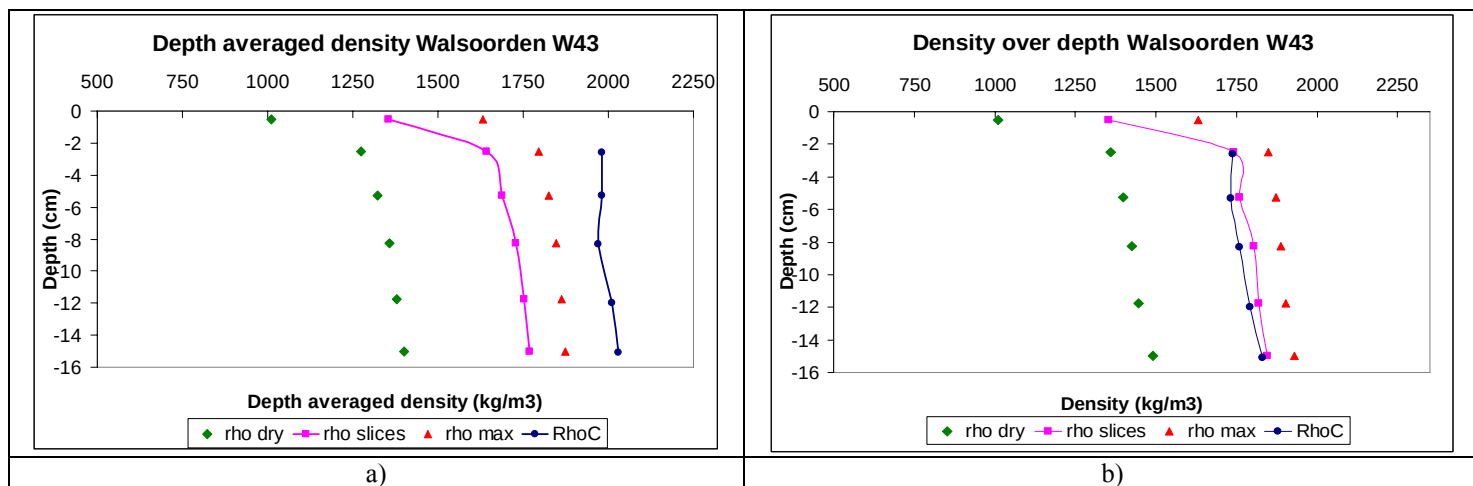


Figure 0.100: Density measurements of RhoC and lab slices, location W-43: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

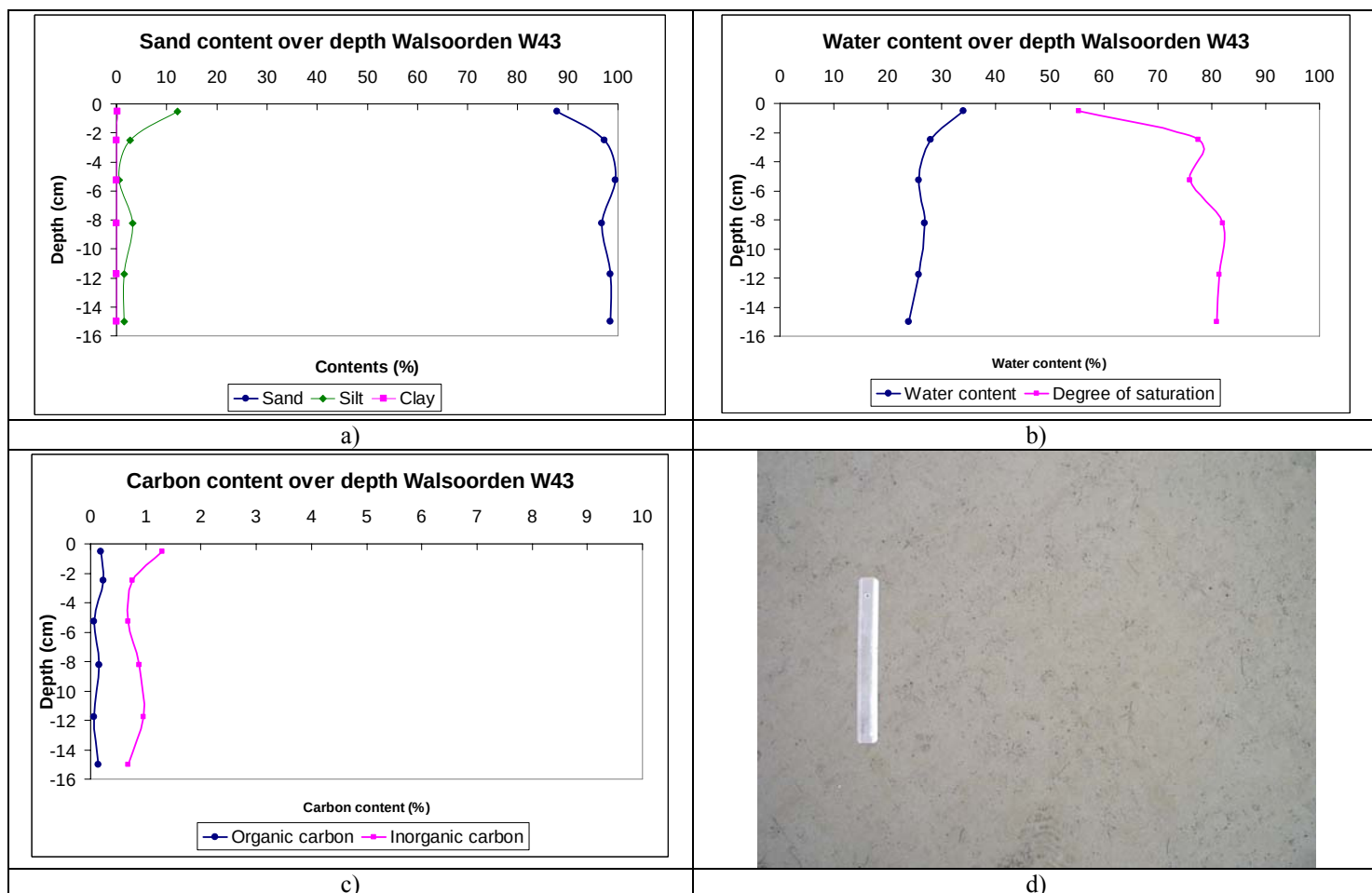


Figure 0.101: Results of lab analysis, location W-43: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

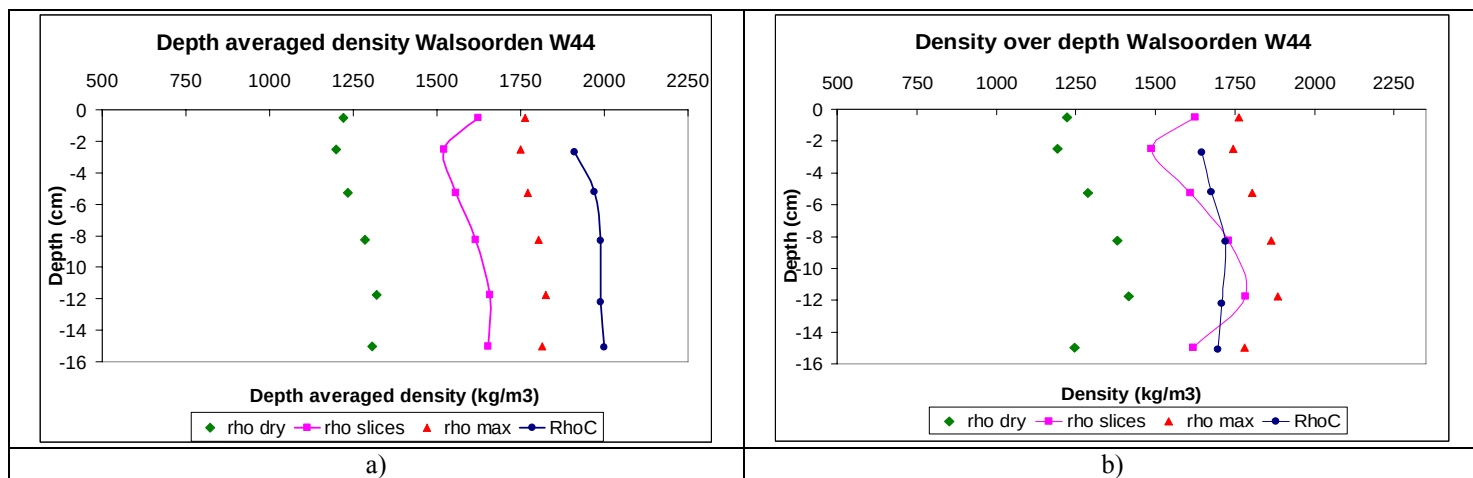


Figure 0.102: Density measurements of RhoC and lab slices, location W-44: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

