MINISTRY OF AGRICULTURE
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Groundwater for the North of Namibia

Volume I a

Summary Report of
Activities of Phase I

Exploration of
Ohangwena II Aquifer
and Preliminary Isotope Study

Federal Ministry for Economic Cooperation and Development

Department of Water Affairs and Forestry

Cooperation Republic of Namibia Federal Republic of Germany

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

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PREFACE

Access to safe fresh water is the main limiting factor for the economic and social development of Namibia. Surface water is mainly restricted to 4 perennial rivers at the Northern and Southern borders. Therefore groundwater in Namibia, as it is true for most arid countries, plays a vital role for the supply of wide areas. As part of the technical co-operation between Namibia and Germany the Government of the Federal Republic of Germany provided financial and technical support through the BGR on the project “Groundwater for the North of Namibia.” Phase I commenced in January 2007 and was completed in the first half of 2010. Currently, Phase II is running until 2013.
The goal of this project is “to improve access to safe drinking water and the project objectives are to provide well founded information concerning the groundwater resources in the Cuvelai-Etosha Basin (CEB) as a basis for Integrated Water Resource Management (IWRM).” Practically, this means a transition process from ongoing investigation and the resulting outputs into applied day to day management of the groundwater resources. To achieve this, the often very specific hydrogeologic knowledge has to be translated to widely understood principles which serve the protection and sustainable use of the different groundwater bodies

It is exactly this approach that has been followed within this project and that will be perpetuated until a *Decision Support System (DSS)* has been developed that enables all decision makers and IWRM stakeholders with different educational background to simulate the effects of any possible planning decision on the water resources *before* implementation.

The first phase of the project however had to focus on the description of available resources in the intervention area CEB. Combining state of the art exploration technologies with intense use of classical hydrogeological field surveys, a formerly unknown deep- seated aquifer, the so called *Ohangwena II aquifer*, could be identified and described for the North Eastern part of the CEB as one of the main outputs. Being a transboundary aquifer system, this resource is shared with Angola in the North and holds a high potential for alternative supply and development of large areas in both countries. The report at hand describes the investigation activities and the derived results which will be later on contained in and exchanged through the *Groundwater Information System* GWIS which is under development in the current phase.
With a strong focus on capacity building additional staff will be enabled to independently plan and conduct groundwater investigations and link it to the management principles of IWRM. The impact of this project will thus enhance the Namibian Water sector in making the optimal use of all its water resources. By promoting the use of groundwater in combination with other resources it will prepare Namibia to adapt to the challenges brought to the water sector through the negative impacts of a changing climate. It will thereby help to secure the social, environmental and economic development of Namibia.

Martin Quinger, Project Manager

Report Series of Volume I

Executive Summary: Groundwater for the North of Namibia – Phase I

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Abbreviation

General Abbreviations

BGR	Federal Institute of Geosciences and Natural Resources of Germany
BMZ	German Federal Ministry for Economic Cooperation and Development
CEB	Cuvelai-Etosha Basin
DWA-BGR	Short form for the project “Groundwater for the North of Namibia” of the Federal Institute of Geosciences and Natural Resources of Germany (BGR) and the Department of Water Affairs and Forestry (DWAF)
DWAF	Department of Water Affairs and Forestry
GROWAS	Database to store groundwater relevant points at DWAF, Geohydrology
IAEA	International Atomic Energy Agency
MAWF	Ministry of Agriculture, Water and Forestry

Technical Abbreviations

3-D	Three dimensional
a	year
ASTER	Advanced Space borne Thermal Emission
CPS	Counts per second
DIN	Deutsche Industrie Norm (German Industrial Standard)
E	East
EDI	Exploration Drilling International
IWRM	Integrated Water Resources Management
m asl	Meter above sea level
m bgl	Meter below ground
N	North
n/a	Not available
Ohm*m	Physical unit for the resistivity of a material
S	South
SRTM	Shuttle Radar Topography Mission
TDS	Total dissolved solids
TEM	Transient electromagnetic method
UTM	Universal Trans Mercator
W	West
WGS 84	Geographic Coordinate System

Summary

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Key words: Namibia, Cuvelai-Etosha Basin, Groundwater Exploration, Geophysical Investigation, Hydraulic Tests, Isotopes

Prior to the first phase of the DWA-BGR Project, a desk study report was conducted to assess the state of knowledge about the Namibian part of the Cuvelai-Etosha Basin (CEB) and to identify actions to be taken to improve the quality of groundwater information. The key findings of this report were used to identify work items that were included in the first phase of the Technical Cooperation Project "Groundwater for the North of Namibia".

Besides several activities within this project (see also Part C of the report series), a large task resulted from the initial exploration and further investigation of the deep seated freshwater aquifers within the Ohangwena Region. This region forms part of the so-called geological structure, the "Cubango Megafan", a post Cretaceous fluvial sedimentary deposit. Its special sedimentary and geological genesis is closely linked to the salt-freshwater distribution of the current groundwater bodies. Hence, a sedimentological investigation parallel to the groundwater exploration was needed and a BGR research project was launched to supply the DWA-BGR Project with background information. The results of this project are also integrated into this summary but are included in a separate report (Report Part B).

A key investigation component of the project was a geophysical campaign that conducted measurements with the transient electromagnetic method (TEM), a non-invasive method to measure electrical resistivity of the subsurface. With results of the TEM, delineation of high and low resistivity layers was interpreted, helping to differentiate between salt or freshwater aquifers. Part C of this report series includes a detailed report of the TEM exploration. Following the TEM measurements, several drilling campaigns were conducted in the most promising areas. Three-dimensional modeling of the TEM results and a lab investigation of drill samples accompanied the field investigation.

Groundwater is utilized within rural areas of the Cuvelai-Etosha basin, where the canal- and pipeline network does not reach the population. However the knowledge of the

subsurface distribution of groundwater bodies is very limited and the current knowledge base is insufficient to quantify the groundwater reservoirs. The large geophysical exploration campaign conducted from March-August 2008 included the measurement of subsurface electrical resistivity at 440 locations within the northern and north-western parts of the Cuvelai-Etosha basin. The measurements that provided information about the deep seated fresh groundwater systems were calibrated utilizing an existing deep borehole that was providing water for a School. The measurements helped to identify a 500 km^2 large area where fresh groundwater in a depth of 200-300 m was indicated. The measurements provide useful and relatively cheap and relevant information of the subsurface. These profiles were used to develop a software-based three dimensional distribution model of fresh water resources and to visualize its potential distribution. Investigative drilling was needed to confirm these results.

A total of three drilling campaigns and two geophysical borehole logging campaigns were conducted during the first Phase to verify the results from the TEM geophysical investigation. All boreholes that were covered within the Ohangwena area were positively verified according to the nearby TEM measurements. In addition to the rotary-mud boreholes which were drilled to set up a monitoring system whilst one was to be used as a trial production borehole, two cored boreholes were also drilled. The core sample-material of these boreholes was subjected to intensive research with the view of gaining a better understanding of the geology of the Cuvelai-Etosha basin. The laboratory tests aimed at shedding light on the characteristics of groundwater-bearing aquifers and the groundwater-exclusion aquitard zones. The determination of hydraulic parameters – utilizing undisturbed cores – shows a distinct separation of the aquifers and aquitards. The mineralogical investigation shows that the aquitards contain a smectite gel (from a smectite clay mineral). This gel-like material is unique and is to date not fully understood and investigations are ongoing. The first samples for a water quality investigation were also collected (Report Part B).

1 Introduction

In January 2007 the project “Groundwater for the North of Namibia” commenced as a 3 year project in the framework of the German-Namibian Technical Cooperation. This project is carried out by the Department of Water Affairs and Forestry (DWAF) in co-operation with the Federal Institute of Geosciences and Natural Resources of Germany (BGR) and it is referred to as the DWA-BGR Project within this text. Funding agencies include the German Federal Ministry for Economic Cooperation and Development (BMZ) and the Ministry of Agriculture, Water and Forestry (MAWF). The main objective of the project is that: The Namibian institutions of the water sector use well founded information concerning the groundwater resources in the Cuvelai-Etosha Basin as a basis for Integrated Water Resources Management (IWRM). Therefore the project activities undertaken are to provide reliable data about the quantity and quality of groundwater resources in the Cuvelai-Etosha Basin (CEB). Furthermore this information has to be presented to relevant planners and stakeholders in a way that allows them to use it appropriately. As an overall goal the project will contribute to enhanced water supply for the population living in the CEB.

This report consists of four major parts:

- Part A concentrates on a summary of activities that concern the exploration of new deep groundwater resources within the CEB and a first effort to specify isotope characteristics of surface and groundwater sources.
- Part B comprises mainly laboratory work that has been conducted within a joint research project of BGR to further investigate sedimentological characteristics of samples derived by drilling activities as documented in Part A. Furthermore, a sedimentological characterization on behalf of identifying major hydrostratigraphic systems is conducted within this research project.
- Part C is the report about the hydrocencus campaign of phase I,
- Part D is a more detailed report of the TEM sounding campaign.

An extensive volume of appendix documents covering work by consultants as well as the results of the activities is also included.

Prior to the first phase of the DWA-BGR Project, a desk study report was conducted to assess the state of knowledge about the Namibian part of the Cuvelai-Etosha Basin (CEB) and to identify actions to be taken to improve the quality of groundwater information (Bittner and Kleczar, 2006). The key findings of this report that is appended in Appendix 1 were used to identify work items for the first phase in a planning workshop. One outcome was the accomplishment of a hydrocencus of boreholes of the CEB to improve information of the database GROWAS (Report Part C, (Lohe and Zauter, 2012) . A second outcome was a campaign for isotope studies that has been integrated within this report (Part A). A third outcome was the exploration and initial investigation of the deep seated freshwater aquifers within the Ohangwena Region. This region forms part of the so called geological structure “Cubango Megafan”, a post Cretaceous fluvial sedimentary deposit. Its special sedimentary and geological genesis is closely linked to the salt-freshwater distribution of the current groundwater bodies.

Figure 1: The extension of Kalahari sediments (orange) of the Cuvelai-Etosha Basin within southern Africa.

General introductions to the CEB, e.g. focusing on climate, geographic or socio-economic topics are readily available (Bittner and Kleczar, 2006; Christelis and Struckmeier, 2001; Cunningham et al., 1992; Mendelsohn et al., 2000). There are reports of the state of the art of the geological settings of the Cuvelai-Etosha Basin (Mendelsohn et al., 2000; Miller, 2008b, 2010; Miller, 1997). However in many studies a focus is set on the southern calcrete formations of the CEB and the development of the Etosha Pan (Buch, 1992, 1996; Hipondoka, 2005; Hipondoka, 2006; Miller, 2008b). The Cubango Megafan and the sandy parts of the Kalahari formation were not in focus of detailed investigation so far, see also maps in Miller (2008, page 24-4) that give an overview of existing deep drillings in the CEB which spare the Cubango Megafan.

Chapter 2 of this report gives an overview of the geological setting of the Kalahari sediments with a focus on its sandy member and hence on the Cubango Megafan. A key investigation component of the project was a geophysical survey using the transient electromagnetic method (TEM), a method to measure electrical resistivity of the subsurface. Results of this campaign are summarized in **Chapter 3**. With results of the TEM measurements, a delineation of high and low resistivity layers was possible, helping to identify either salt or freshwater aquifers. This was conducted with the support of a 3-dimensional subsurface model which is discussed in **Chapter 4**. Following the TEM measurements and the delineation of deep seated fresh-water zones, three drilling campaigns were conducted in the most interesting target areas. Significant amounts of investigation and research were concentrated on these boreholes, some of it well documented in reports (Kaufhold and Dohrmann, 2009a, b, 2010; Walzer, 2010; Wyk, 2009a, 2010), but also within laboratory results and short documentations. **Chapter 5** comprises the setting and general results of the three drilling campaigns and two geophysical borehole logging campaigns as well as one geodetic survey. **Chapter 6** focuses on aquifer parameters derived from the above-mentioned campaigns and laboratory work. Finally, **Chapter 7** concludes this report with results of a basin-wide isotopic campaign, conducted together with the IAEA. A short conclusion in **Chapter 8** serves as a cross reference to the discussion in Part B that includes the laboratory results of sample investigations. In Table 1, an overview of all activities and additional reports with the completion date of the Ohangwena II aquifer is given. Some of the reports are also integrated into this summary report.

Table 1: Overview of activities, results and reports that were conducted in Phase I.

Type	**Description**	**Time conducted**	**Location of data or report**	**Data Format**
Desk Study Report: Cuvelai-Etosha Groundwater Investigation	Extended report of general geographical and geological situation of the CEB	2006	Appendix 1	Pdf
TEM soundings	Pictures of TEM soundings and Report Part C	10-2008	Part C Appendix 2	Pdf WMF
Drilling campaign I: 201045, 201046, 201047				
General Information	Drilling report for three deep boreholes in Cuvelai-Etosha Basin, including lithology, hydraulic tests, chemistry, well structure Detailed lithology description (Miller)	03-2009	Part A Appendix 1 Appendix 3	Pdf Excel Excel
Hydrochemistry	Windhoek Lab Excel Sheets	05-2009	Appendix 1 Appendix 8	Excel
Mineralogy and Sedimentology	Analysis of lowest clay sample of 201045 Grain size distribution, XRF, XRD and Heavy Minerals of crushed samples	07-2009 06-2009 12-2010	Part B Appendix 4	Pdf Excel
Micropaleontology	Short report for diatoms of lowest clay sample (Fenner)	06-2009	Part B	Pdf
Drilling campaign II: Core drills 201216 and 201217				
General Information	Drilling report: included in thesis of Walzer) Detailed lithology description (Miller) Litholog and corephotos (Gersdorf)	03-2010 04-2010	Part B Appendix 1 Appendix 4	Pdf Excel Pdf
Mineralogy etc.	Full analysis of core samples 201216, 201217 (Walzer, Kaufhold et al.: BGR Lab)	01-2010 05-2010	Part B	Pdf
Micropalaeontology	report: Silt fraction analysis for minerals, fossils (Fenner)	04-2010	Part B	Pdf
Hydraulics	Core sample hydraulic investigation (included in thesis of Walzer)	03-2010	Part A Appendix 1	Pdf
Drilling campaign III: 201345-201348				
General Information	Drilling report including lithology, hydraulic tests, chemistry, well structure (van Wyk)	03-2010	Part A Appendix 1	Pdf Excel
Hydrochemistry	Windhoek Lab Excel Sheets (Rügheimer)	04-2010	Part A Appendix 1 Appendix 8	Excel
Geophysical Campaigns				
Campaign I: Terratec	Geophysical Logging in the CEB (report: Terratec, Symons)	09-2009	Part A Appendix 6	Pdf WCL
Campaign II: Poseidon	Logging was conducted but no report delivered, raw data available	03-2010	Part A Appendix 7	WCL
Additional activities				
3D Model Ohangwhena II	3D Model Ohangwhena II based on TEM soundings (Zeilfelder)	06-2009	Part A	Pdf
Isotope Study	Tritium, H-2, O-18, C-14 (Nick, Lindenmaier)	12-2009	Part A	Pdf
Groundwater recharge	Master Thesis on Groundwater recharge (Starke, in German)	04-2010	Appendix 1	Pdf

2 Summary of the Geology of the Cuvelai-Etosha Basin

By André Walzer and Falk Lindenmaier

The geology of the Namibian part of Cuvelai-Etosha basin has been most extensively described by Miller (2008) and Miller (2010), and most of the information comprised here is from these sources. An overview of the geology of the CEB catchment area that comprises the CEB and parts of Kunene and Cubango Rivers is shown in Figure 2. With regard to development and efforts made in the first Phase of the DWA-BGR Project on the Ohangwena II Aquifer, the report will focus on the north-eastern region of the CEB, and hence lies within the Ohangwena Region.

As the onset of the Kalahari sedimentation is uncertain, it was set at the end of the Cretaceous or the beginning of the Tertiary. It is marked that degradation and active incision gradually gave way to aggradation and deposition as the older Karoo rocks were exposed and subject to erosion and weathering before sedimentation resumed. Hence, the base of Kalahari probably is heavily incised with bedrock of Karoo or older formations which may consist of more than 50 m of weathered surface rock in some areas (Miller, 2008: p 24-5). The depositional environment of the CEB was dominated by calcrete development in the southern and western margins. In the north, the Kunene and Cubango-Okavango river systems dominated a clastic sedimentary environment.

For the past 70 Ma years, the Owambo Basin has been filling up with sand, silt and clay that was eroded from higher grounds surrounding the area. For sediments within the Ohangwena Region, mountains in central Angola contributed to the sedimentary material (Figure 2) but also a considerable amount of Kalahari sediments might have been reworked. Cycles of climate change with wet and dry periods followed each other (Mendelsohn et al., 2000). The Etosha Lake must have had different extensions and water depths or might have been dry. Rivers drained into the basin bringing sedimentary deposits with them, called the Ombalantu, Beiseb, Olukonda and Andoni formations (Miller, 2008a). Aeolian components are also found. Ombalantu represents the base and Andoni the top of the named formations. These four formations form the youngest unit of the basin and are part of the Kalahari Sequence. The following lithological and stratigraphical descriptions of the Kalahari formations are based on the work of Miller (Miller, 2008b, 2010; Miller, 1997) and mainly consider the sediments and distribution within the Cuvelai-Etosha Basin as part of the larger Owambo Basin.