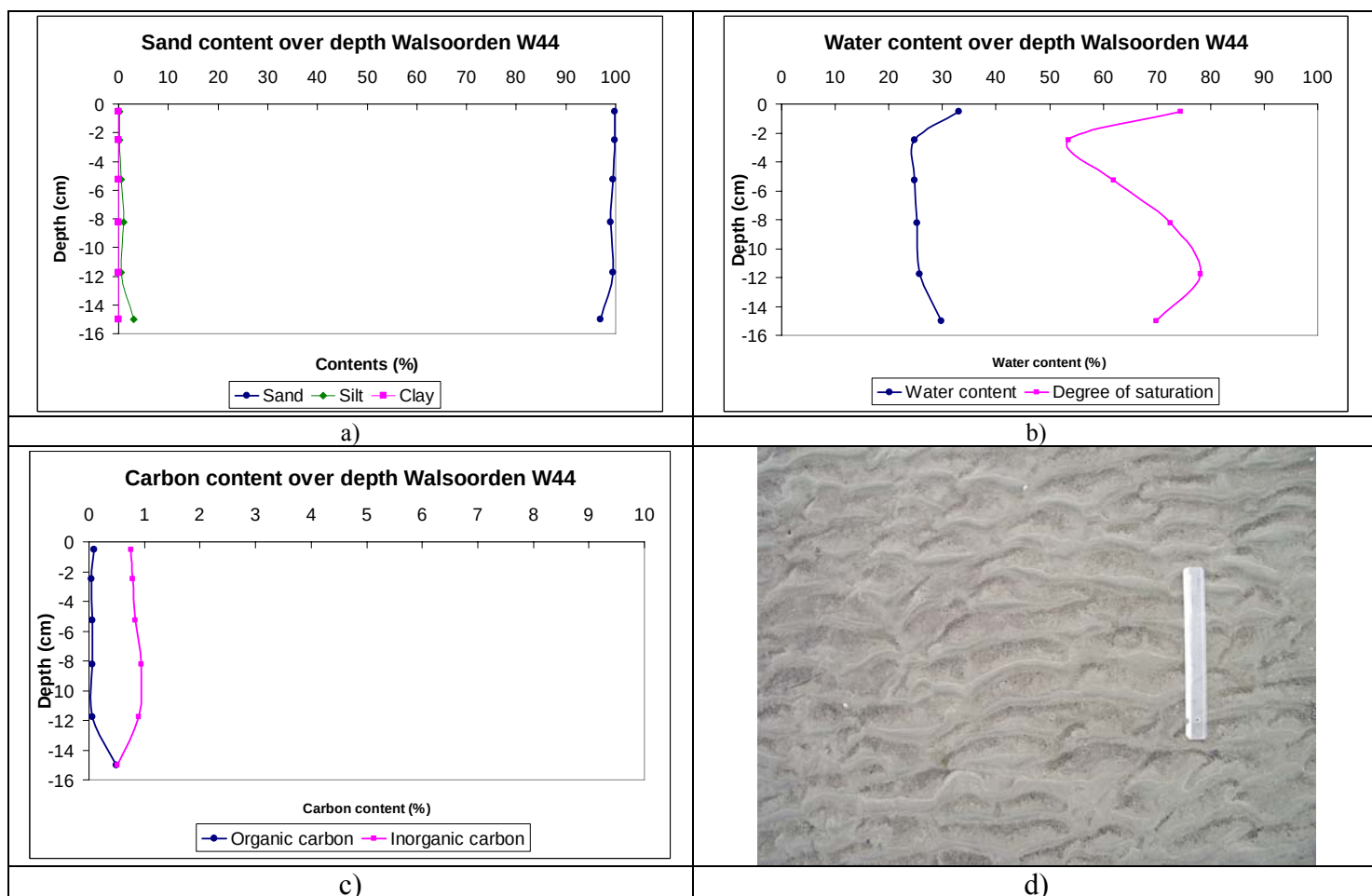
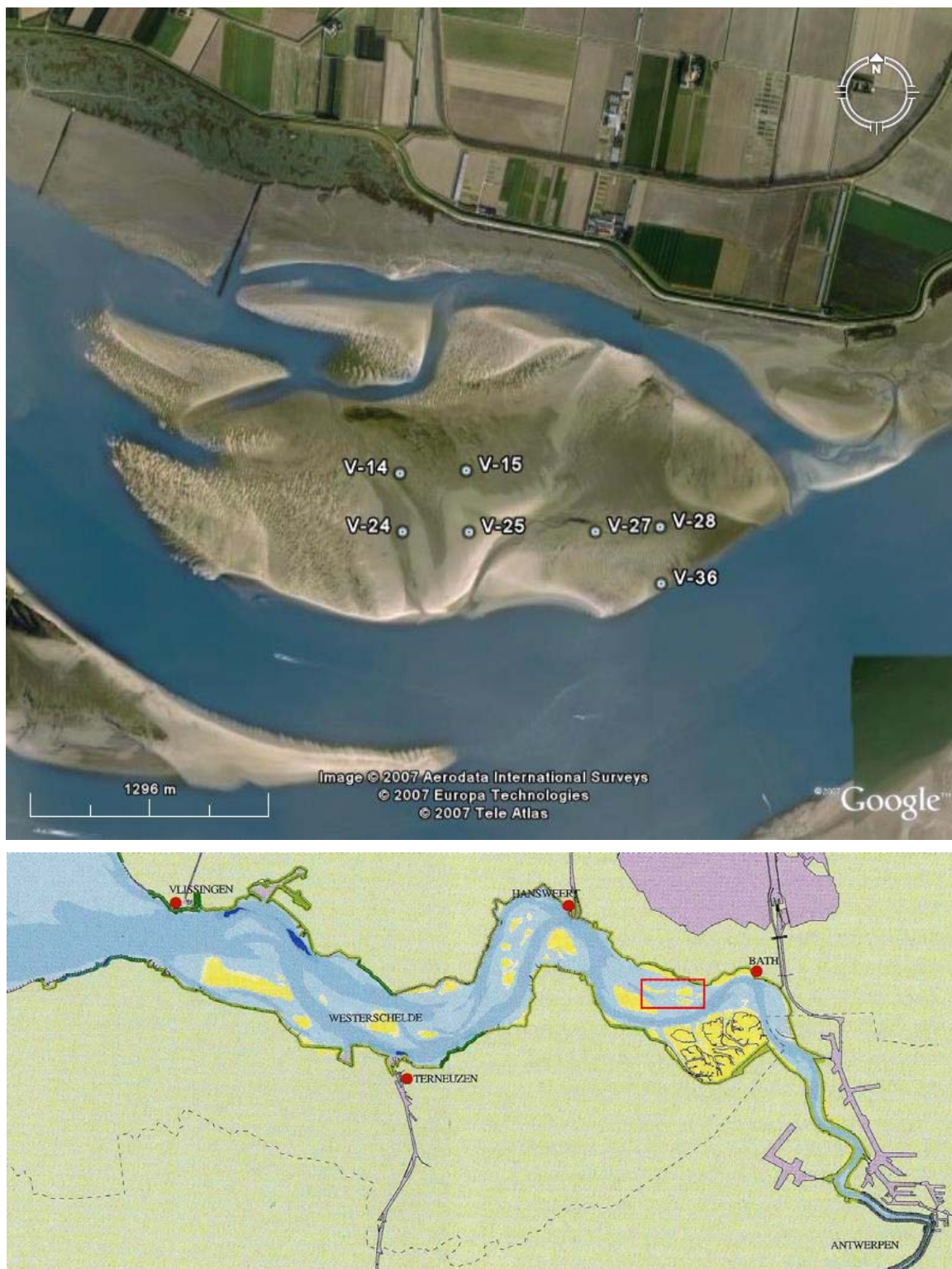


Figure 0.103: Results of lab analysis, location W-44: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

D.4 Data Plaat van Valkenisse

D.4.1 General overview



D.4.2 Radiometric measurements

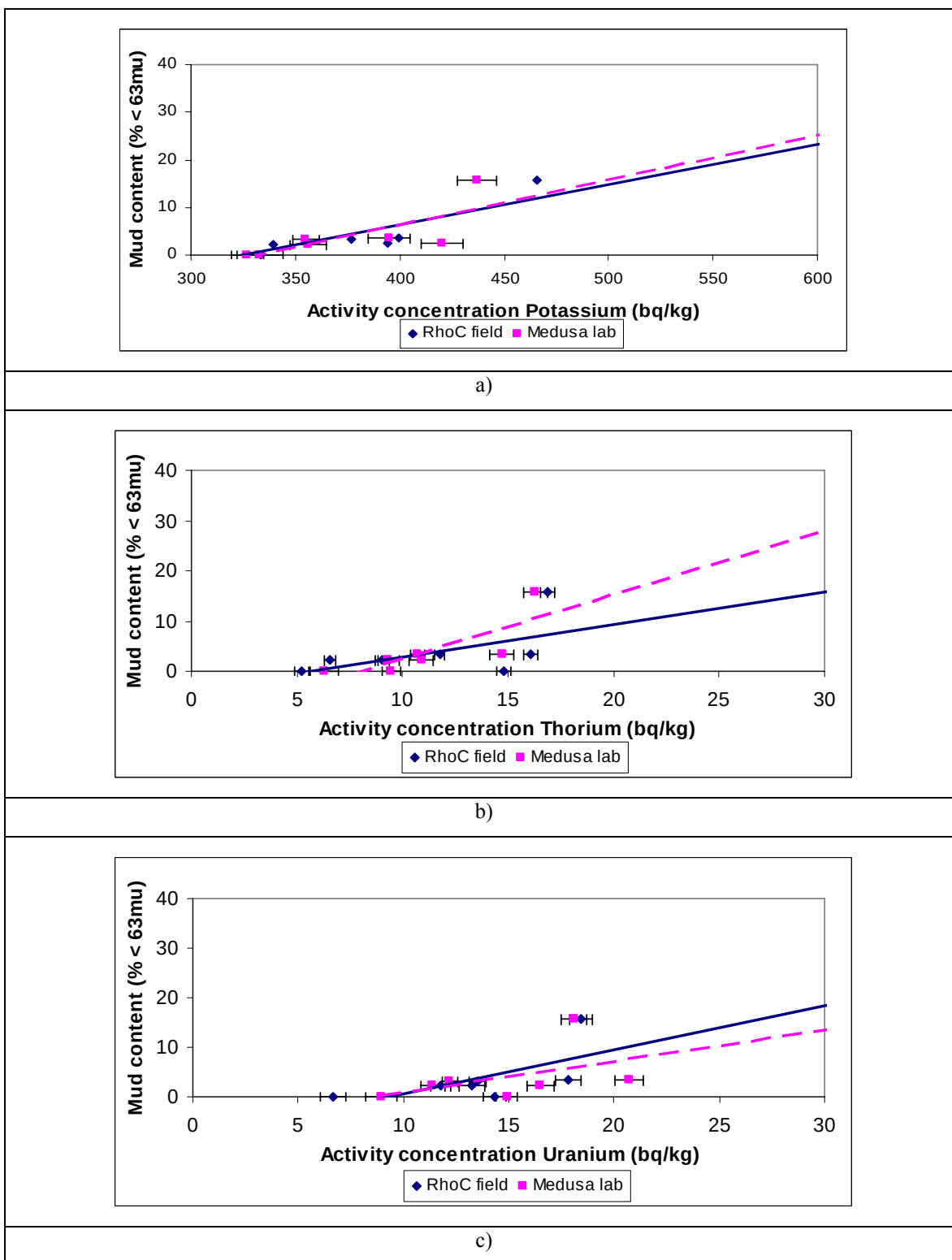


Figure 0.105: Radiometric measurements set out against mud content. Lines indicate linear best fit. a) Potassium activity concentrations. b) Thorium activity concentrations. c) Uranium activity concentrations.

D.4.3 Density measurements of RhoC and lab analysis

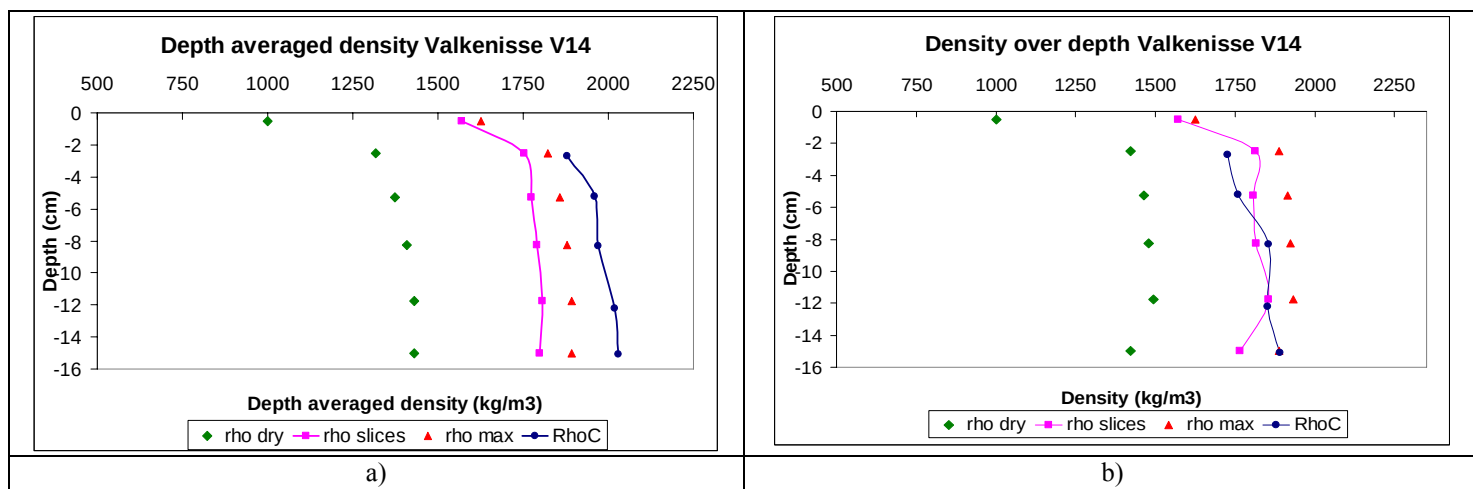


Figure 0.106: Density measurements of RhoC and lab slices, location V-14: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

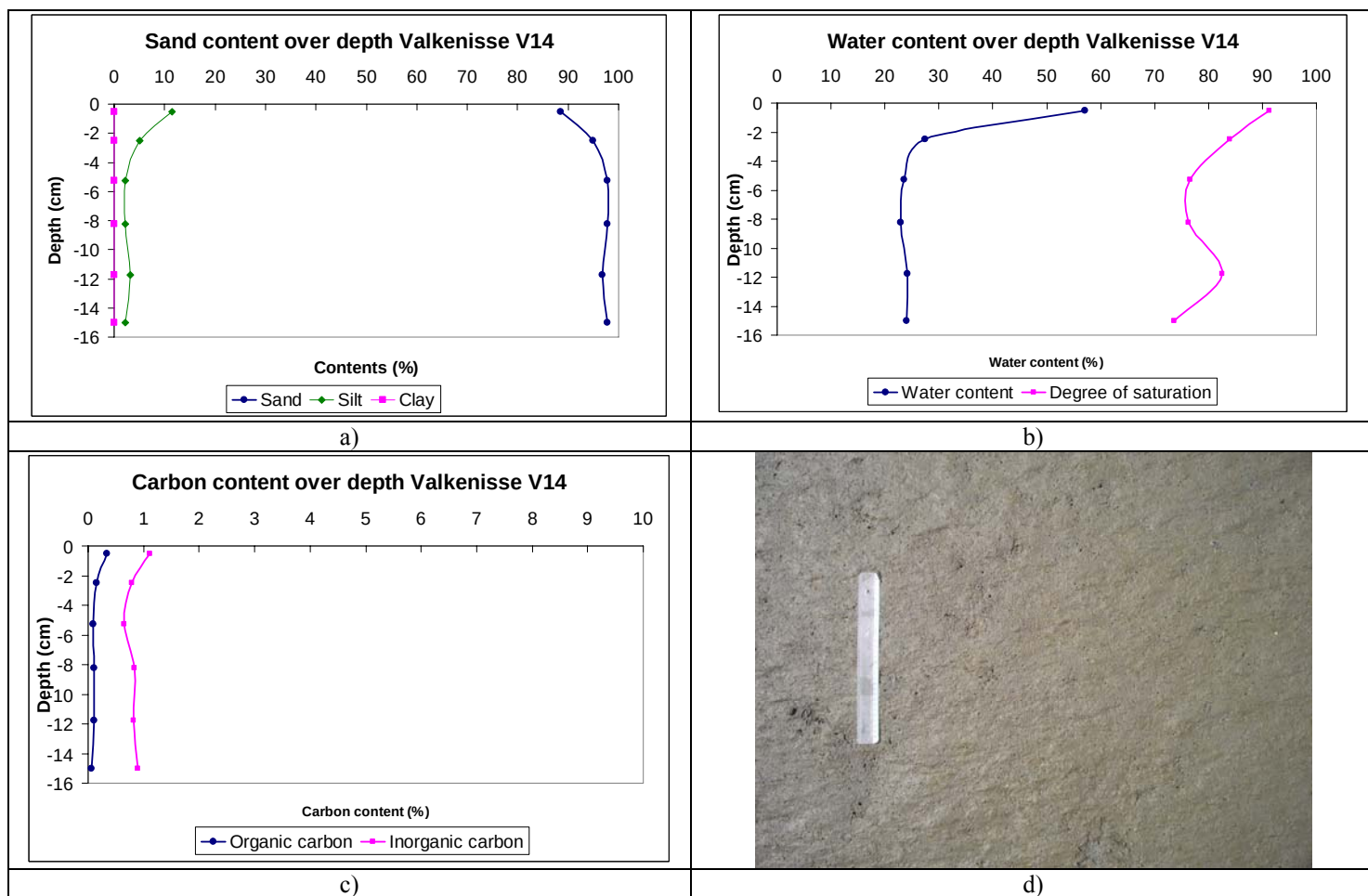


Figure 0.107: Results of lab analysis, location V-14: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