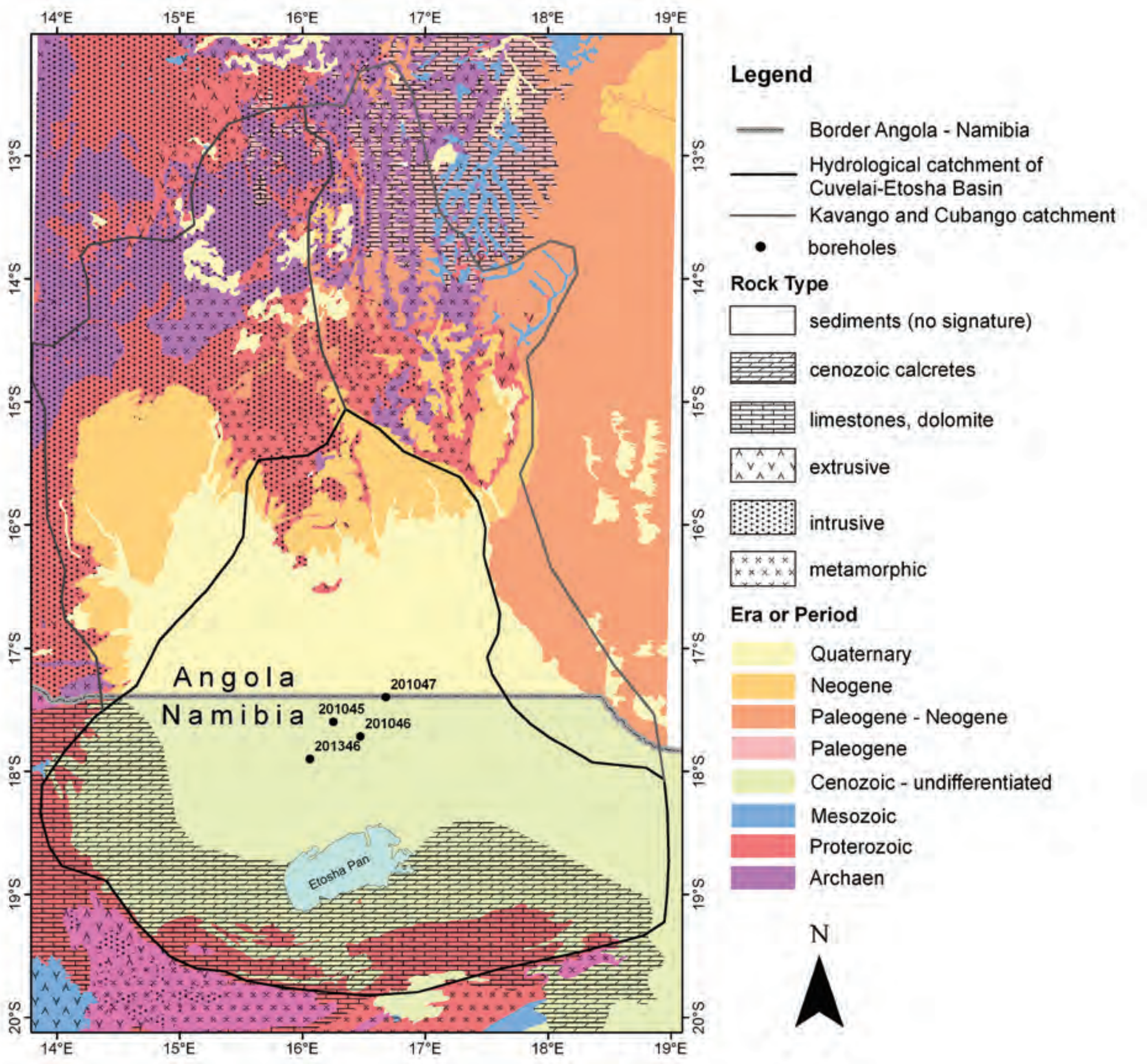
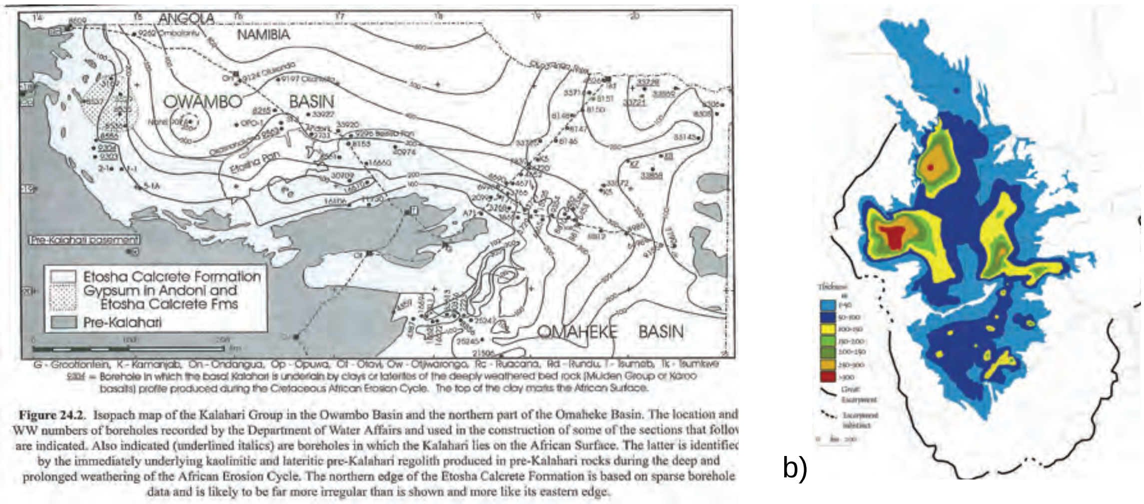


Figure 2: Overview of the geology of the CEB – from the Digitized Carta Geológica de Angola 1:1.000.000 (de Araújo et al., 1988) and the Simplified Geological Map of Namibia (1:2.000.000) (Geological Survey of Namibia). The major drilling sites of the DWA-BGR project are also shown, not all drilled boreholes are mentioned as some were drilled near to each other.

Miller (2008) states that during the whole time since the Cretaceous the still-existing depression of the basin existed and contained lakes according to the climatic circumstances. Generally, the Kalahari Succession might thicken to about 600 m to the north, respective towards the Angolan border but thins eastwards to the pre-Kalahari basement outcrops along the Kavango River (Figure 3a) according to Miller (2008). A discrepancy to his figure is found in figures of Haddon (2005) (Figure 3b) and the geological maps of Angola and Namibia (de Araújo et al., 1988; Miller and Schalk, 1980) who describe smaller depths of up to 450 m with a depression center where the DWA-BGR project boreholes were drilled (Figure 4).

Much of the sediment in the Owambo Basin is largely unconsolidated or only partially consolidated and appears to have been deposited by the sand-dominated Cubango Megafan in the east and the much smaller, mud-dominated Kunene megafan in the west. Some cemented sands are logged as sandstones in some archive borehole logs, although cementing is usually limited and weak. Exactly when Kalahari deposition began and what constitutes the base of the Kalahari in the Kalahari basin is not well defined, the lowest Ombalantu formation could be Cretaceous or early Tertiary. In Namibia, Botswana and South Africa, the base of the Kalahari Group is taken as the first unconsolidated or semi-consolidated sediments that overlie solid basement rocks, commonly of the Karoo Supergroup.



a) b)

Figure 3: a) Isopach map from Miller (Miller, 2008b) of Kalahari sediment depth and b) estimated Kalahari sedimentary depths in the Great Escarpment of Southern Africa. The figure was taken from Hipondoka (2005) but is a map of Haddon (Haddon, 2005), showing that the Owambo Basin has the thickest Kalahari sedimentary deposits and that the Ohangwena Region is located at the eastern border of this largest depression (red).

Ombalantu Formation - A basal, red, fine-grained, semi-consolidated but friable formation with variably silicified mudstones but almost entirely consisting of clay. Formerly it has been described as "sandstone" or "siltstone" but in fact it is a mudstone with varying grades of silicification. Some silt and sand is found and at the base it might contain pebbles (borehole WW9296). It does not crop out and it has a broad elongate distribution extending from the south-east to the north-west of the basin and reaches a maximum thickness of 80 m. According to Miller (2008: figure 24.8) it does not necessarily exist in the Ohangwena Region but this might also be due to inadequate depths of existing boreholes. Gypsum and Gypsum crystals occur in the upper part of the formation. Miller (Miller, 2008b) evaluates its deposition to be mainly from the accumulation of fine clastics in a shallow, low energy, deltaic environment. A restricted continental basin with a significant and sufficient amount of evaporation was required to lead to the appearance of gypsum.

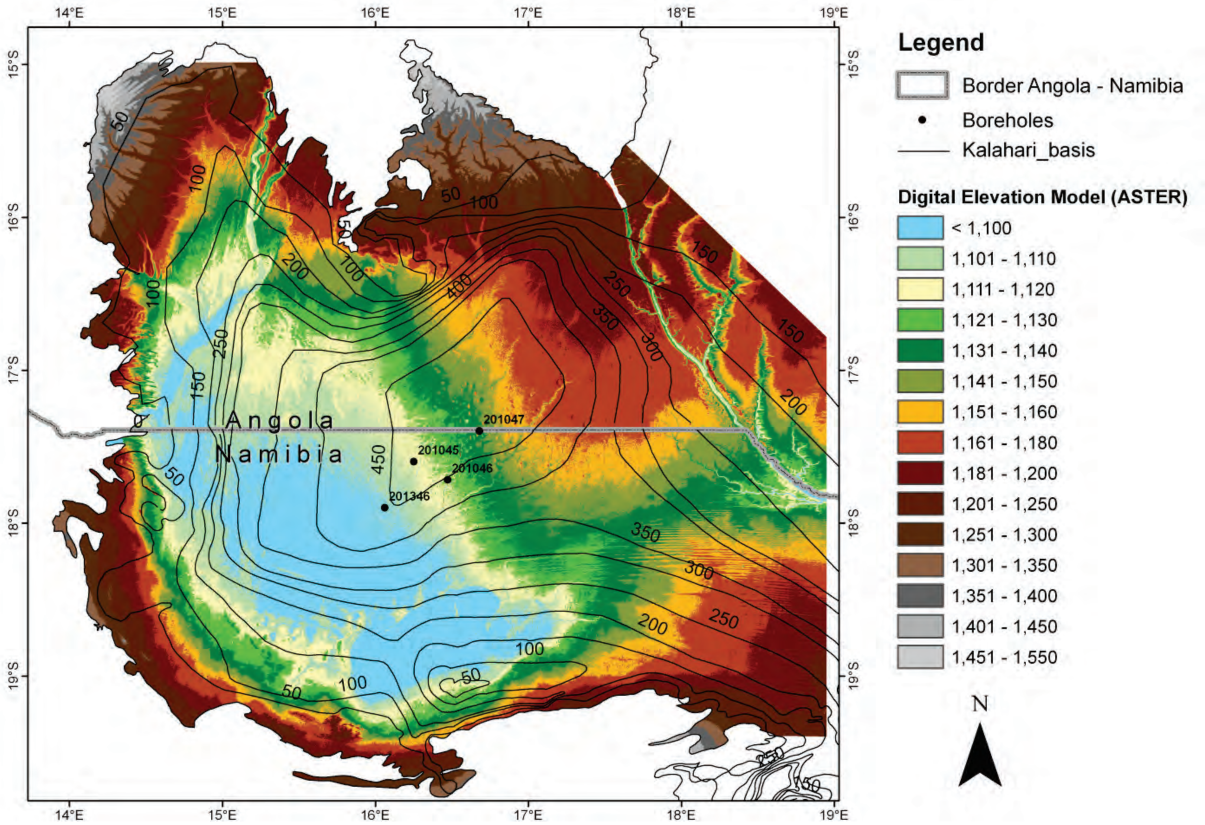


Figure 4: Digital elevation of the Kalahari Sediments in the CEB and parts of Kunene and Cubango Catchments with depth contour lines from geological maps of Namibia and Angola (de Araújo et al., 1988; Miller and Schalk, 1980), please note the varying scale of surface elevation.

The Beiseb Formation is a gravel deposit which is widespread, generally reddish in color and represents a period of rapid and extensive input of material from the basin margins. It consists of well rounded sand and clay stone clasts which are set in a matrix of fine to medium grained, argillaceous, and calcareous to dolomitic sandstone. With a maximum thickness of 47 m, it is the thinnest of the Kalahari Formations (Miller, 2008b).

Olukonda Formation - A friable, poorly consolidated, reddish brown, poorly sorted massive sand and sandstone formation with a limited distribution but a broad elongate sub-outcrop similar to the Ombalantu Formation. It contains a few thin gritty and pebbly layers and is up to 152 m thick. Bittner and Kleczar (2006) describe the principal layering in the Cubango Megafan area and allocates the freshwater containing sands below the aquitard to the Olukonda formation.

Andoni Formation - It occurs throughout the Owambo Basin as a cover to all underlying units and consists of inter-bedded white medium grained sand, light greenish clayey sand

and green clay. In zones, the predominant sand varies in thickness between 10 and 200 m and shows an unconsolidated, slightly pyritic or hematitic condition. The top part of the section contains numerous irregular-shaped dolocrete and calcrete nodules which are embedded in polished, angular to sub-rounded grains of quartz which in turn make up to 90 % of the sand. Sorting improves upwards in the sequence. The appearance of clay layers within this formation varies in thickness between a few centimeters and 150 m (Ombalantu borehole in Miller (Miller, 2008a)). They are often silty and/or sandy. Around the Etosha pan, different lithologies are found in the Andoni Formation, for further details see Miller (Miller, 2008a).

A significant contribution to the sedimentary evolution of the CEB is written by Miller (2008; page 24-12) and is cited here in full to contribute to the discussion of findings in this report: “The occurrence of a clay-rich zone separating an upper brackish aquifer from a lower freshwater aquifer (authors: possibly within the Andoni formation) may well be a rather general feature of the regional Cubango-Okavango and the Kwando Rivers and their fan systems since that same superposition of aquifers with an intervening aquitard occurs east of the Kwando river in the Caprivi. The intersected parts of the sand-rich Cubango Megafan contrast markedly with the clay-rich Andoni and Olukonda Formations in the western parts of the Owambo Basin (…). This contrast seems to illustrate a marked difference between the Paleo - Kunene depositional system and the Cubango Megafan, the former mud dominated and the latter sand dominated. Another surprising and significant difference is the fact that although the catchment of the Kunene system in Angola is not significantly smaller than that of the Cubango system, the Kunene fan is nowhere near as large and well developed as the Cubango Megafan, even where the Kunene system emerges from the confining highlands in the region of 17°S (…). In fact, there is no obvious Kunene megafan and although the Kunene is considered in this volume to have contributed a significant amount of sediments to the Owambo Basin, an alternative consideration is that the clays in the western part of the Owambo Basin are, instead, the distal deposits of the Cubango Megafan”, end citation.

3 Geophysical Investigation

by Friedrich Schildknecht and Falk Lindenmaier

This chapter forms a summary of the extensive report of the TEM sounding campaign supervised by Schildknecht (2008) within this series of reports (Report Part D).

3.1 Method

The transient electromagnetic method (TEM) belongs to the time-domain methods within the group of electromagnetic geophysical methods. It measures the amplitude of a signal as a function of time. The TEM methods work by a transmitter transmitting a pulse, typically a current switched of very quickly. The measurements are then made after the primary fields disappear. The measured electromagnetic fields are evaluated by the Maxwell's equation, see Christiansen et al. (2009).

A twofold system is required: a transmitter loop (usually a wire in a square loop, e.g. 40 m x 40 m for a depth of maximum 150 m) is used to give an electric impulse to the ground that is then captured as a secondary magnetic field by a receiver coil (way smaller than the transmitter loop). The signal received is then processed further. A typical sounding consists of several thousand single pulses; the bulk of received signals are used to filter unwanted noise signals. Christiansen et al. (2009), p190f: "The measurements are made by transmitting a direct current through the transmitter loop. This results in a static primary magnetic field. The current is shut off abruptly which due to Faradays Law induces an electrical field in the surroundings. In the ground, this electrical field will result in an electrical current which again will result in a magnetic field, the secondary field. (…) Measuring the current in the receiving coil will therefore give information about the conductivity as a function of depth – this is called the sounding." end citation. Observations taken are rather strictly valid for a vertical magnetic dipole source over a homogenous halfspace, but with reasonable assumptions resistivity-depth related coherence can be established. Inverse fitting of the curves combined with calibration to existing lithological information results in depth related layers of specific resistivity values.

3.2 Approach

The geophysical survey was carried out by Gregory Symons Geophysics (GS). The data was usually evaluated by BGR staff immediately after registration, generally on the evening following the daily fieldwork. So, a constant re-adjustment of locations for further measurement points was possible. For the evaluation of soundings, the INTERPEX software IX1D was used. The measuring instruments were provided by a sub-contractor and Zonge representative, Neville Brown from Geophysical Surveys and Systems (GSS). The measurement devices are Zonge devices (www.zonge.com); a Zonge GDP 16 receiver and on the transmitter side a Zonge generator-driven power supply. Before and regularly during the campaign, calibration and re-calibration procedures were conducted.