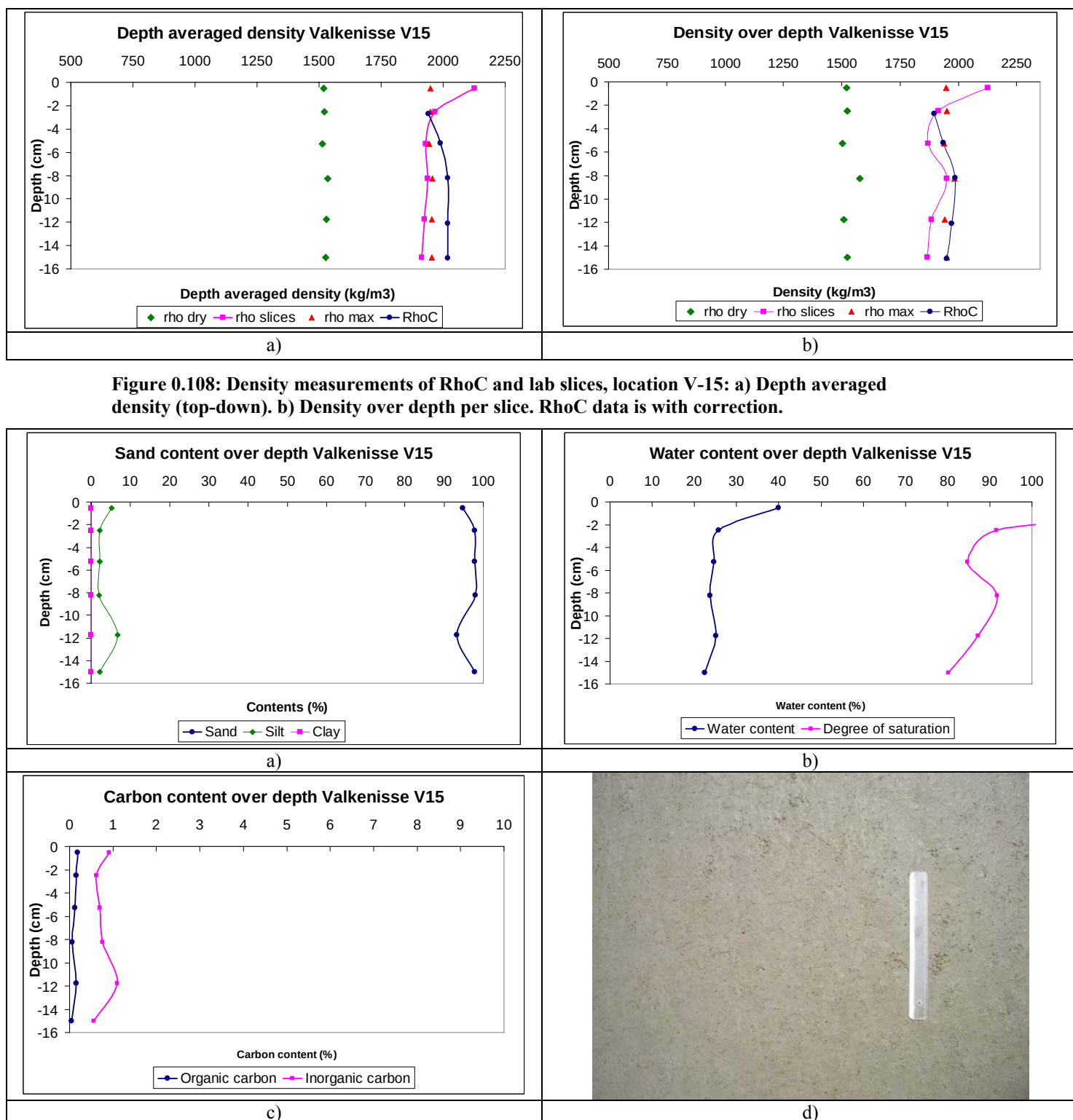


Figure 0.109: Results of lab analysis, location V-15: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

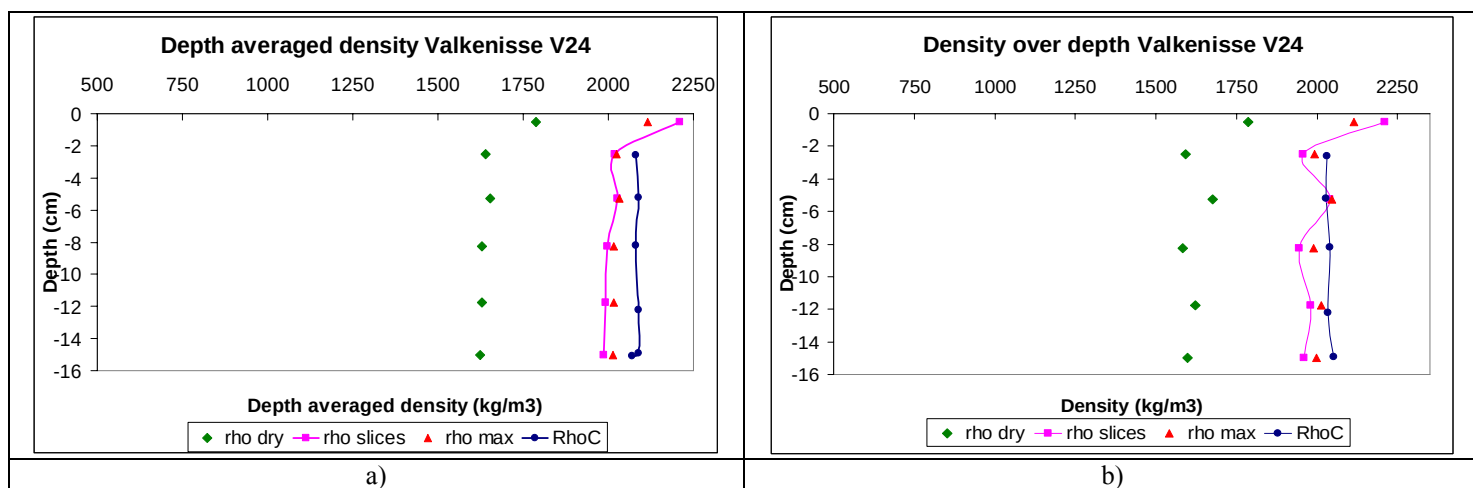


Figure 0.110: Density measurements of RhoC and lab slices, location V-24: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

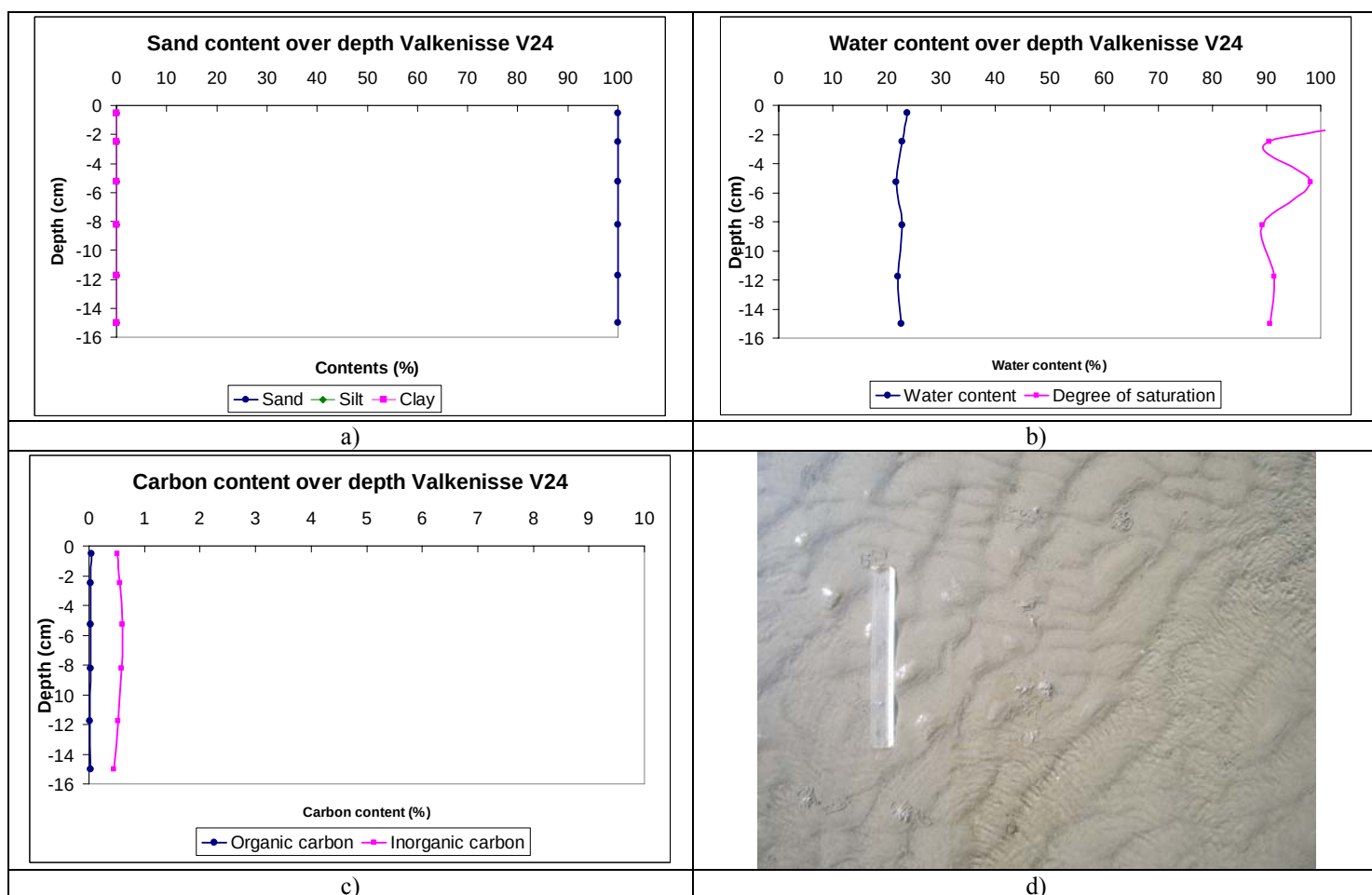


Figure 0.111: Results of lab analysis, location V-24: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