A key location for the measurements was the area around borehole WW37070, the Eenyama school borehole location (Bittner, 1998). A comparison of the BGR-owned Zonge GDP-32 receiver with the Zonge GDP-16 receiver was conducted and it was decided that the older GDP-16 turned out to be more reliable. Based on these tests, the survey was carried out with a 300 m x 300 m square transmitter loop and frequencies of 2 Hz and 4 Hz. As far as possible a uniform analysis of 1 Hz and 4 Hz soundings was attempted. If this was not possible, the interpretation with the lower-fitting error was used. In general these were 4 Hz measurements.

The soundings (measurements) were organized in profiles, named with capital letters from "A" to "K", according to the order of measuring. Sounding "C550" is a sounding on profile C with the number 550. With the exception of profile A and B, the differences in numbers of two soundings on one profile correspond roughly to their distance in kilometres. As profiles were often extended in both directions, the sounding numbers do not correspond generally to the distance to the starting point of the profile.

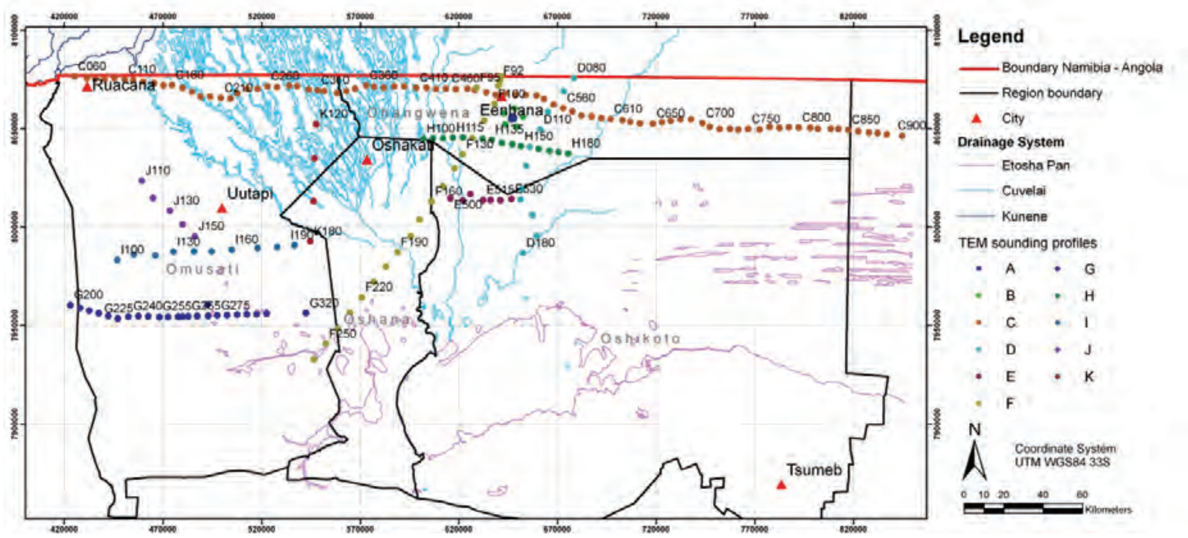


Figure 5: Overview of TEM soundings in the CEB.

The setup of the soundings was made up for the detection of deep freshwater layers; therefore the near surface information is not reliable. Principally, sandy aquifers with fresh water content show a resistivity of around 20 Ohm*m, higher resistivities could account for dry sediments or hard rock, lower resistivities account for salty or clayey sediments. These values are based on the Eenyama school borehole (WW37070) and on knowledge from similar sounding campaigns.

3.3 Results

Besides a profile of soundings across the east-west elongation of the CEB, two regions within the CEB were investigated in more detail with the TEM soundings: These are the western Ohangwena Region and the Omusati Region, including some parts of the Ishana Region.

3.3.1 Calibration measurements for a deep seated high resistivity layer

Profiles A and B were used to identify a possible deep seated aquifer with the calibration well being WW37070 at Eenyama. The soundings yielded good results for both profiles. However it should be noted that the interfaces of the TEM soundings do not totally correspond with the aquifer definitions that were conducted during drilling (Bittner, 1998). This is discussed in more detail in Chapter 5.2 and Walzer (2010).

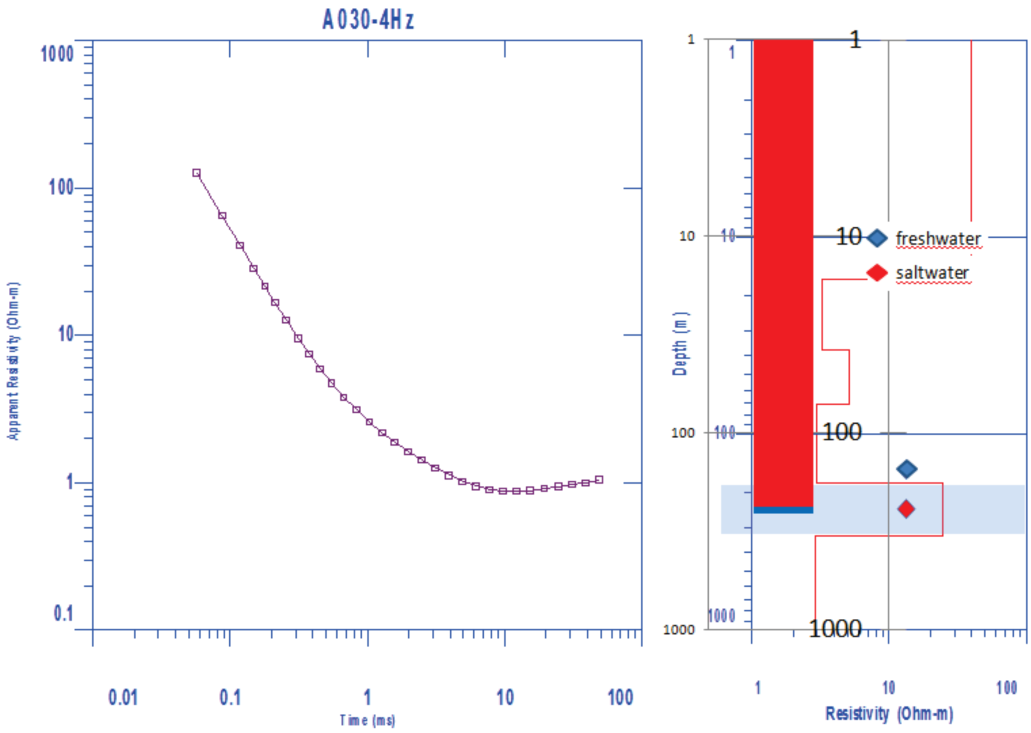


Figure 6: Sounding curve and interpretation of sounding A040 (Schildknecht, 2012). Blue squares in the left part of the figure indicate measured apparent resistivity. The solid line corresponds to the layering model on the right. The ascending branch is perfectly matched with a layer of 26 Ohm*m from 180 m to 310 m depth. The diamonds on the right indicate depth of the two existing water samples. The red diamond corresponds to >3000 mg/l, the lower one to <745 mg/l. The red-blue bar graph represents fresh and saltwater according to (Bittner, 1998).

3.3.2 West-east transect across the Cuvelai-Etosha Basin

Profile C extends sub-parallel to the Angolan-Namibian border and spans the CEB from west to east. Roughly three parts are identified within this profile, a western, a central and an eastern part.

Profile C West: is represented by soundings C170 to C400 (Figure 8a). Some of these soundings show a deep seated thin layer of high resistivity that is according to resistivities possibly representing fresh water. However this layer seems not to be continuous and a certain ambiguity to different material is possible. Basically, this part is not trustworthy according to a sole interpretation of TEM soundings, and further exploration drilling, would be needed here for calibration of soundings as the sedimentary system is different to the one around the Eenyama borehole WW37070.

Profile C Central: starts approximately with sounding C410 but becomes significant with C440 (Figure 8b). A well developed deep seated "fresh water" area is seen below a layer with lower resistivity until sounding C570. The low resistivity layer extends from the surface down to a depth of 150-200 m. Below that, the fresh water layer extends to a depth of 300-350 m before a low resistivity layer is encountered again.

Profile C East: From C570 to approximately C840 the upper low resistivity layer vanishes and a deep high resistivity layer is seen that indicates freshwater (Figure 8b). From C840 to C900 the deep high resistivity layer gets disturbed by some low resistivity spots. The bottom of the high resistivity layer rises from C580 with a depth of almost 400 m towards a depth of 200 m from C700 westwards. The upper Aquifer Ohangwena I (KOH1) is not seen on the TEM soundings in between C500 and C580.

3.3.3 Delineation of a deep seated high resistivity layer in western Ohangwena Region

Profiles D and F: were positioned so that they approximately represent the eastern and western border of the deep high resistivity layer (Figure 5, Figure 8c and d). Location D080 at the Angolan border shows a significant deep high resistivity layer and this layer diminishes at D140 and vanishes at D160. In profile F the high resistivity layer is less pronounced than in profile D. Some soundings like F090 did not show the high resistivity layer, even although the surrounding soundings do, and F090 was technically good. More towards the southern edge of the profile, the high resistivity layer changes to spots of high resistivity within a zone of low resistivities.

Profiles H and E: complete the spatial extent of the high resistivity layer in the Ohangwena Region.

A detailed delineation of the Ohangwena deep fresh water aquifer (Ohangwena I or KOH2) in 3 dimensions is presented in Chapter 4.

3.3.4 Exploration in the Omusati and Ishana regions

Profiles G, I, J, K are located in the western part of the CEB. They were aimed to explore the groundwater situation that is fed from hard rock aquifers further to the west. Sedimentary rocks are mainly sand, clay and calcrete/ dolocrete but also evaporitic deposits are found. It is thought that a basal coarse grained layer might be found below the upper Kalahari sediments that is in connection with western aquifers and might bear fresh water. The soundings in the western exploration area show no clear indications for the existence of a deep aquifer. The data situation is not comparable with the results of the investigations in the east. Nevertheless, there are certain indications of a freshwater horizon. Prospective areas are circled in blue in Figure 7. In drilling campaign II this area has been drilled, so far unsuccessful (see Chapter 5.4).

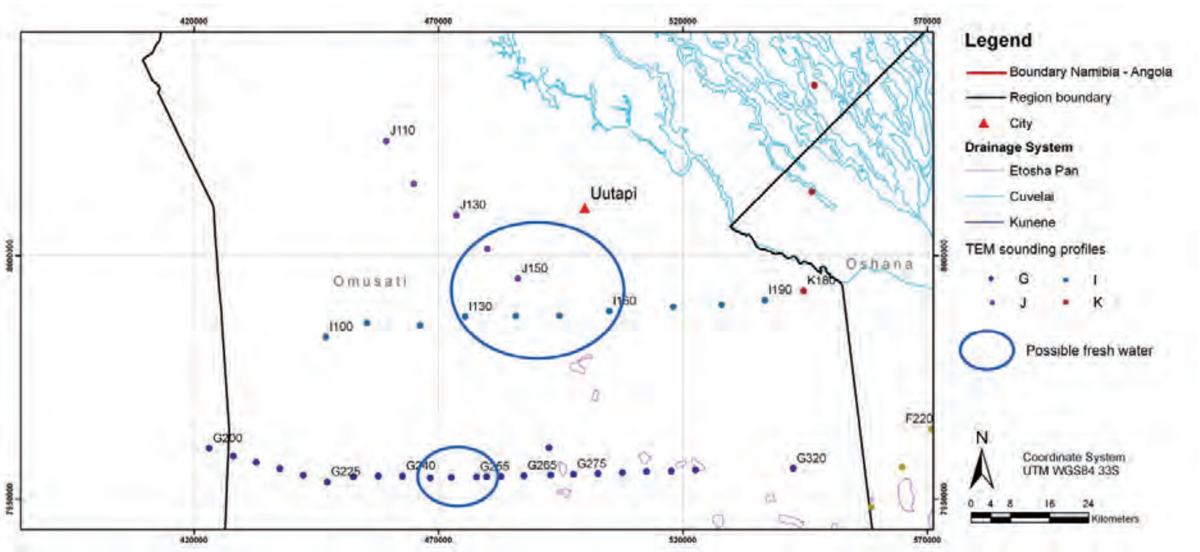


Figure 7: Areas in Omusati region where TEM soundings show possible deep fresh water resources.

Statements

- TEM soundings were successful for exploration of a deep seated aquifer in the Ohangwena Region.
- Possible deep seated fresh water areas were located in the Omusati Region.

Recommendations

- Further calibration of soundings with boreholes is needed for the C West Profile, Ishana Region respectively and the Omusati Region.

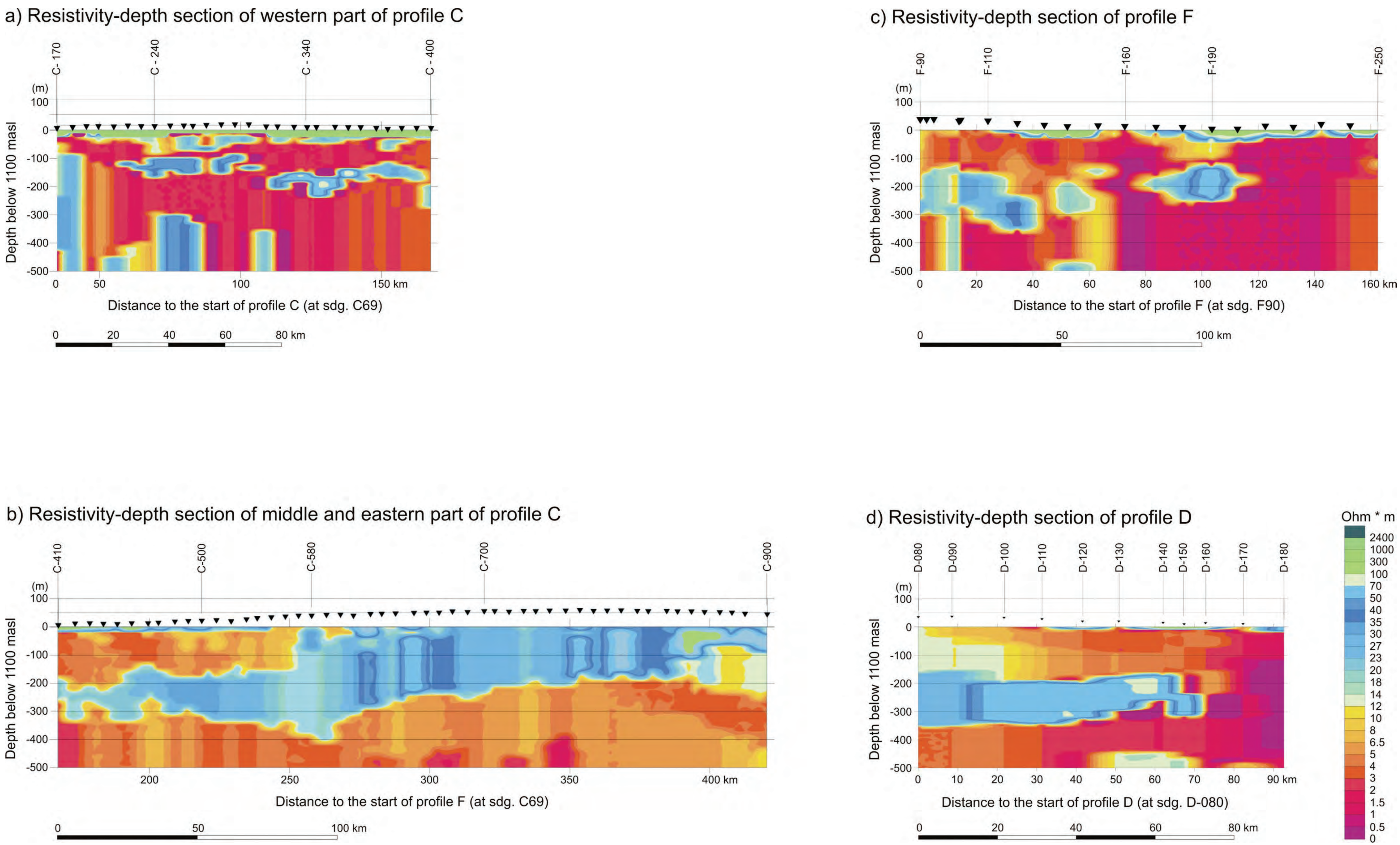


Figure 8: Profiles of interpolated TEM soundings according to Schildknecht (2008); a) profile C West; b) profile C East; c) profile F and d) profile D.

4 3D- Model of TEM Soundings

Authors: Sarah Zeilfelder and Falk Lindenmaier

4.1 Introduction and General Outline

In June 2009 (Zeilfelder, 2009) presented her internal BGR report for a three-dimensional (3-D) hydrogeological interpretation of the TEM-soundings. This structural 3-D model was developed with the software GSI3D (Mathers and Kessler, 2008) and focuses on classified resistivity profiles of selected TEM-soundings. The model was re-investigated and adjusted by Falk Lindenmaier in 2010 after some TEM-soundings were re-interpolated and hence their quality improved.