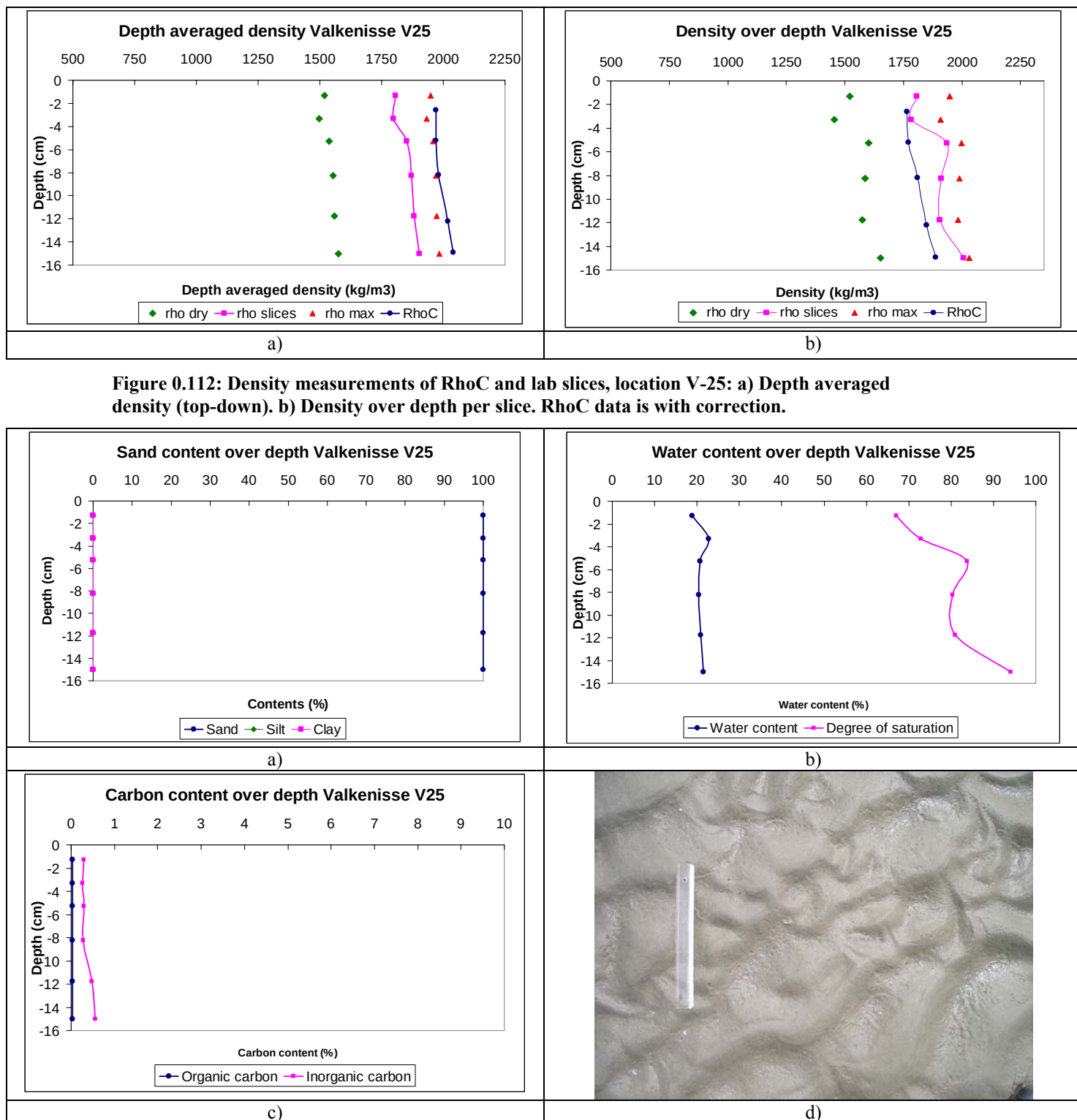


Figure 0.113: Results of lab analysis, location V-25: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

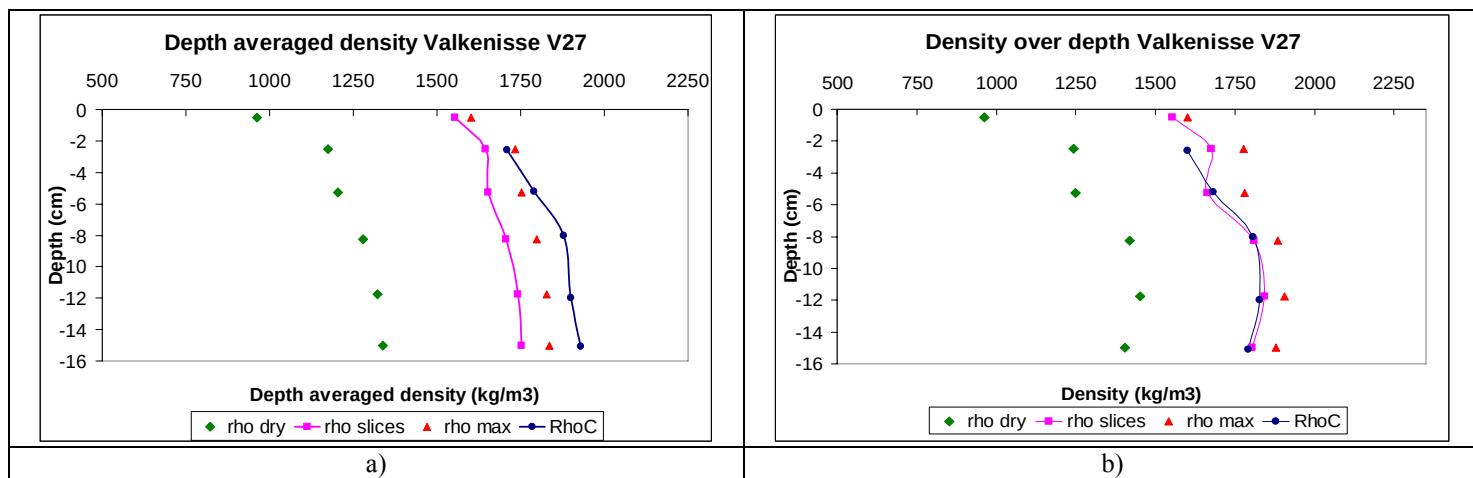


Figure 0.114: Density measurements of RhoC and lab slices, location V-27: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