The investigated area surrounds the Eenyama School borehole WW37070 (Bittner, 1998), see also Figure 9. There, water is abstracted from a deep-seated fresh-water aquifer since 1998 (Bittner, 1998) and it was the key location and calibration point for the TEM-investigations. Due to the focus, only a selection of TEM-sounding locations from the geophysical investigation is included into the 3-D model (Figure 9).

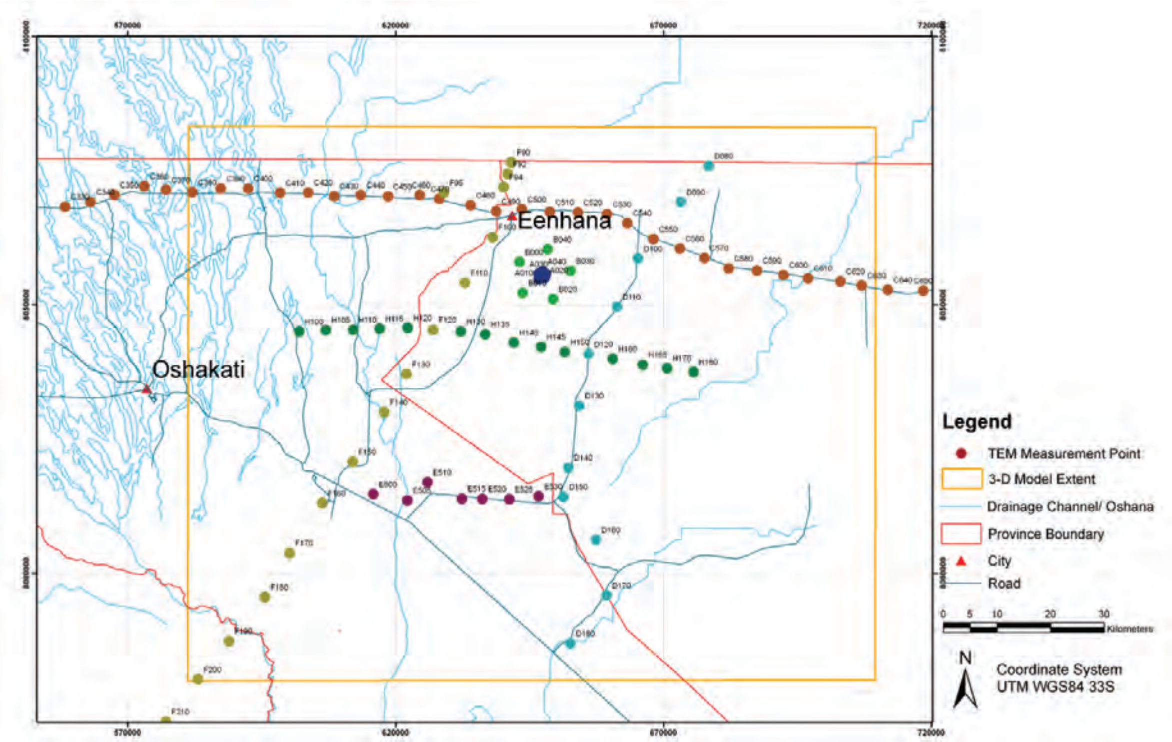


Figure 9: Selection of TEM-points for 3-d resistivity class model around the Eenyama School borehole WW37070.

From each TEM-sounding, interpolated resistivity values in [Ohm*m] from various depths were provided as text-files and integrated into the database also containing projected

GPS-coordinates in UTM Zone 33S WGS84. The resistivity profile contains block-wise values for specific depth-from and depth-to ranges (Figure 6). These could be classified into four classes considering the borehole information of the Eenyama borehole as well as experience (Table 2).

For the 3-D model, one possible interpretation of the data was taken and the resistivity class border for the freshwater aquifer was set to higher than 20 Ohm*m. Resistivity values lower than 3 Ohm*m indicate an aquitard with clay and/ or higher salt content and values between 3 and 20 Ohm*m represent a kind of intermediate stage, possibly with brackish water. This classification was essential to relate the intensely dispersive values to either zones with freshwater or brackish water. However, the borders of classes should not be taken as too fixed as measurement and interpolation errors can lead to diffuse results, e.g. saltwater on top of freshwater layers disturbs deeper resistivity signals. Also, the focus of investigation was put on the deeper subsurface, the uppermost 50 m bgl should be neglected for interpretation. Hence these were added to the class “undifferentiated”. The undifferentiated area was extended down to the beginning of the freshwater horizon, which is in a depth of around 200 to 250 m bgl. At a greater depth, results from interpolated TEM measurements also become diffuse so that depths below 500 m bgl were not further considered. The interpretation of TEM resistivity is based on the assumption that a certain resistivity range belongs to either water with low salt content or vice versa. Of course, certain resistivity ranges can also come from clayey layers which might have a lower resistivity than for e.g. sandy layers.

Table 2: classification of resistivity ranges for the 3-D modeling

Class	Resistivity range [Ohm*m]	Description
S	> 20	freshwater in the subsurface has a high resistivity and hence every value higher than 20 Ohm*m was related to freshwater
C_SS	3 - 20	an intermediate condition was set to this resistivity range with some clay content and intermediate saltwater content
SC	< 3	low resistivity values indicate high clay and saltwater contents and were differentiated separately
X	no differentiation	for the near surface (about the upper 80 m) no differentiation was made

4.2 Model Description

A total of 83 TEM measurement points were included into the GSI3D project, while 9 of these TEM points were not included in the cross sections which are one of the primary depth structures that build up the 3-D model. The digital elevation model is based on SRTM data (NASA, 2000) and was coarsened to a raster cell size of 150 meters. The position of cross sections was mainly oriented alongside the TEM-lines but also a sub-parallel system was followed so that profiles are oriented NE-SW and NW-SE. A set of cross sections borders the selected area to improve 3-D interpolation. No additional geological or geophysical information was used for the setting up of the 3-D model. During the construction of the salt-fresh water boundaries it was considered that saltwater is denser and undercuts the fresh water and that a typical sloped interface exists. No specific data exists that explains how the interface between salt and freshwater is in reality. The intermediate layer and the low resistivity layer are drawn according to the resistivity results, and in some border areas this results in a thick low-resistivity layer (SC) and no intermediate layer (C_SS). This might confuse the observer as this does not represent typical geological layering. This is mainly applicable in the west of the freshwater body where a higher salinisation can be assumed.

The undifferentiated X-layer slopes gently from 1160 m asl in the northeast to about 1080 m asl in the southwest. According to Miller (Miller, 2010) the Ohangwhena aquifer system belongs to the Cubango Megafan. Considering the model area, the megafan culminates towards borehole WW201047 and fades out towards the Etosha basin bottom near borehole WW201348. As no further differentiation was done in the TEM soundings this layer has no further specific characteristics.

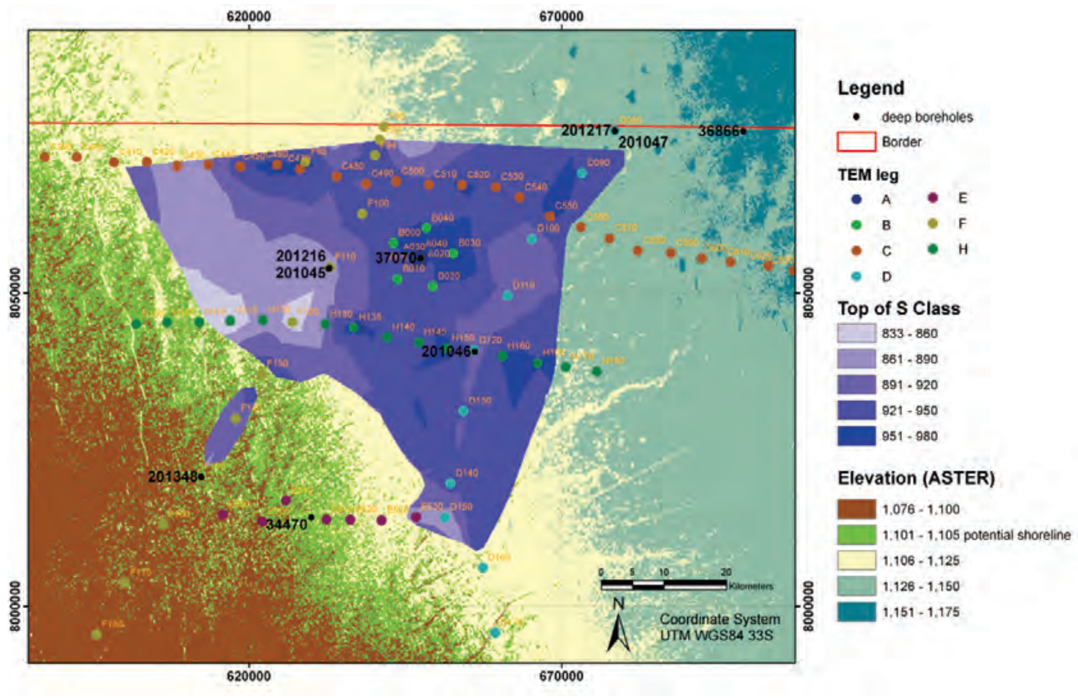
The freshwater S-layer as modeled in GSI3D has the shape of a triangle with a northern border, equivalent to the border with Angola, an eastern border and a border from NW to SE (Figure 10a, Figure 11).

- The northern border is most clearly related to the Angolan border and further soundings are needed in this regard. However the TEM soundings from profile F become more diffuse towards the border, especially TEM soundings F90 and F95 show more diffuse results. For profile D the results are optimal as it was also shown by the borehole site WW201047 (Chapter 3.3). It is noted that the surface inclination of the megafan should be further considered for the interpretation of the Ohangwhena II aquifer shape. This border does not represent a natural border.

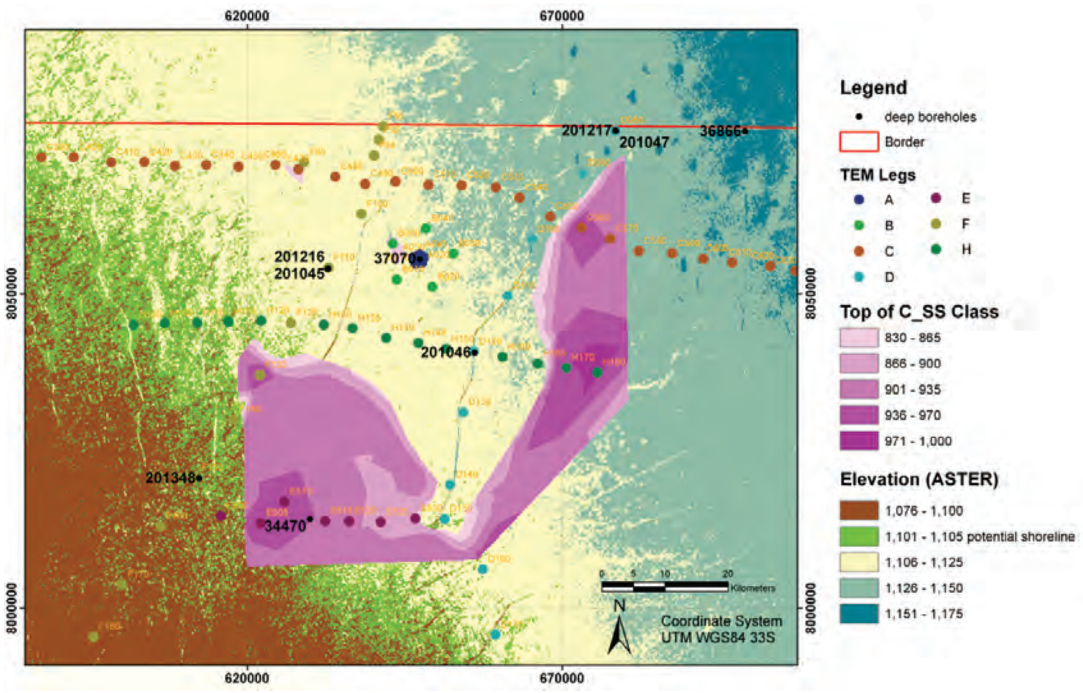
- The eastern border experiences a similar interpretation problem as TEM soundings are not set radial to the megafan structure which likely influences the shape of Ohangwena II aquifer. Towards the culmination point of the megafan it is considered that the confining layer between Ohangwena I and II diminishes and both aquifers merge. This is not clearly seen in the TEM-points thus far. A clear shape of high resistivity layers in an approximate depth of 180 to 300 m fades towards a more diffuse shape at C570, individual TEM sounding are found in appendix 2. According to Figure 8b where an interpolation method was applied and not classes set, the confining layer fades more clearly. However, this does not fully correspond with the lithological layering as far as it is known. Further structural interpretation and data is needed here. The same is observed in the profile from H160 towards H170, in-between these two points the confining layer seems to diminish. Only core drilling would help to better understand the change observed in the TEM soundings. Hence, the band of C_SS class as it is shaped in the 3-D model in the east (Figure 10, Figure 11) is currently questionable and a careful re-interpretation is needed with the support of boreholes and especially cored boreholes. For display in Figure 10, the shape of the border was straightened to show that this is not the natural end of the aquifers, it is rather plausible that the aquifer shapes similar to the topography of the Cubango Megafan.

- The NW-SE border most likely represents a structural border towards the core of the basin. It follows alongside the megafan curvature, respective alongside the 1100 to 1105 m asl contour lines. It is difficult to set up a clear definition but it seems that this 1100 to 1105 m asl elevation range also represents a weak knick point in the elevation distribution, see also Miller (2010) about the inclination of the Cubango Megafan. The boundaries position is interesting concerning the Etosha pan geology: Miller (2008b) - page 24-23) proposes a terrace on 1100 m asl which is supposedly older than 140000 years. If this elevation represents some sort of Etosha lake condition, there might be a connection to the salt-freshwater boundary. In general, the interpretation of the TEM-profiles for the S-layer is somewhat constricted to the fact that they are not in radial alignment to the curvature of the megafan. A Paleolake Etosha that has developed until about 4 Ma might have had higher water levels Miller (2010).

The intermediate C_SS-layer (Figure 10b) shows the most complicated set up; from a larger region in the south-western corner the intermediate layer follows the eastern border of the S-layer as a band; it coats the S-layer in the east. Some pockets of intermediate area are located below the S-layer, these pockets could represent saltwater below the freshwater. However, the variability in the TEM-soundings is great for intermediate values below freshwater values and with drawing all of these pockets a very complex picture would evolve. These features should rather be interpreted with care if implications are drawn for drilling new wells.



a)



b)

Figure 10: Thickness distribution of salt- and freshwater body according to the 3D TEM measurement models, overburden and bases do not have a represent able meaning and were not displayed. The green band represents the elevation band of 1100 to 1105 m asl as a potential state of water level at 140 k years. Please note that the border of layers is due to the model extent and represents results from TEM soundings. Lithological layers are suspected to have a somewhat different shape.

Two aspects complicate the interpretation of TEM soundings for hydrogeological structural modeling in the Ohangwhena II aquifer. First, for exploration the salt-freshwater distribution in a sedimentological unit is of primary interest. The TEM sounding cannot clearly distribute between clay-rich layers, which supposedly follow with the depth in the sediment column or saltwater pockets underlying freshwater. So, currently the 3-D model lacks a clear distinction of the base layer, and here further interpretation is needed. Principally, the possibility that salt water pockets or tongues exists below the freshwater, needs to be considered in further investigation.

Generally, all surfaces of the 3-D model that results from the layer depths of the TEM soundings are quite uneven, and no specific trend is seen. This could also represent sedimentological layer morphology. However at the moment, further refinement is needed before a more distinct answer is possible. Figure 11 shows the 3-D mode.

Statements

- 3D model of TEM measurements gives an understanding of the freshwater distribution and shows a boundary towards the basin depression (north-west to south-east).
- Northern and eastern boundaries of 3-D model are limited to extension of measurements and do not represent real boundaries.
- TEM soundings do not exactly represent lithological layering and hence need a careful sedimentological interpretation.

Recommendations

- A refinement of TEM measurements might help to interpret drillings. Refinement should be preferably radial to topography of the Cubango Megafan
- Further calibration of TEM measurements with new boreholes including geophysical logging is recommended.
- Integration of measurements with boreholes in the 3D Model

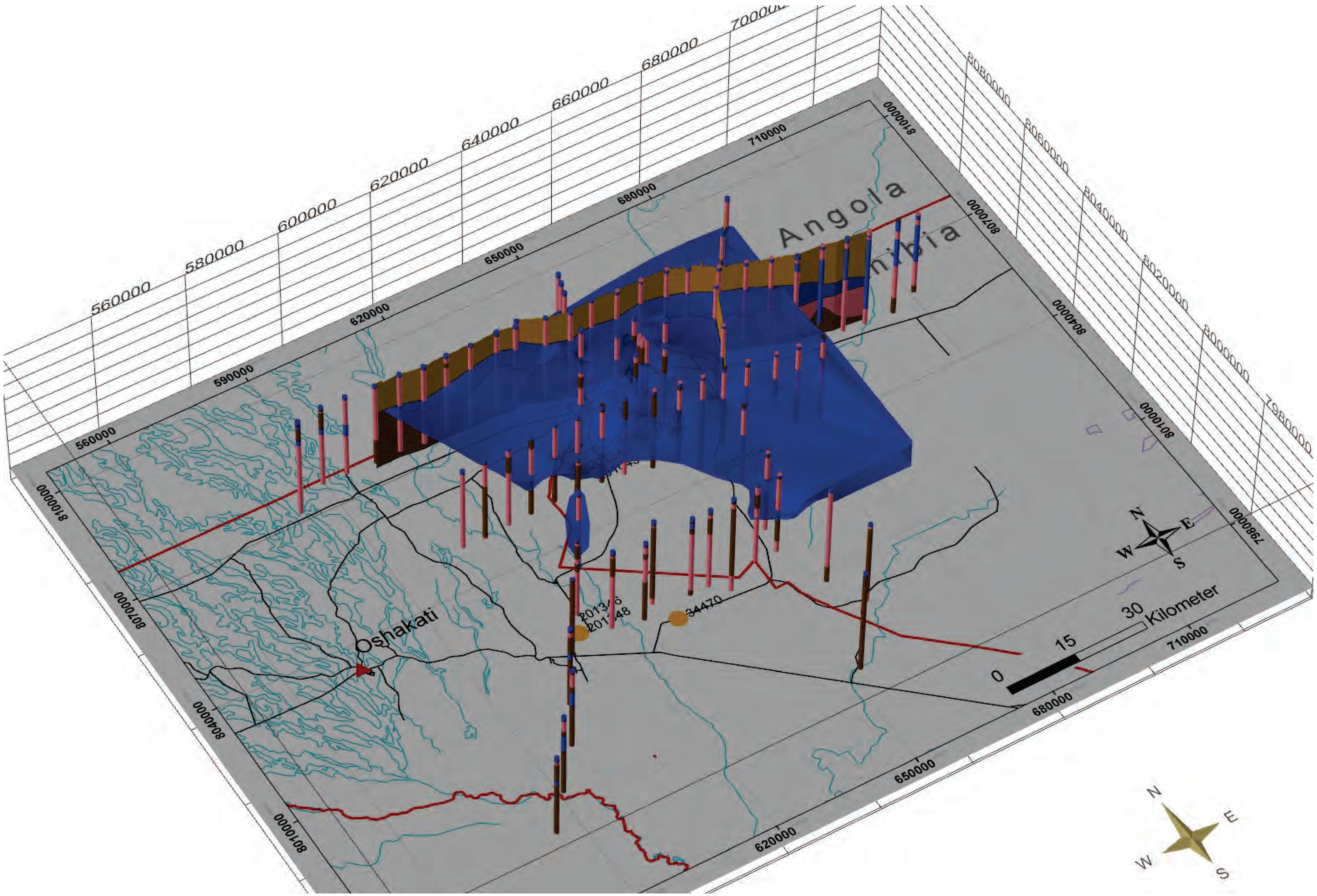


Figure 11: Three-dimensional view on the freshwater body within the modelling software Gsi3D. TEM sounding classification according to Table 2: S (fresh water) in blue; C_SS (brackish water) in pink; SC (salt water or clay) in brown.

5 Drilling and Geophysical Borehole Logging Campaigns

By Braam van Wyk, André Walzer, Rüdiger Ludwig and Falk Lindenmaier

The results of the TEM-measurements were used for the location of a first set of boreholes drilled with a mud-rotary method. All boreholes were placed near TEM points with freshwater in greater depths. In a second campaign at two of these locations, core drilling was conducted retrieving the first deep cores ever retrieved on the Cubango Megafan. A third drilling campaign at the end of DWAF-BGR Project Phase I added more observation boreholes for pumping tests and also a borehole within the saltwater region of the aquifer.

5.1 Position of Boreholes

During a field trip in January 2011 almost all newly drilled boreholes could be visited and locations were measured with a Trimble ProXRT Receiver system using additionally the Omnistar signal to measure the elevation of the boreholes (Figure 12, Table 3). During the campaign, a test signal was available which cut off after some minutes. A long lasting measuring interval was not possible to obtain better elevation results. It is recommended to re-measure the location with a purchased long-lasting signal or a different method of height determination.

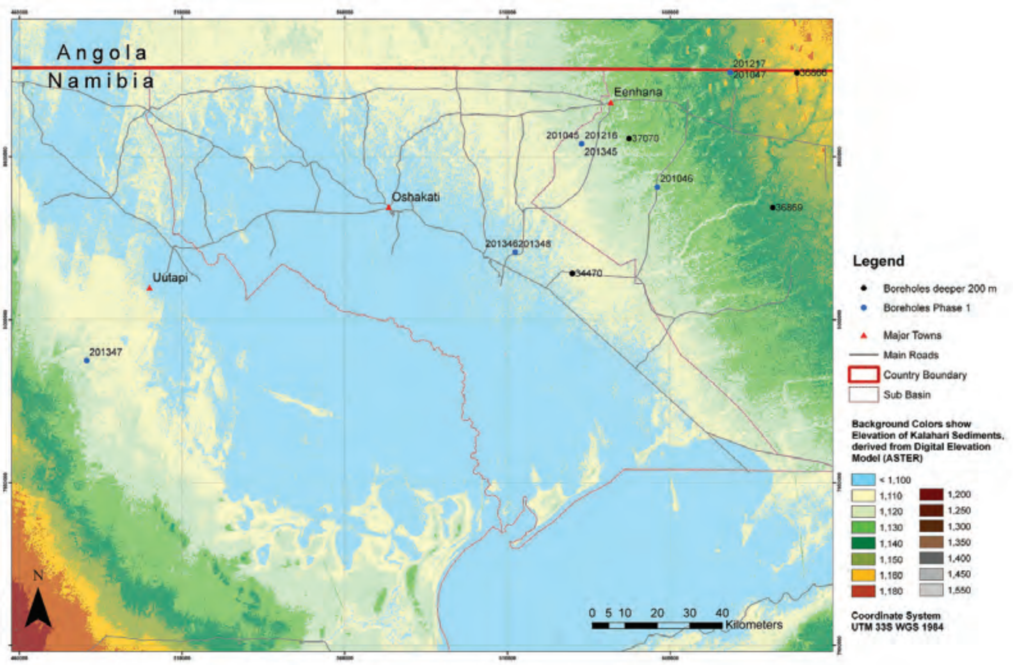


Figure 12: Location of boreholes of drilling campaign I to III.

A better vertical precision than in Table 3 should be possible, however a vertical precision of maximum of ± 0.27 m is considered to be precise enough for groundwater leveling. One GPS station was found alongside of road D 3405 east of Eenhana and was also measured. This point could be used for additional calibration of the borehole location measurements in this area if exact coordinates will be retrieved.

Inclination is very low between the points. Between WW201047, the borehole furthest from the megafan morphology and WW201046 there is a distance of 41.7 km with a height difference of 14.4 m. Between WW201047 and WW201045 there is a distance of 50.6 km and a height difference of 19.7 m. Between WW201047 and WW201346 there is a distance of 86.1 km and a height difference of 34.9 m (Table 3).

Table 3: a) results of elevation and coordinate measuring campaign and elevation differences from WW201047. b) Calculated heights and distances from the north-eastern most borehole WW201047.

a)	Schwarzeck		UTM WGS 84 33S		Elevation	Vertical Precision
Borehole	Longitude	Latitude	Easting	Northing	collar top m asl	m
WW201045	16.252858061750	-17.596343466625	632858.186	8053943.151	1112.47	0.35
WW201046	16.472939833250	-17.715046948500	656109.574	8040640.334	1117.80	0.50
WW201047	16.681270551750	-17.395282224000	678516.976	8075840.579	1132.23	0.35
WW201215	16.252894340600	-17.596475098800	632861.939	8053928.561	1112.44	0.48
WW201345	16.252126164250	-17.596811203750	632780.182	8053891.912	1112.64	0.33
WW201346	16.061656158250	-17.897687148500	612381.908	8020726.669	1097.35	0.30
WW201348	16.061926838000	-17.898253164000	612410.224	8020663.881	1098.00	0.35
GPS STN 04-06	16.359667010000	-17.468271466000	644293.253	8068035.773	1117.91	0.55
Eehnhana outside fence	16.335978334375	-17.479887795875	641768.791	8066768.247	1117.34	0.49

b)

Borehole from 201047	distance between [km]	elevation between [m]
WW201045	50.638	19.76
WW201046	41.727	14.43
WW201047	86.089	34.88

5.2 Drilling Campaign February-March 2009: Boreholes WW201045-WW201047

A first drilling campaign was conducted and the borehole locations were selected based on the suggestion of Schildknecht (2008) with locations spanning the proposed freshwater area as derived from TEM measurements (Figure 12). Three mud-rotary boreholes were drilled from February till March 2009. Geophysical borehole logs were taken before PVC piping was installed, pumping tests were conducted and water samples were collected for analysis in the Namibian Analytical Laboratory Services CC as well as at BGR labs. During the second geophysical borehole logging campaign, these boreholes were logged again, this time within the construction piping.

A detailed report was written by van Wyk (2009a), who was also the hydrogeologist on site. This report is found in Appendix 1. A short geophysical report from Terratec Inc. is also available (terratec, 2009), see Chapter 5.5. A technique for the horizon-wise abstraction of the groundwater during the drilling (EDI Fluid Finder) was applied for these boreholes to better identify deep freshwater horizons. An expert from Exploration Drilling International Inc. accompanied the drilling (Könemann, 2009), see also van Wyk (2009a).

Detailed lithological descriptions were produced by van Wyk (2009a) and also by Miller (2010), however it should be noted that the lithology was defined with cuttings from the mud rotary drilling, which, especially at greater depths, becomes more difficult to interpret as mixing of cuttings is greater and travel time also increases. Figure 13 gives an overview of the preliminarily defined lithology (by van Wyk, 2009a) and a hydrogeological interpretation (Walzer, 2010), and a gamma as well as bulk soil conductivity logs, in comparison with the surrounding boreholes. The profile is arranged from north-east to south-west, radial to the topography of the Cubango Megafan. Detailed interpretation was taken from the reports of van Wyk (2009a) and Walzer (2010). A detailed discussion integrates the results of further drillings and investigations and is found in the discussion chapter of Report Part B.

Additional to this, Appendix 3 gives details of the lithology as well as a shortened overview of the most important features of the retrieved cuttings. From the mud-rotary drilling it is seen that an easy differentiation of layers is difficult. However the geophysical logs greatly help to set up a delineation of aquifers and aquitards (Figure 13).

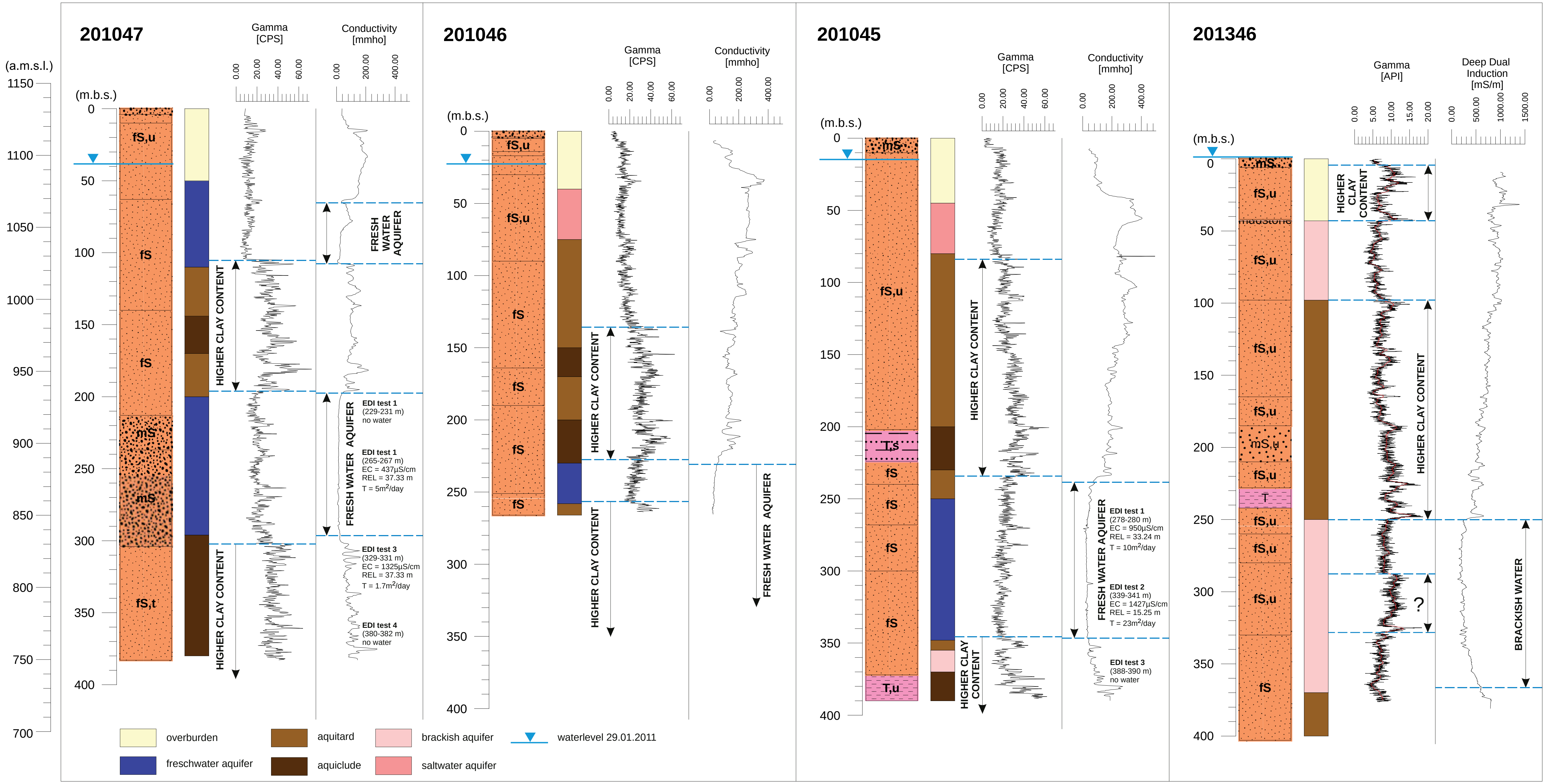


Figure 13: An idealized profile from NE to SW with all major borehole locations, the aquifer delineation in the second column is based on lithology, geophysical logs as well as hydraulic investigation from Wyk (2009) and Walzer (2010). Figure changed after Dill et al. (2012).

5.3 Core Drilling Campaign May-July 2009: Boreholes WW201217 and WW201218

Two cored boreholes were drilled between May and July 2009 since the motivation for further investigations on the hydrogeological characteristics of the project area based on the information that was obtained from boreholes 201045, -46 and -47. These two cored boreholes (WW201216, WW201217) were positioned close to the sites of WW201045 and WW201047 respectively. Core borehole WW201216 was positioned a 12 m distance from WW201045 while a 100 m distance is between WW201217 and WW201047.

The drilling observation, work documentation and organization of sampling and laboratory investigation was conducted by Walzer (2010). Miller (2010) did a detailed sedimentological description of the cores, while Gersdorf set up a borehole catalogue to visualize core information (Appendix 4) and samples were taken for laboratory investigation (see corresponding chapters in Report Part B). Investigation of the cores is still ongoing.

Figure 14: Drill head and core catcher for coring of borehole WW201216 and WW201217, which is mainly used in hard rock formations , figure from Walzer (2010).

The core material was withdrawn from the depth of 80 m to 390 m at site WW201216, and 80 m to 320 m at site WW201217. Core drilling took place based on the wireline diamond coring HQ-3 size. This includes a tube with an inner diameter of 61.1 mm inside a rod which shows an inner diameter of 96 mm. Figure 14 gives an example of the diamond core drilling bits that were used (bottom-right) and shows the core catcher (top-left) that prevents the core from sliding out of the tube during operation. Both tube and rod have a length of 3 meters. The drilling fluid was a synthetic polymer mix made up of CAP21 and water. Recurring core loss and immense water loss was detected during coring. The water loss in particular was suspected to relate to cavities within the unconsolidated rock. Therefore, DRILLVIS was added to the drilling fluid from the depth of 263.15 m at site WW201216. DRILLVIS is a drilling viscosifier with a high molecular weight comprised of polyacrylamide/ acrylic acid copolymers. It provides faster hardening and a higher viscosity compared to CAP21. Hence, a decrease in water loss as well as a very viscous drilling fluid was observed from 263.15 m bgl at borehole WW201216. Throughout the drilling of borehole WW201217 only DRILLVIS was used. Constant circulation of drilling fluid could not be monitored. The drilling fluid was recycled whenever mud pits where almost full so that at least a minimum of 10000 liters (two 5000 liter tanks) was provided at all times.

Core loss was a re-occurring problem, especially in the unconsolidated sands of the lower aquifer. The core loss can be due to material properties; however the core catcher is important for the retrieving of the core. As supposedly a hard-rock core catcher was used (Figure 14), the core loss can also be attributed to this.