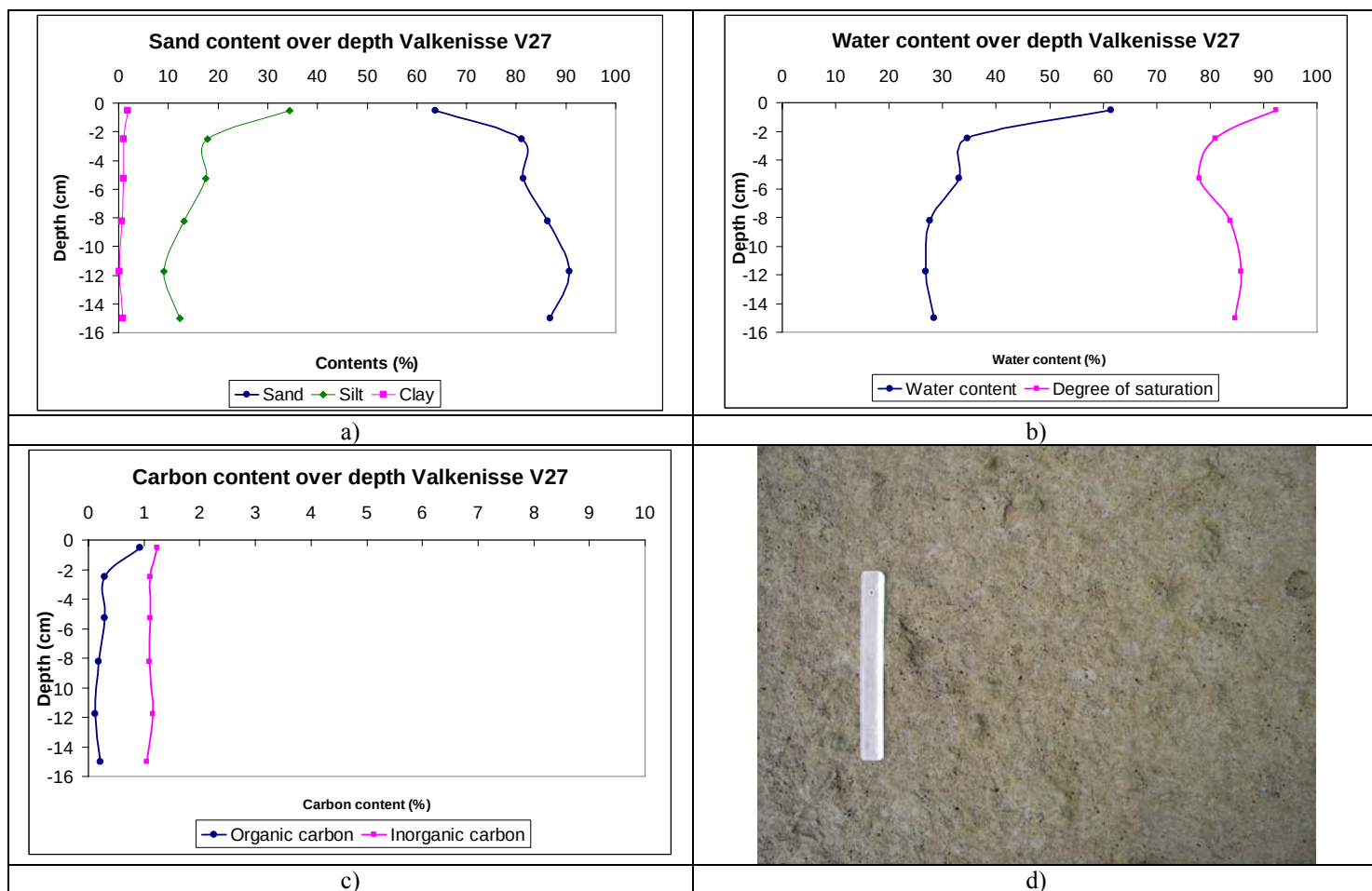


Figure 0.115: Results of lab analysis, location V-27: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

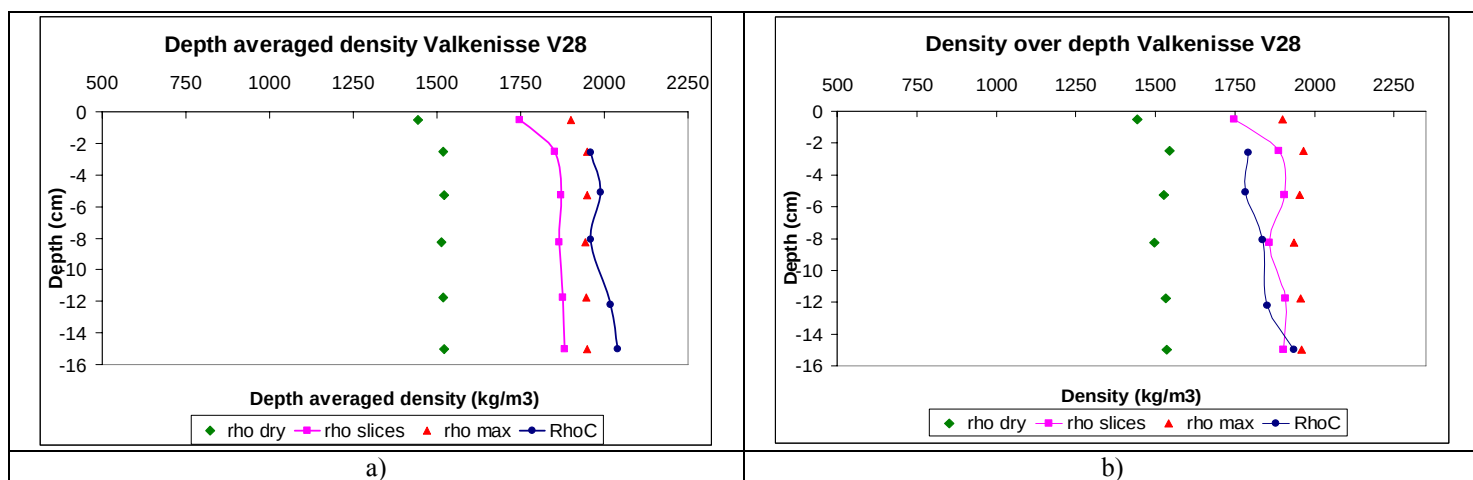


Figure 0.116: Density measurements of RhoC and lab slices, location V-28: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

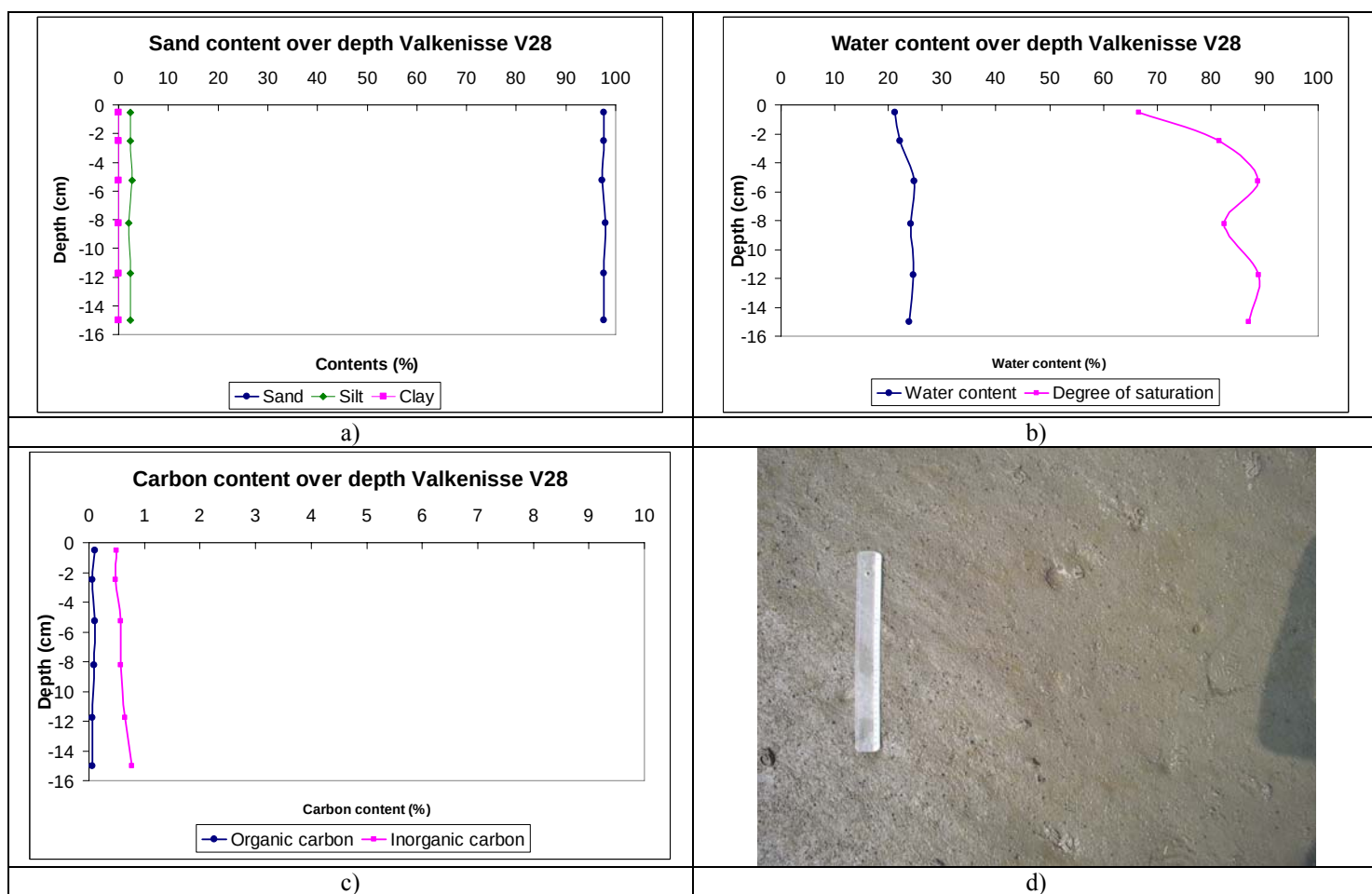


Figure 0.117: Results of lab analysis, location V-28: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