Miller conducted a very detailed core description which was integrated into the core description section in Appendix 4. Figure 15 compares logs from the cuttings (Wyk, 2009a), a hydrogeological interpretation (Walzer, 2010), the condensed description of Miller, and displays the core loss, which was essential especially in borehole WW201216. This comparison shows principally the difficulty to use cuttings or even core descriptions to delineate hydrogeological features in the uppermost Kalahari sequences of the Cubango Megafan: Sample investigation in the clayey layer (T,s) showed that in average the clay content is less than 20 % (see corresponding chapters in Part B). A detailed discussion of results follows at the end of Part B.

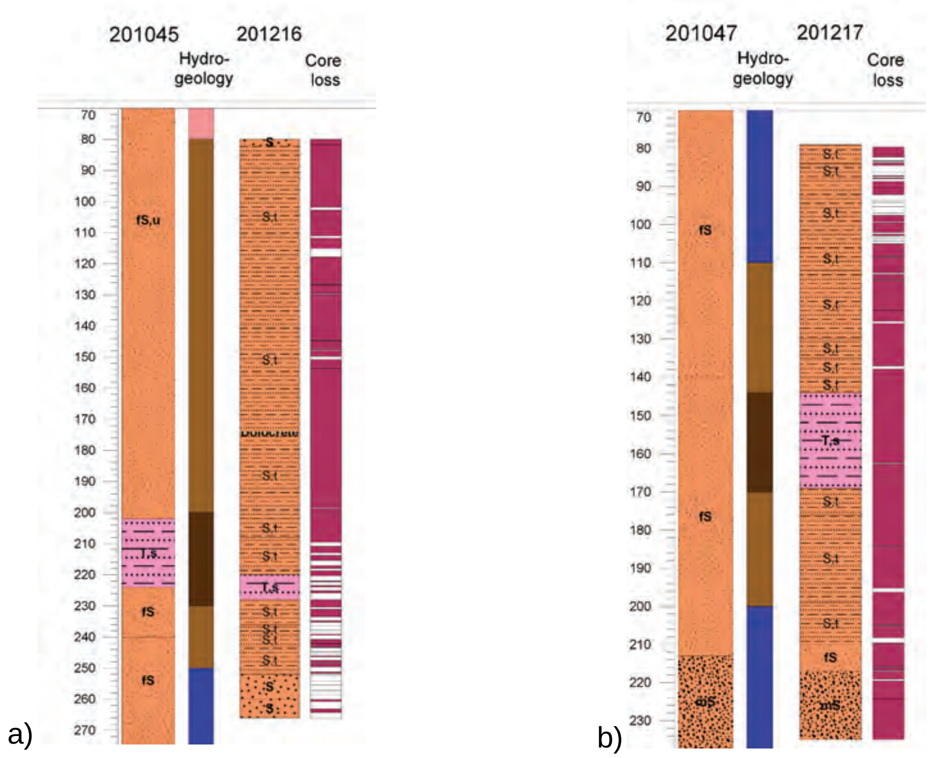


Figure 15: Comparison of lithology from coring versus mud drilling and spaces with core loss a) boreholes WW201045 and adjacent WW201216; b) boreholes WW201047 and adjacent WW201217, see also Appendix 3. Composition description is simplified from a German standard (Preuss et al., 1991): S (sand), f (fine), m (medium), t or T (clay), u (silt).

5.4 Drilling Campaign February-March 2010: Boreholes WW201345-WW201348

A third drilling campaign was conducted within Phase I of the project. Borehole information as was provided in a short report, is available since drilling (Wyk, 2009a) and is added within this report in Appendix 1.

A second borehole was drilled at the WW201045 location (this is WW201345), and a pumping test is planned at this site and hence a deep observation well was needed. The WW201345 observation well is 89.6 m from WW201045 (Table 3). A shallower observation well, WW201215, 15.1 m from borehole WW201045. Currently no detailed information is available for the shallow observation well. The pumping test is scheduled for 2012.

Boreholes WW201346 and WW201348 were drilled at the same location and a site outside of the proposed freshwater aquifer was chosen to conduct a negative test for the TEM-points. Borehole WW201346 was drilled to a final depth of 404 m and borehole WW201348 was drilled to a final depth of 297 m. Borehole WW201348 is contains a higher part of the brackish aquifer as is evident from salt content within the aquifer column. Water levels in both boreholes are artesian. However, at the moment, no pressure gauges are installed and water is free flowing. The water level is approximately 1 m above ground as indicated in Chapter 6.1 and Figure 13. These boreholes must be capped properly during the next drilling cycle.

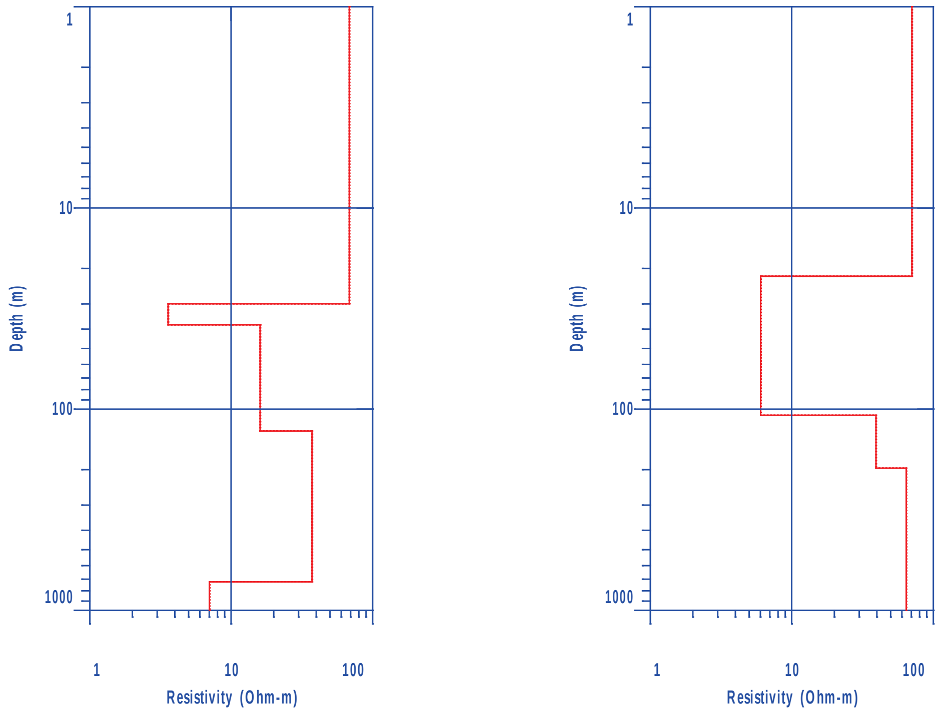


Figure 16: TEM sounding I130-1Hz and I140-1Hz in between which borehole WW201347 is located. The rise in resistivity below 100 m seems to be related to the clay layer as determined in the borehole log.

Borehole WW201347 is located in the Omusati Region. TEM measurements show promising results in this area, however the drilling was not successful, a low production aquifer with unsuitable water quality was found at a depth of 103 m. Below that, hard sandstone, probably Mulden quartzite was found. Figure 16 shows the adjacent TEM-profiles which indicate higher resistivity below 100 m, the resistivity seems to coincide with less conductive material other than freshwater, or water that is found in a fissured aquifer. A more detailed cross check of the TEM measurements with the drilling results is needed. A renewed calibration of TEM measurement in this region is necessary.

Statements

- Drilling campaigns were successful to affirm results of the TEM campaign.
- The cuttings from rotary drilling and detailed core descriptions cannot be used exclusively for a hydrostratigraphic interpretation. Grain size variation of major components is low and significant differences are hardly distinguishable.
- The survey of boreholes with a differential GPS and Omnistar signal gave improved, but not sufficient accuracy of height leveling for boreholes.

Recommendations

- Pressure caps and recording at WW201346 and WW201348 are still needed.
- Establish a survey of boreholes with DGPS and an Omnistar signal or with a different survey method in future campaigns.
- Establish a simple but uniform coding for drill cuttings especially for Kalahari sediments (e.g. a flow-chart for drillers).
- Always collect cutting samples for lab investigations.

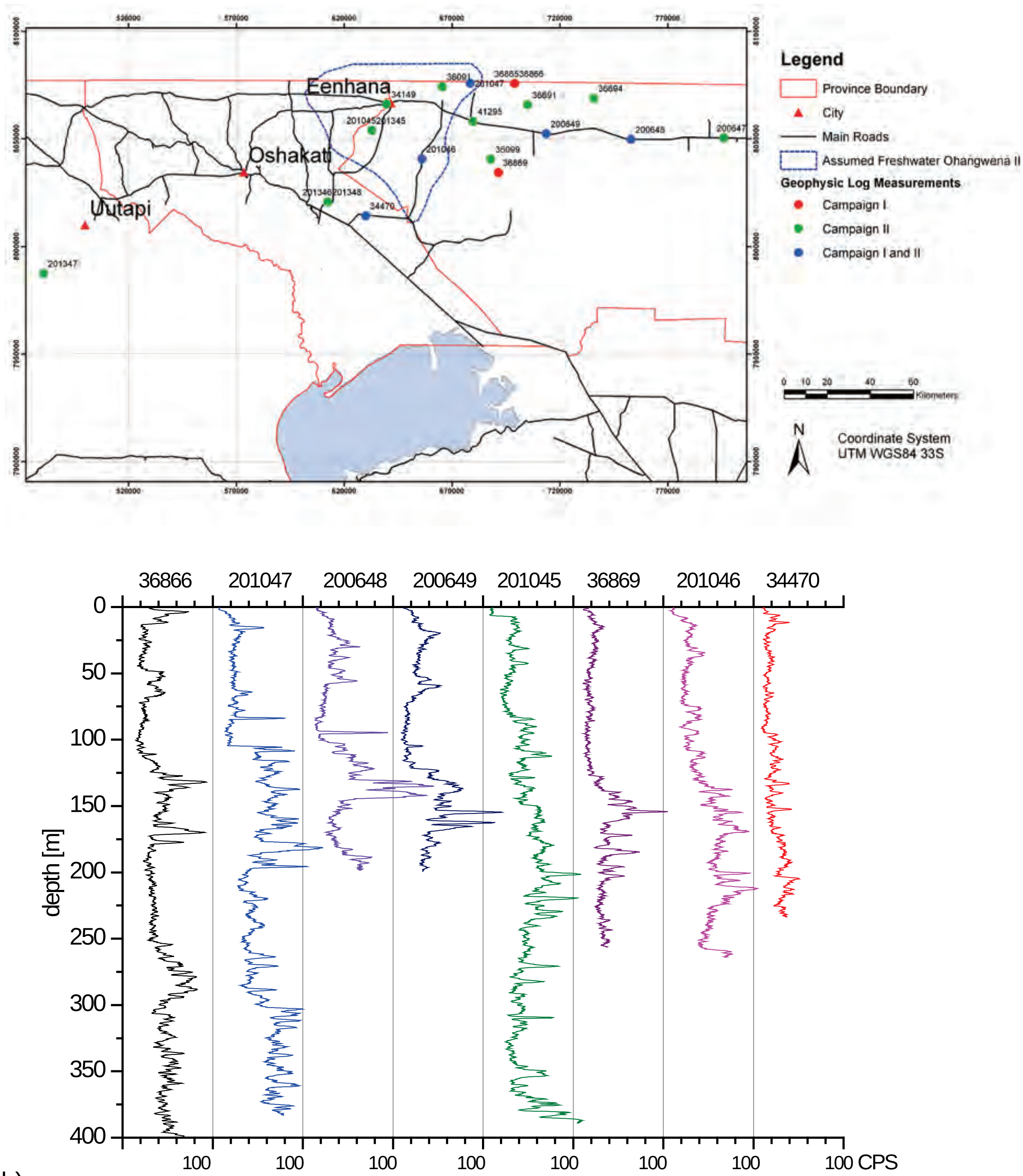
5.5 Geophysical Borehole Logging Campaign I (Terratec, Spring 2009)

During the first drilling campaign, Terratec Geophysical Services Namibia conducted a geophysical logging program (terratec, 2009), particularly within the open boreholes drilled during the first drilling campaign. In addition, other deep boreholes were also investigated. A total of 9 boreholes were investigated, three of them in open boreholes (WW201045-WW201047) while all others were in installed boreholes (WW200648, WW200649, WW34470, WW36865, WW36866, WW36869). The borehole logging program included natural gamma ray (CPS), short and long range conductivity (mmho), fluid resistivity (µS/cm), apparent formation resistivity (ohmm) and temperature (°C) (see Table 4). Not all of the logs resulted in profiles which are usable for interpretation. The best results were obtained within the open boreholes and for natural gamma rays and for conductivity. In the report (terratec, 2009) the logging of a magnetic susceptibility log was recorded. However the relevant data files seem to contain some other log types as it is similar to a negative log of the conductivity log. One possible explanation would be the low content of magnetic minerals within the sediment column and an imprinting of other signals. Using the raw data caution has to be taken and headings as well as units need to be cross checked. For example, for the short and long range conductivity the unit mmho was used, this could either be mS (Milli-Siemens) – and then the reference distance has been omitted-, or it is S*m. This is why a unit conversion was not conducted and the original unit was used in figures.

Table 4: Overview of available geophysical logs of campaign I; x: data is available; (x): data is available but meaningless due to the application in an installed borehole. For WW201045 several logs are available at different times, before and after construction of boreholes.

Borehole Number	Natural Gamma	Conduc-tivity Short Range	Conduc-tivity Long Range	Fluid Conduc-tivity	Fluid Temp era-ture	Apparent Resistivity	Magnetic Susceptibility Short Range	Magnetic Susceptibility Long Range
Units	CPS	mmho	mmho	µS/cm	°C	ohmm	CPS	CPS
WW34470	x	x	x	x	x			
WW36865	x	(x)	(x)	x	x			
WW36866	x	(x)	(x)	x	x			
WW36869	x	(x)	(x)	x	x			
WW200648	x	x	x	x	x	(x)		
WW200649	x	x	x	x	x	(x)		
WW201045	x	x	x	x	x	x	(x)	(x)
WW201046	x	x	x	x	x	x		
WW201047	x	x	x	x	x	x		

a)



b)

Figure 17: a) Overview of boreholes visited during the two logging campaigns of Terratec during 2009 and Poseidon during 2010. b) Graph of all gamma ray logs taken during the first campaign, a relation of gamma ray logs to specific layers is possible. Data is displayed in counts per second [CPS].

In Figure 17a, an overview of the location of the geophysical borehole logging campaigns is given, the gamma logs were plotted in Figure 17b according to their position in lines from east to west and north to south. A similar pattern of high and low gamma rays in the logs is visible; however a detailed correlation has not yet been done.

Also it is not yet clear which minerals are exactly producing the rays. According to Harald Dill (BGR staff, pers. communication) Muscovite might be more dominant in the upper part of WW201045, and Feldspar more in the lower part. Authigenic smectites, in contrast seem to have less K^{40} inside. Other active elements seem to be too rare to be significant. Generally, the investigations show that the overall clay content is low, mostly below 10 % as indicated by the grain-size distribution of WW201045, WW201216 and WW201217. The graphs in Figure 17b are smoothed to better indicate zones of higher and less activity. More detailed logs are found in Appendix 6.

5.6 Geophysical Borehole Logging Campaign II (Poseidon, Spring 2010)

During spring 2010, Poseidon Geophysics (Pty) Ltd conducted a geophysical borehole logging survey of several boreholes, including freshly drilled deep boreholes WW201345-WW201348 from the second drilling campaign. Not all of these new boreholes were logged before borehole construction was completed, so that some of the logs have disturbances due to the casing, and borehole stabilizers. Boreholes logged before construction are WW201347 and WW201348. The extent of the full logging program is not clear as the final report is still outstanding. Five boreholes were not logged as they were blocked or equipped with a pump (WW200646, WW34153, WW37069, WW37070, WW40627 and WW40917).

Table 5: Overview of available log files from Poseidon Geophysics.