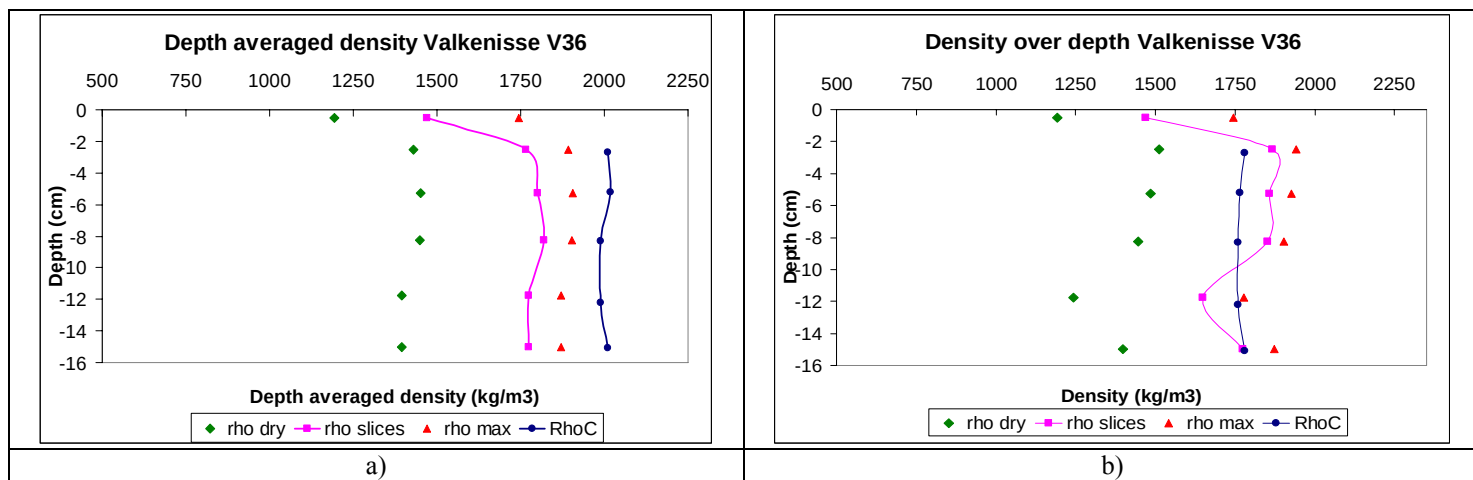


Figure 0.118: Density measurements of RhoC and lab slices, location V-36: a) Depth averaged density (top-down). b) Density over depth per slice. RhoC data is with correction.

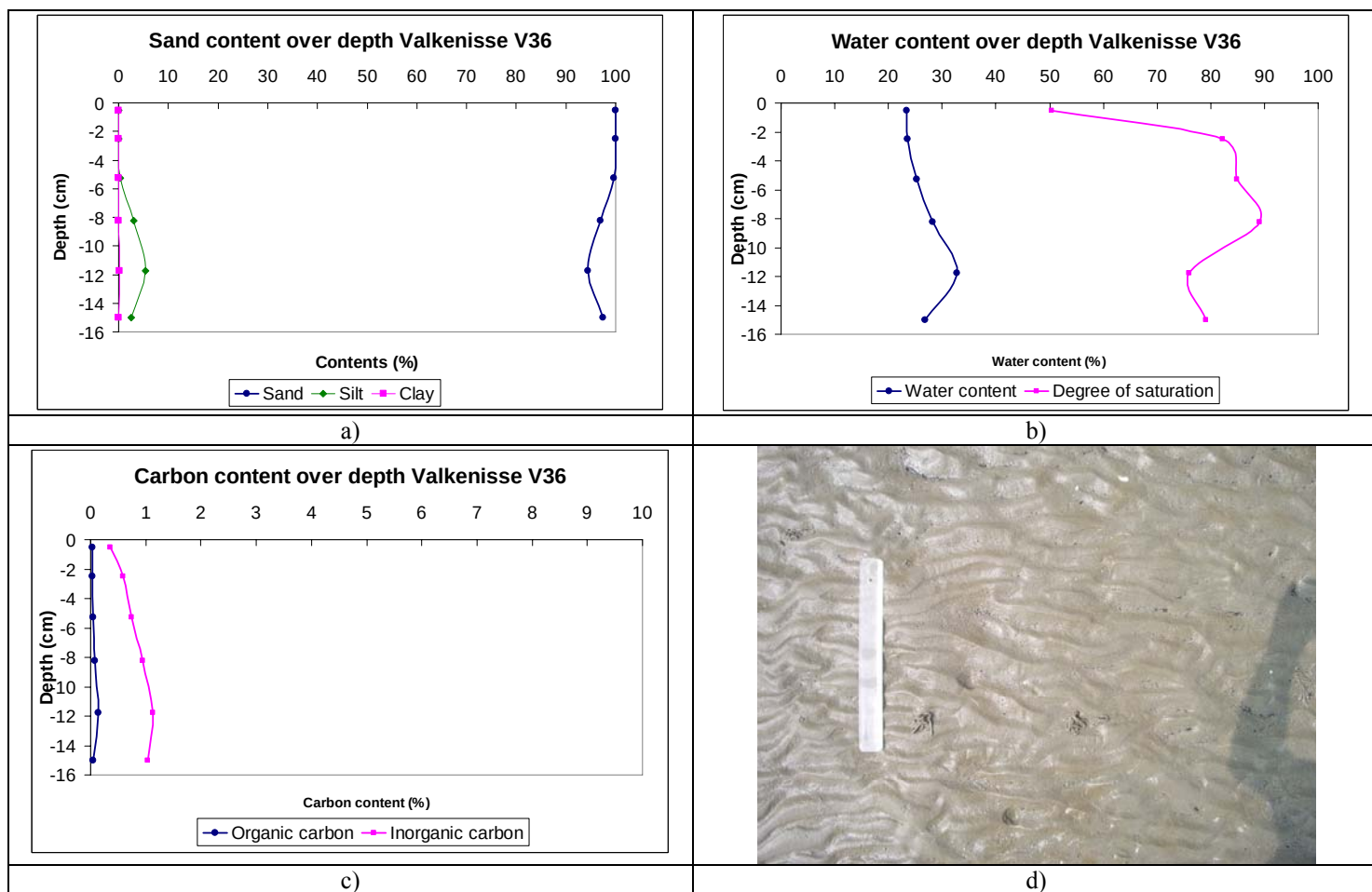


Figure 0.119: Results of lab analysis, location V-36: a) grain size analysis. b) water content and saturation. c) carbon content. d) Photograph of top layer (scale bar = 30cm).

Appendix E Fingerprints and computed mud contents

E.1 Saeftinghe

Lab fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	718.72	48.78	55.47
mud content = 0%	374.78	13.52	15.34

RhoC fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	679.06	48.58	62.92
mud content = 0%	381.47	14.25	9.17

Figure 0.120: Fingerprints derived from field and laboratory data for Saeftinghe flat. The values are the activity concentrations [Bq/kg] at the indicated mud contents.

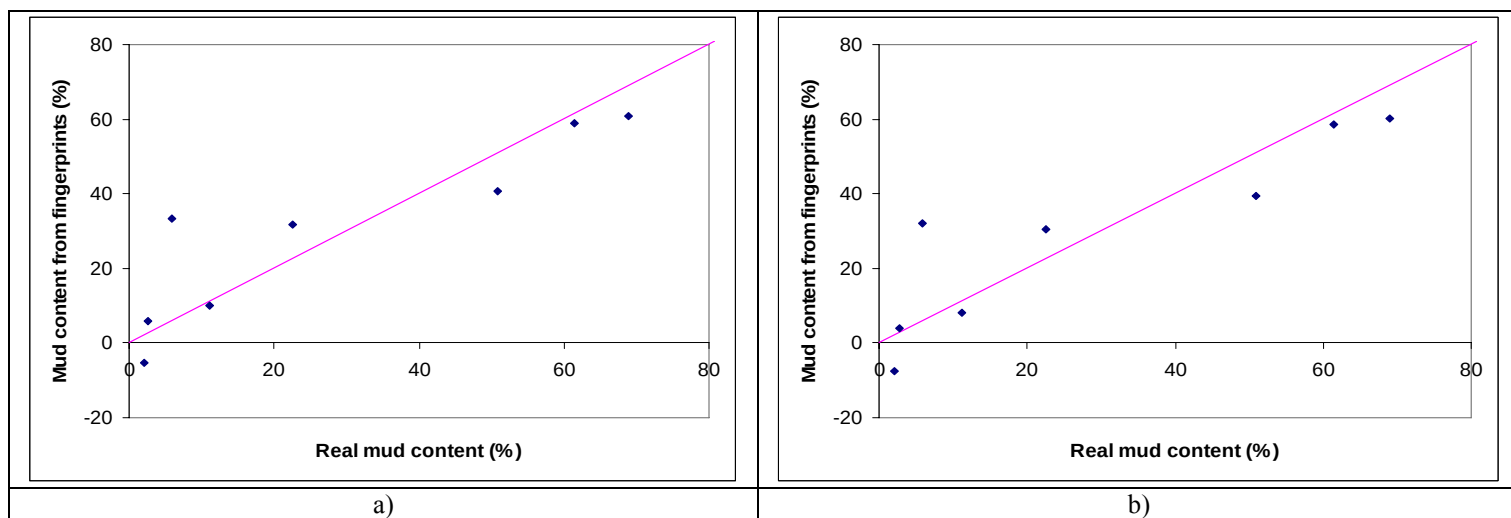


Figure 0.121: Mud contents according to activity concentrations for Saeftinghe. The continuous line indicates the line of perfect agreement. In a) the lab data is used. In b) the RhoC field data is used.