Probe Result	3-Arm Calliper Distance in (mm)	Dual Density Natural Gamma (API) Long Spaced Density (gm/cc) Short Spaced Density (gm/cc) Calliper (mm)	Single Induction (mS/m)	Dual Induction (mS/m)	Magnetic Susceptibility (CPS)	Sonic Porosity (-)	Neutron Porosity (CPS)
WW200647	x	x	x	x	x		x
WW200648	x	x	x	x	x		x
WW200649	x	x	x	x	x		x
WW201045	x	x	x	x	x		x
WW201046	x	x	x	x	x		x
WW201047	x	x		x	x	x	x
WW201345	x	x		x	x	x	x
WW201346*	x	x	x	x	x	x	x
WW201347	x	x		x	x	x	
WW201347a**		x			x	x	
WW201348	x	x			x		
WW34149	x	x				x	
WW34470	x	x	x		x	x	
WW36091	x	x	x	x	x		x
WW36099	x	x	x	x	x		x
WW36691	x	x	x	x	x		x
WW36694	x	x	x	x	x		x
WW36865	x	x					x
WW41295	x	x		x	x		x

* Also short normal resistivity, ** another probe type used

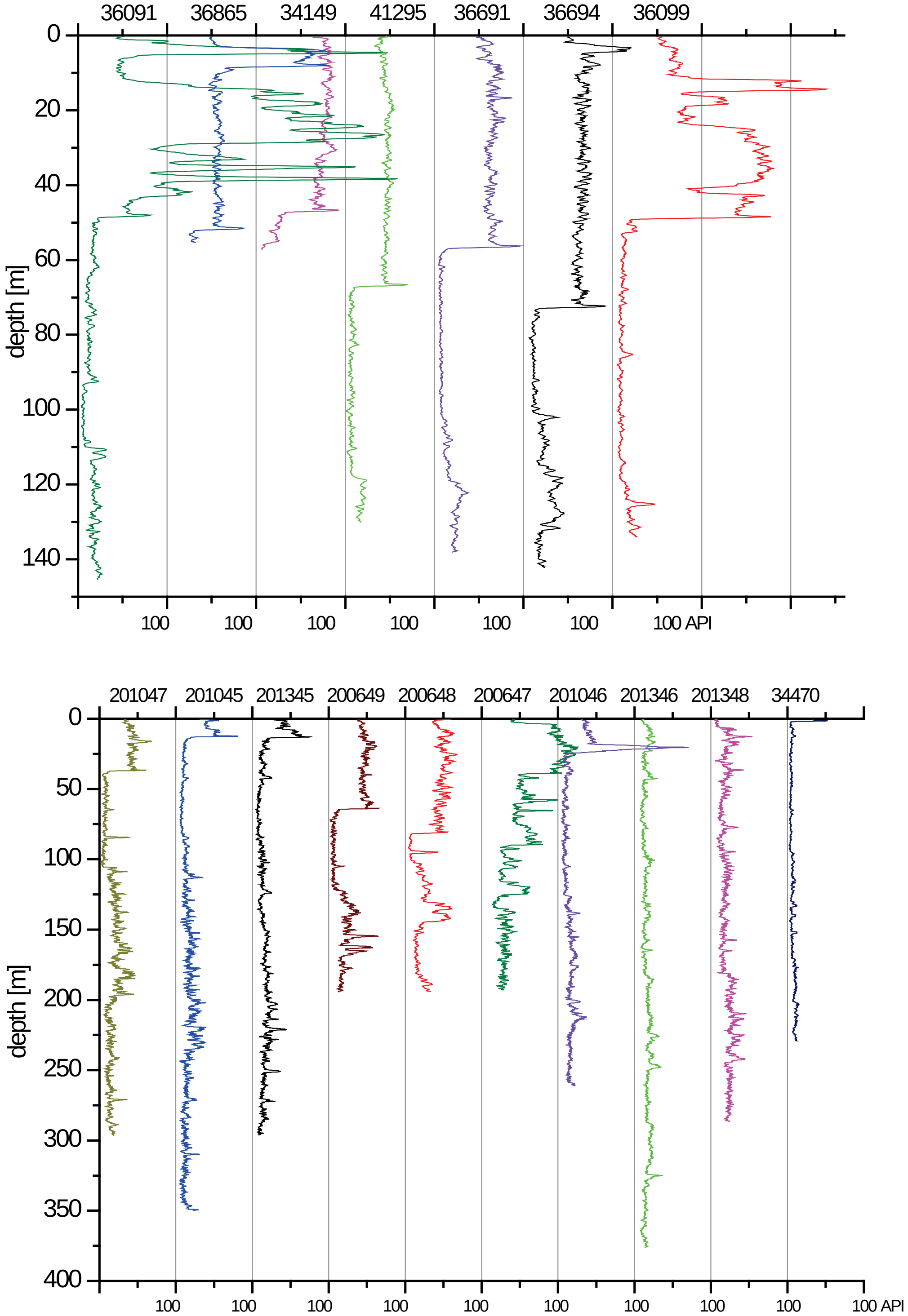


Figure 18a) Natural gamma logs from borehole logging campaign II from Poseidon Geophysics. Please note that raw data is displayed, jumps are possibly due to changes during logging or on account of anomalies due to encountering the water level. Data was calibrated and displayed in API units.

The gamma logs show anomalies and are generally of less quality than the ones from the first campaign, which is seen in boreholes WW201045-47. The gamma probe seems to be old and too weak to give good signals. The single and dual induction logs are relatively good for most of the boreholes; and the magnetic susceptibility needs further validation. When magnetic pinches or spacers are used the signal is quite disturbed.

Statements

- Borehole geophysics is a promising method to delineate aquifers, aquitards as well as fresh and saltwater resources in the Cuvelai-Etosha Basin, especially in the Cubango Megafan sediments.
- Gamma ray and bulk soil conductivity are minimum requirement for interpretation of hydrostratigraphy.
- Magnetic susceptibility did not prove relevant yet but may be of interest in areas with higher clay content.
- Gamma ray logs of Poseidon CC are almost impossible to interpret.

Recommendations

- Borehole geophysics needs to be conducted before installation of casing – otherwise the interpretation becomes significantly more difficult or impossible due to casing, pinches and borehole stabilizers (location should be recorded during construction).
- Be cautious with weak gamma ray detectors as Poseidon CC seemed to be using (weak signal compared to logs of Terratec).
- Improve the terms of reference with precise documentation of log data and well established raw data files for ease of interpretation. The available data was in parts not reliable, especially concerning meta information.

6 Aquifer Parameters

By Braam van Wyk, André Walzer, Rüdiger Ludwig and Falk Lindenmaier

6.1 Preliminary Groundwater Pressure Map

In the course of leveling of the boreholes, water levels were measured manually with a hand held dipper on 29.01.2011 and compared with the digital water level recording in some of the boreholes. These values were used for a preliminary estimation of the pressure level of the Ohangwena II aquifer. The current situation of data availability and quality gives a result with a decreasing water level towards the NE. The distance between WW201045 and WW201047 is 50.6 km, with an elevation difference of 19.76 m which is an inclination of 0.00039 and the water level inclines by -0.00009 down to WW201045. With the assumption of approximately 1.0 to 1.3 m above ground of artesian water level at borehole WW201346, a further slight increase towards the SW could be assumed (see also Figure 13). The inclination of increase is, however, quite small and it is suggested to include newly drilled boreholes of Phase II and an improved leveling, before a calculation of a groundwater pressure map is considered. It should be noted that borehole WW201045 and WW201345 are only 89.1 m apart and the difference of the height of the water level is 35 cm, which is within the uncertainty scale of the Omnistar measurements.

Table 6: Summary of preliminary results of water level heights of the field investigation on 29.01.2011.

Borehole	Elevation collar top m a s l	Collar height cm	Water Level Level Troll m below collar top	Water Level Dipper m below collar top	Elevation water level m a s l
WW201047	1132.23	94.00	38.54	38.50	1093.73
WW201045	1112.47	79.30	14.32	14.24	1098.23
WW201345	1112.64	134.40	no device	14.77	1097.88
WW201215	1112.44	108.00	37.70	37.70	1074.74
WW201046	1117.80	81.50	22.26	22.21	1095.59
WW201346	1097.35	needs to be adjusted	no device	artesian (+1)	-
WW201348	1098.00	needs to be adjusted	no device	artesian (+1)	-

6.2 Pump tests

Test pumping consisted of a step-drawdown-test followed by a 48-hour constant rate test, both with their respective recovery periods (Wyk, 2009a, 2010). Usually four, one hour steps were conducted during step testing and recovery for the step before the constant rate test was done, to at least 95% recovery. The inside diameter of the casing was 141 mm. Hence the maximum pump size that could fit in the casing had a delivery of 16 m^3/h at the respective pumping heads. These rates were sufficient to establish aquifer parameters. Considering the great depth and the confidence in the relative large thickness of the overlying aquitard(s), the pumped water was immediately discharged at surface. Data collected included the rest-and pumped water levels, regular discharge measurements and electrical conductivity recordings. Discharge rates were taken both by flow meter readings and by using a 20 liter bucket with a stop-watch.

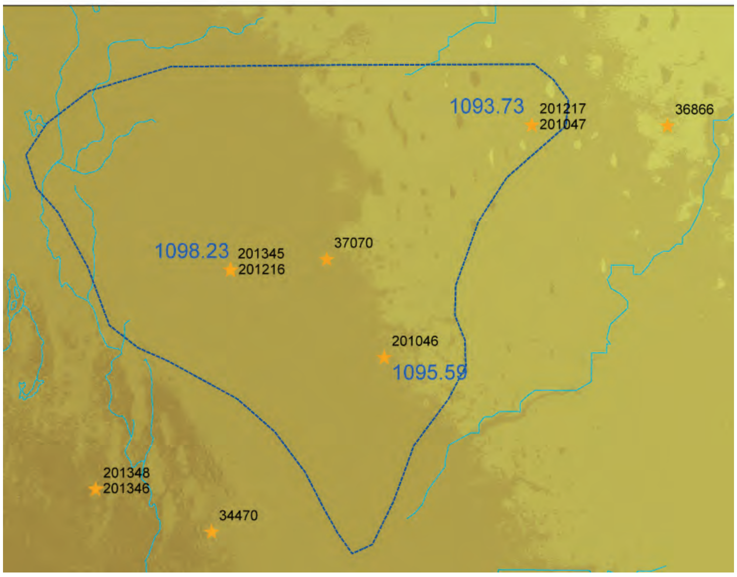


Figure 19: Sketch of groundwater pressure level measured with dipper on 29.01.2011 combined with newly derived elevation information. Groundwater flow direction would be approximately from west to east in opposite direction of surface elevation (light brown indicates a higher elevation).

Since test pump records from observation boreholes were absent, storativity values cannot be derived accurately. Transmissivities however were calculated using two techniques. The Aquitest software was used to estimate T-values by means of the Neuman- and Theis method(s) using data from the constant rate test (Table 7). The step tests were analyzed with a special method for step tests according to van Wyk (2009), calculation details are also found there (Appendix 1).

For verification reasons, a recalculation of some aquifer parameters were conducted by Walzer (2010) during his hydraulic investigation of cored samples and these results are included in Table 7. The transmissivity was evaluated from the constant rate test by means of the method of steady state flow in confined aquifers after Thiem & Dupuit. The step test was evaluated by using Cooper & Jacobs' method for unsteady state flow in confined aquifers (Krusemann and De Ridder, 1970). Adjusted aquifer thickness values were used for the recalculation according to results from the core drilling. The resulting hydraulic conductivities for WW201045, -46 and -47 respectively are 1.8, 2.3 and $1.3*10^{-5}$ m/s (see Table 7). It is noted that this seems to be extraordinarily good for aquifers with depths of 200-300 m bgl.

Table 7: Hydraulic parameters derived from constant rate tests and step tests after (Walzer, 2010; Wyk, 2009a).

Borehole	depth drilled [m]	fresh water area TEM [m]	fresh water area drilled [m]	filtered area(s) [m]	confining layer [m]	water level before pump test [m]	yield at 1 m draw-down [m^2/h]	trans-missivity Step Test Method [m²/d]	Hydraulic Conductivity (Walzer) [m/s]
WW 201045	390	200-350	228-350	238-346	85-210	13.59	4.8	106	1.8 E-5
WW 201046	266	250-400	223-??	236-259	136-210	21.6	1.5	34	2.3 E-5
WW 201047	383	190-390	200-300	214-194	105-178	37.7	2.4	51	1.3 E-5
WW 201345	300	200-350	229-299	260-294		14.1	1.2	28	
WW 201346	403	-	-	338-372		ca. -1.0	3.5	75.6	
WW 201347	175	-	-	74-114		10.3	0.2	n/a	
WW 201348	297	-	-	257-291		ca. -1.0	0.3	n/a	

The tested aquifer in borehole WW201347 is assumed to have unconfined conditions. For all other tested boreholes confined conditions were observed, and boreholes WW201346 and WW201348 are under artesian conditions. A final static water level is needed and until this is available the final results of hydraulic tests cannot be made available.

6.3 Testing Hydraulic Conductivity on Undisturbed Core Samples

From core samples shipped to BGR, undisturbed parts were taken for a laboratory analysis of vertical hydraulic conductivity. Together with results of the mineralogical investigation, namely the REM pictures, the hydraulic characteristic of the aquitards can be determined.

The hydraulic conductivity of the subsurface is highly influenced by pore volume and pore size distribution. It is related to the structure and texture of the subsurface to a large extent, and determines the flow behavior of the groundwater (Reimann, 2004). Moreover, it is an anisotropic value, i.e. it varies within the three directions of space. Under laboratory conditions it is usually tested for one dimension, mostly vertical which was done within this investigation.

According to DIN 18130 (1998), a convenient method for specifying the hydraulic conductivity (k-value [m/s]) can be performed by using a tri-axial cell. To draw conclusions from tri-axial testing it is necessary to describe the rate of flow through a porous medium within a framework that implies the condition of continuity as well as conditions of Darcy's law. Basically, this requires laminar flow, steady state and analysis in a macroscopic range. Several different pressures and measurement times were applied to the samples and variation within measurements for one sample were considered to be of no relevance. However, Walzer (2010) states that real pressures could not be applied as this would have required prolonged measurement times. A detailed description of methods and the breadboard construction used, is found in Walzer (2010), Chapter 3.2.1, 3.2.2 for the methods and Chapter 4.5.1 for the results.

Hydraulic conductivity values range between 7.45×10^{-6} [m/s] and $3.51 \cdot 10^{-12}$ [m/s] at borehole WW201217 (WW201047) and from 8.94×10^{-8} [m/s] to 7.10×10^{-13} [m/s] at borehole WW201216 (WW201045). According to DIN 18130, all values received relate to poor or very poor water permeability. Core samples WW201216 and WW201217 demonstrate a similar vertical development. Higher k-values in the upper regions are decreasing downwards and show their minimum at 201 m for WW201216 and 151 m for WW201217 respectively. The hydraulic conductivity of underlying samples reveals an increasing development at increasing depth. To draw further conclusions from the examined sediment, it is essential to refer these values to the evaluated hydrogeological layers and rock formations they have been taken from. Figure 20 displays measured and calculated values of hydraulic conductivity in relation to depth. At borehole site WW201045, the uppermost retrieved sample already lies within the aquitard zone. However, a decrease of hydraulic conductivity is seen, until it rises again at a depth of

250 m. The lowermost sample is considered to be within the Ohangwena II aquifer. It has a vertical hydraulic conductivity of approximately 9 x 10^{-8} [m/s]. The horizontal hydraulic conductivity derived from pump testing lies at approximately 1.8 x 10^{-5} [m/s]. Considering differences within vertical and horizontal (or general) hydraulic conductivities, these values are still plausible.

Table 8: Results of determination of vertical hydraulic conductivity with the tri-axial method

Borehole	Sample ID	Depth from [m]	Depth to [m]	Pressure [m - H2O]	Duration [min]	K-value [m/s]	Mean K-value [min]
WW201216	19	127.14	127.25	7	1225	7.11E-10	
				20	1580	1.54E-10	
				50	1418	3.37E-10	4.01E-10
	22	136.8	136.90	20	335	2.47E-11	
				20	950	4.26E-12	
				20	7000	4.49E-12	
				20	7000	1.24E-11	1.15E-11
	28	153.95	154.04	20	2830	1.77E-11	
				60	1380	6.36E-12	1.20E-11
	45	201.53	201.63	20	4000	n.a.	
				60	3500	n.a.	
	52	218.45	218.56	20	8050	2.16E-12	
				60	3330	7.10E-13	1.44E-12
	54	219.52	219.60	20	7062	6.79E-12	
				60	2640	4.98E-12	5.89E-12
	72	248.5	248.60	20	6050	5.97E-10	
				60	319	1.56E-09	1.08E-09
	73	249.02	249.13	5	107	9.77E-10	
				10	90	2.14E-09	
				20	1509	6.75E-09	3.29E-09
	81	266.02	266.13	2	105	8.35E-09	
				5	130	8.94E-08	4.89E-08
WW201217	9	90.02	90.13	4	160	2.21E-07	2.21E-07
	18	99.68	99.80	2	536	6.27E-08	6.27E-08
	25	105.19	105.30	1	540	1.06E-06	1.06E-06
	38	118.26	118.38	10	5440	9.07E-12	9.07E-12
	43	126.43	126.55	20	8873	2.94E-11	2.94E-11
	55	151.76	151.88	20	1120	4.60E-12	
				20	12830	3.51E-12	4.06E-12
	70	195.91	196.03	20	11365	3.29E-11	3.29E-11
	84	213.56	213.70	0.19	152	4.57E-06	
				0.24	350	7.45E-06	6.01E-06

At borehole site WW201047, samples from above and below the aquitards could be measured. Sharp knick points both in the gamma log and the conductivity log give clear boundaries for the hydrostratigraphic units. The hydraulic conductivity values give a corresponding pattern. Values for the aquifer above the aquitard (Ohangwena I Aquifer) are plausible considering results from Van Wyk (2009b). Though Van Wyk calculated transmissivities, the estimated horizontal hydraulic conductivities lie within a similar magnitude to the values plotted in Figure 20. Values below the aquitard (Ohangwena II Aquifer) are also in a range that is similar to the pumping test (1.3 x 10^{-5} m/s) considering the space dimensions, vertical and horizontal hydraulic conductivities respectively.