E.2 Molenplaat

Lab fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	1209.52	44.82	48.21
mud content = 0%	300.40	8.21	10.76

RhoC fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	894.61	43.06	53.68
mud content = 0%	351.63	8.44	6.28

Figure 0.122: Fingerprints derived from field and laboratory data for Molenplaat flat. The values are the activity concentrations [Bq/kg] at the indicated mud contents.

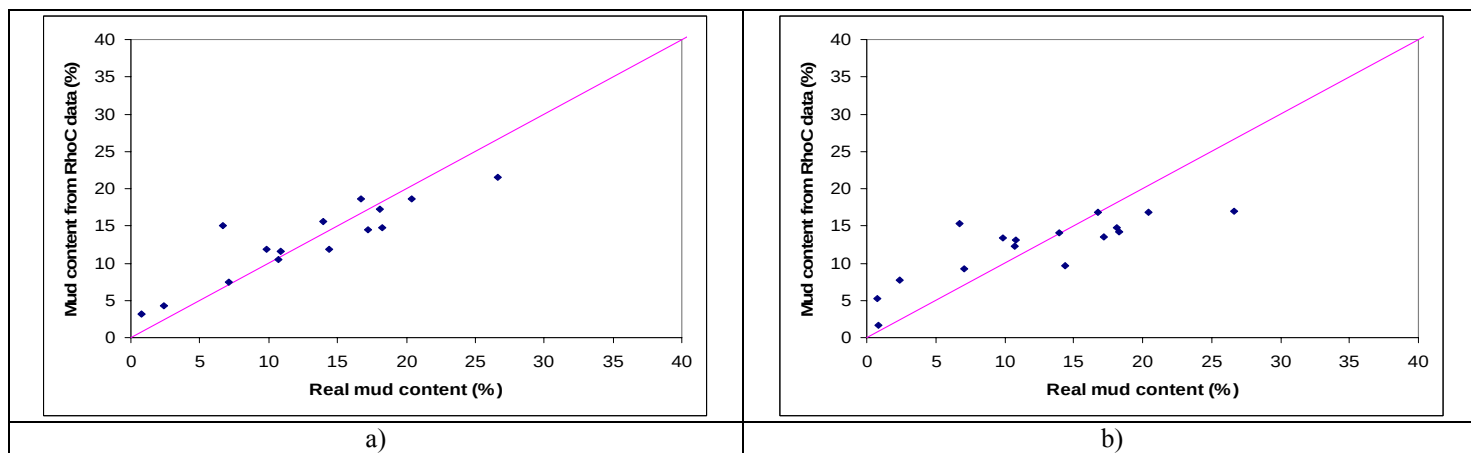


Figure 0.123: Mud contents according to activity concentrations for Molenplaat. The continuous line indicates the line of perfect agreement. In a) the lab data is used. In b) the RhoC field data is used.

E.3 Walsoorden

Lab fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	654.66	37.92	36.06
mud content = 0%	392.79	12.35	18.78

RhoC fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	558.04	38.66	35.15
mud content = 0%	427.94	13.34	16.68

Figure 0.124: Fingerprints derived from field and laboratory data for Walsoorden flat. The values are the activity concentrations [Bq/kg] at the indicated mud contents.

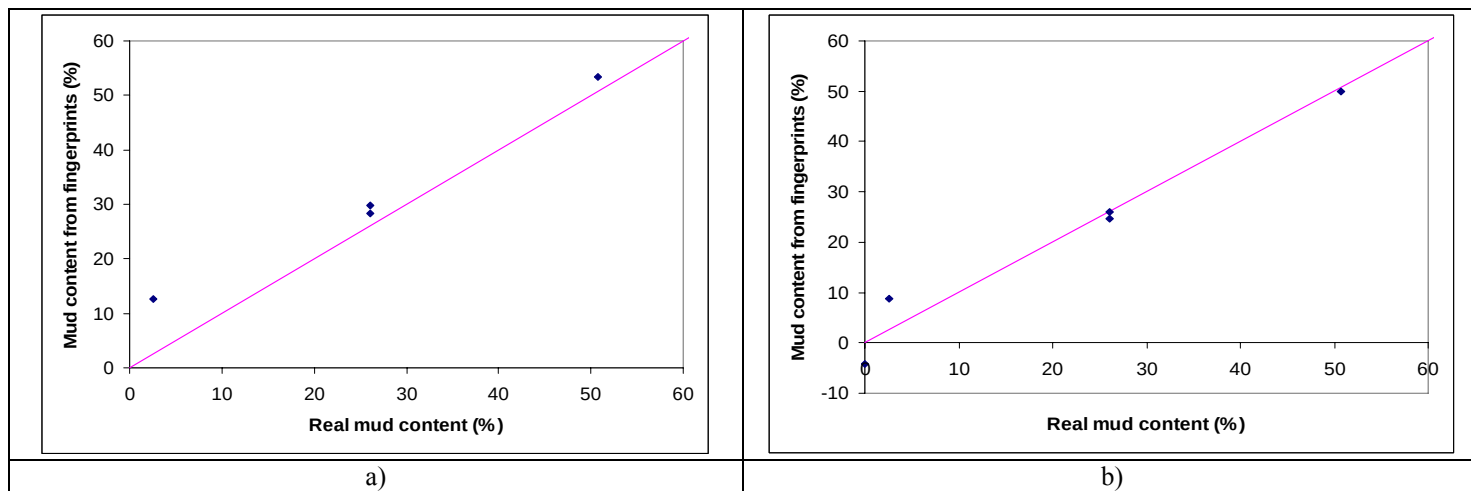


Figure 0.125: Mud contents according to activity concentrations for Walsoorden. The continuous line indicates the line of perfect agreement. In a) the lab data is used. In b) the RhoC field data is used.

E.4 Valkenisse

Lab fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	1393.85	86.44	168.58
mud content = 0%	333.62	8.06	8.48

RhoC fingerprint	^{40}K	^{232}Th	^{238}U
mud content = 100%	1511.31	160.47	121.86
mud content = 0%	326.16	5.47	9.32

Figure 0.126: Fingerprints derived from field and laboratory data for Valkenisse flat. The values are the activity concentrations [Bq/kg] at the indicated mud contents.

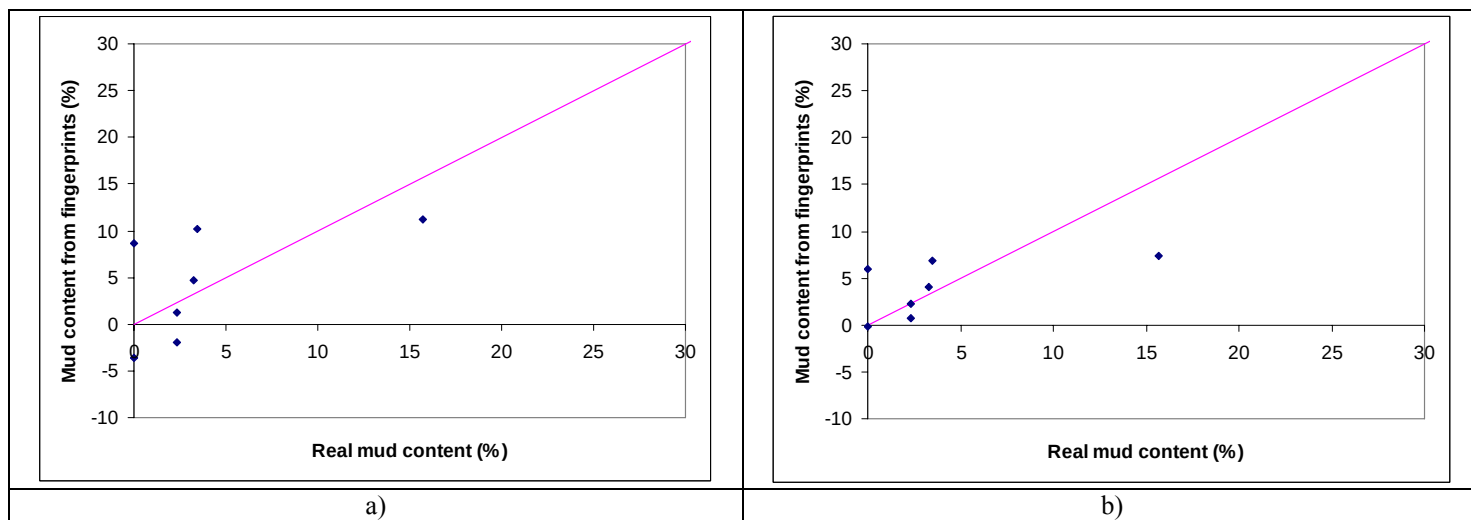


Figure 0.127: Mud contents according to activity concentrations for Valkenisse. The continuous line indicates the line of perfect agreement. In a) the lab data is used. In b) the RhoC field data is used.