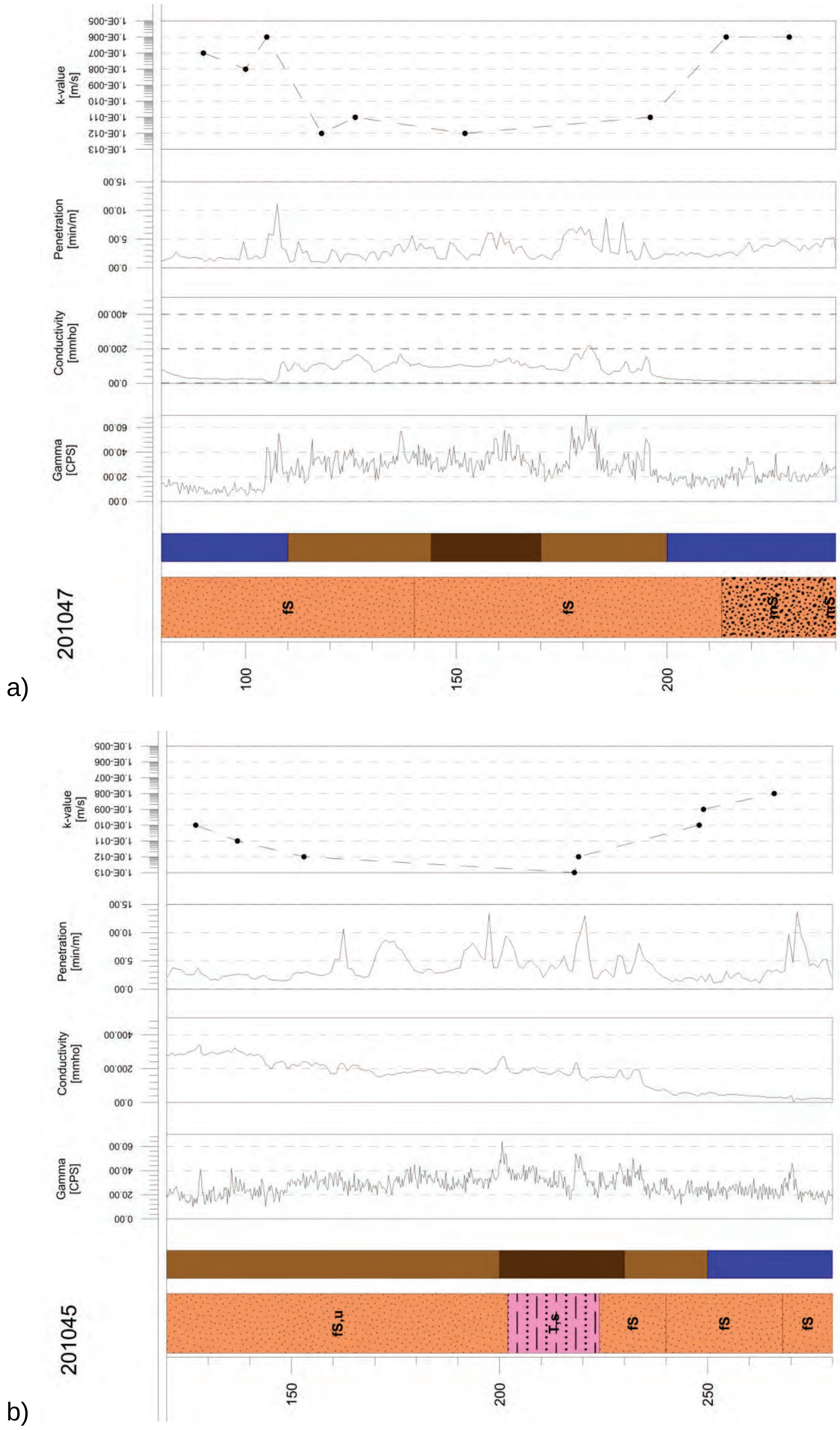


Figure 20: Values of hydraulic conductivity compared to borehole log and geophysical logs; a) at site of borehole WW201045/ WW201216 b) at site of borehole WW201047/ WW201217.

6.4 Water Samples Taking & Water Laboratory Results

A Fluid Finder of Exploration Drilling International (EDI) was used during drilling of most of the deep boreholes. It is a sampling tool attached to the drill string between the drill bit and the centralizer with the purpose of the unique sampling and testing of specific groundwater-bearing horizons. The dimensions of the EDI are 1.9 m x 0.17 m and the total open area through which flow can occur is 45 cm^2. It requires drilling to be done by means of the rotary mud method, direct flush only, which is a disadvantage for exploration drilling when accurate geological samples are desired. For water sampling, drilling is terminated and filter gravel is emplaced over a 4-6 m section in the annular space between the tool and the borehole. The drill string is opened at the surface and a pump is lowered down the drill pipes.

The fluid finder presented problems with the straightness of the boreholes. It is not manufactured with wings, and since it is attached to the drill string between the drill bit and the centralizer, which is normally attached immediately after the drill bit, it caused considerable deflection when hard layers were encountered. The operation of the tool was satisfactory after wings were welded on the fluid finder. Another problem encountered was the bridging of the gravel pack on top of the centralizer, in which it is difficult to produce a clear water sample. Added to this during such cases the pumping erodes the wall cake (and even produced a cavity) of the borehole, enhancing the risk for collapse when drilling continues.

Water samples were taken in some boreholes during drilling with the help of the fluid finder to evaluate horizon-specific water content; and these samples are listed in Appendix 8. After construction of the borehole and the pumping tests, another sample was taken in each borehole and analyzed by Analytical Laboratory Services CC, Windhoek. In 2009 one of the samples was split and also analyzed in the BGR-lab in Hannover; the comparison of values is also listed in the Appendix 8. In Appendix 8.1 the pump-test samples are ordered in a NE-SW direction sub-radial to the direction of the sedimentation direction of the megafan. An increasing salinity and fluoride content is visible. Borehole WW201047 has excellent drinking water quality with low fluoride content. All other boreholes need a treatment of dilution with other water prior to drinking use as the fluoride content is above the Namibian water quality limits of groups A-C. Total dissolved solids (TDS) as an indicator for salinity increases from about 300 mg/dm^3 in the northeast (WW201047) to 700-900 mg/dm towards the southwest (WW201045) within the freshwater zone. A diffuse and long-extending zone between freshwater and brackish water within the aquifer is enhanced by boreholes WW201346 and WW201348. While

WW201348 is filtered in the upper part of the aquifer WW201346 is filtered over the whole range. The content of dissolved solids is lower in the upper part of the aquifer at the location of these two boreholes. Borehole WW201347 is located in the far west and represents a different aquifer system; and this is indicated by the high Calcium-content compared to the very low Calcium -content of the Ohangwhena II aquifer.

Statements

- First water level measurements indicate a falling pressure head in the direction of increasing topography. This is in contradiction to the physical laws, but the following items need to be considered: low number of tested boreholes within a large area, unclear setting of filters in aquifers (combined with pressure levels of several aquifers). A basin wide pressure system influenced by unknown factors. Finally, the method of leveling is likely not precise enough.
- The hydraulic conductivity is low for the almost 100 m thick confining layer. A leakage between upper aquifers to the Ohangwena II aquifer can be excluded.
- General hydraulic conductivity derived by step pump tests indicates a good yielding Ohangwena II aquifer. Values are in correspondence of vertical hydraulic conductivity measurements which are about one order of magnitude smaller than pump test results.
- Water quality decreases towards the west, treatment or mixing of water might be necessary.

Recommendations

- The water level monitoring needs to be improved in terms of quantity and quality of measurements, especially considering the low hydraulic gradient.
- A more detailed description and monitoring of the water quality (especially TDS and Fluorid) in the vertical and lateral extent is needed for abstraction recommendations.

7 Isotope Survey of the Cuvelai-Etosha Basin

In 2008, a joint effort by the IAEA and DWA-BGR to improve isotope sampling and investigation commenced. Besides field trips and sampling, a training workshop was also conducted by the IAEA (Nick, 2008). The sampling and isotope determination is intensified in Phase II so that this chapter represents only a documentation of the work done.

In February 2008 during the extensive flooding 15 surface water samples were collected from ponds, dams and the Oshana channels. Furthermore 5 rainfall events were sampled. However these were random spot-samples within longer rainfall events during which the total amounts were not measured.

In July 2008 a reconnaissance sampling campaign was conducted, which covered 11 boreholes and 2 surface water pans. The distribution of the samples can be seen in Figure 21. These samples were analyzed for stable isotopes (O-18 and H-2), tritium and some also for radiocarbon age dating(C-14).

Sampling was done in cooperation with the IAEA and was integrated into the activities of a training course of an IAEA specialist *Callist Tindimugaya* in Windhoek and in the field.

Analysis of the samples was conducted in three locations: stable isotopes were analysed at BGR headquarters in Hannover, while tritium was analysed in iThemba Labs in South-Africa and C-14 was analyzed in the AMS lab at the University of Kiel.

There has been no previous isotope study which has covered the entire area of the Cuvelai-Etosha basin. However in the past, studies and compilations have been conducted in parts of the basin and around the area as follows:

- Isotope hydrological study in Eastern Owamboland, Etosha Pan, Otavi Mountain Land and Central Omatako Catchment including Waterberg Plateau (Geyh, 1997);
- Tsumeb Groundwater Study (Report of the groundwater quality and isotope hydrology /recharge; (GKW Consult & Bicon Namibia, 2003));
- Groundwater Investigations of the Oshivelo Artesian Aquifers (Bäumle, 2004)
- Recharge, groundwater quality and flow mechanisms of the Oshivelo and Kalahari aquifers (Cuvelai-Etosha basin) (Herczeg, 2004).
- Groundwater Investigations in the Oshivelo Region (Margane et al., 2005)
- Atlas of Isotope Hydrology (IAEA, 2007)

A detailed review of the first four studies is given in the latter report by Bäumle (2004). These studies focus mainly on the south-eastern part of the CEB. During Phase I of the present project the main area of investigation has been in the north-east of the CEB due to the presence of a deep freshwater aquifer of assumed high potential for water supply. Thus, only the data gathered by Geyh (1997); in the north-east of the CEB will be taken into consideration in this section.

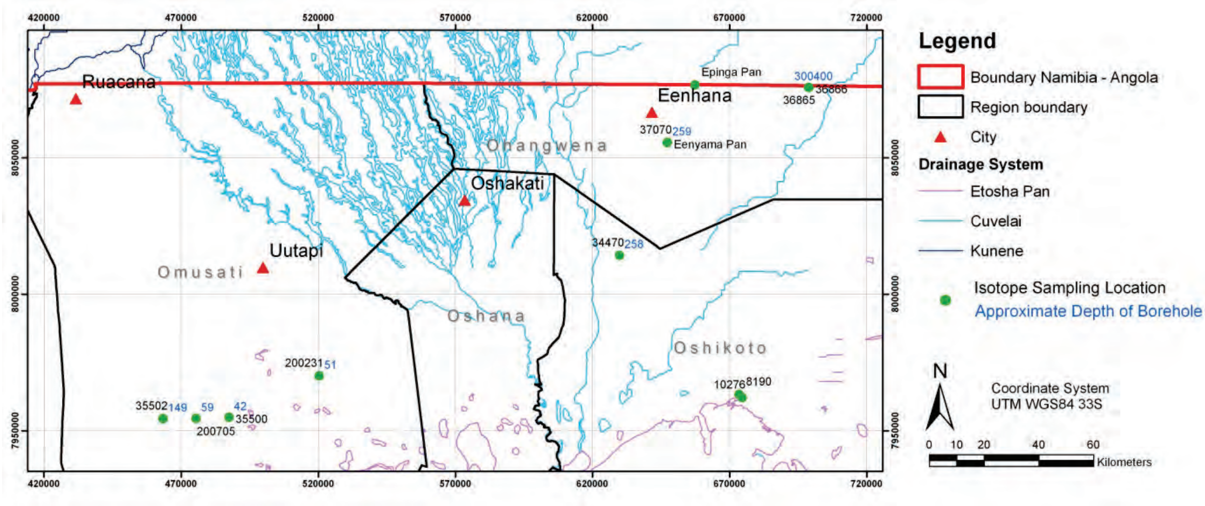


Figure 21: Overview of boreholes which were used for isotope sample investigation with total depth of borehole.

7.1 Spatial distribution

Figure 22 shows the distribution of uncorrected δO-18, δH-2 and tritium values. The final drilling depth for half of the sampled wells or boreholes were unknown and therefore values cannot be attributed to a certain aquifer, and it is rather speculative to interpret the spatial depth distribution of isotope values, e.g. for specific aquifers.

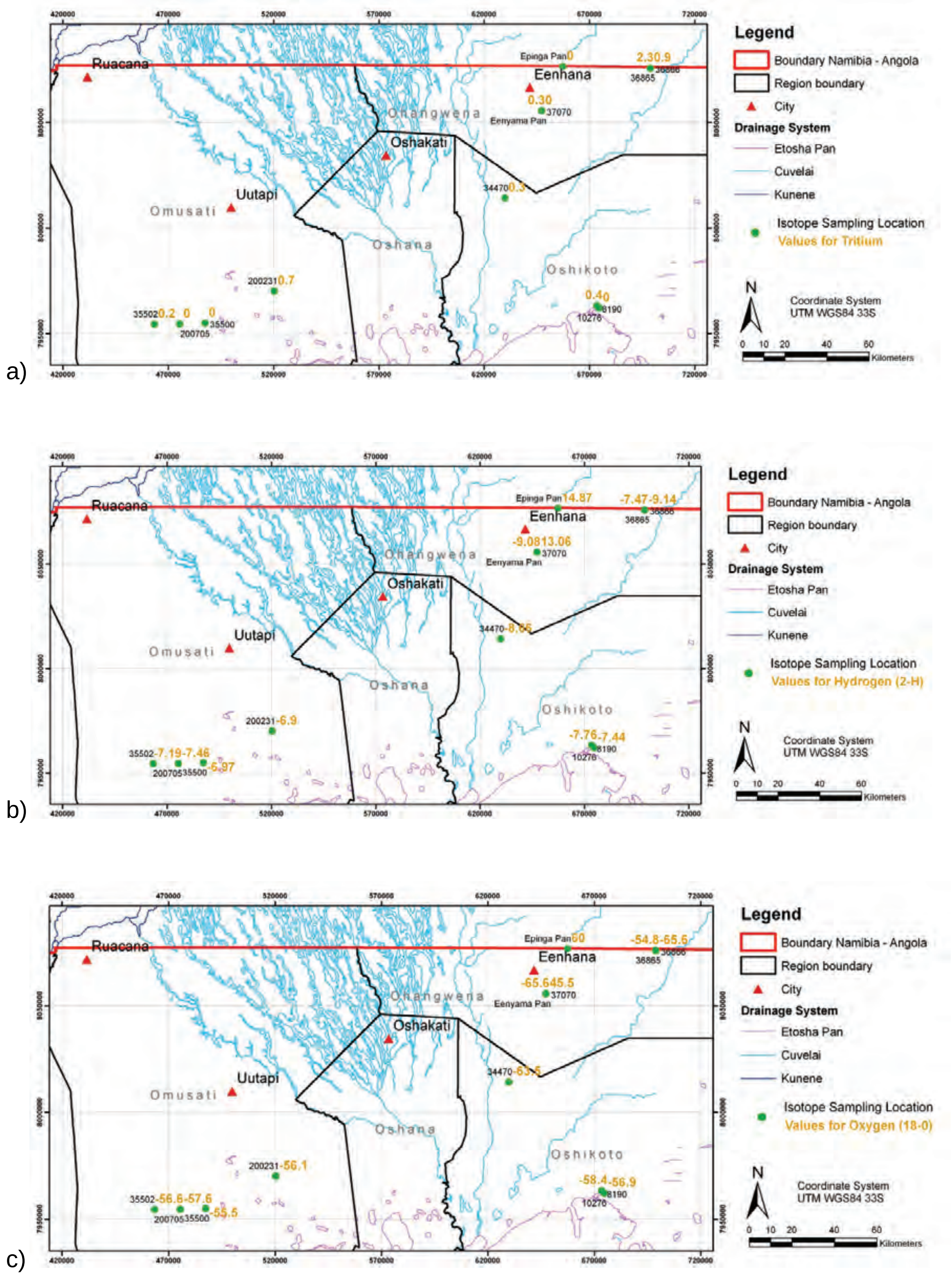


Figure 22: Display of results for Tritium (a), stable Isotopes H-2 (b) and O-18 (c) in the Cuvelai Etosha basin.

7.2 Preparation of Data for Analysis

7.2.1 Reference System Meteoric Water Line

The diagram of the stable isotopes (Figure 23) includes the samples of the two sampling campaigns.

The Global Meteoric Water Line (GMWL; $\delta D = 8^* \delta^{18}O + 10$) does not necessarily fit for the interpretation of the measured values. In the report of Verhagen (2005, given in Margane et al. (2005)) there are Meteoric Water Lines (MWL) given for Tsumeb and Cuvelai. It is not mentioned where the data for these MWLs originate from or how reliable this information is. Nevertheless, these MWLs are expressed in the diagram in order to give an idea. There is a need for the establishment of a local meteoric water line (see recommendations).

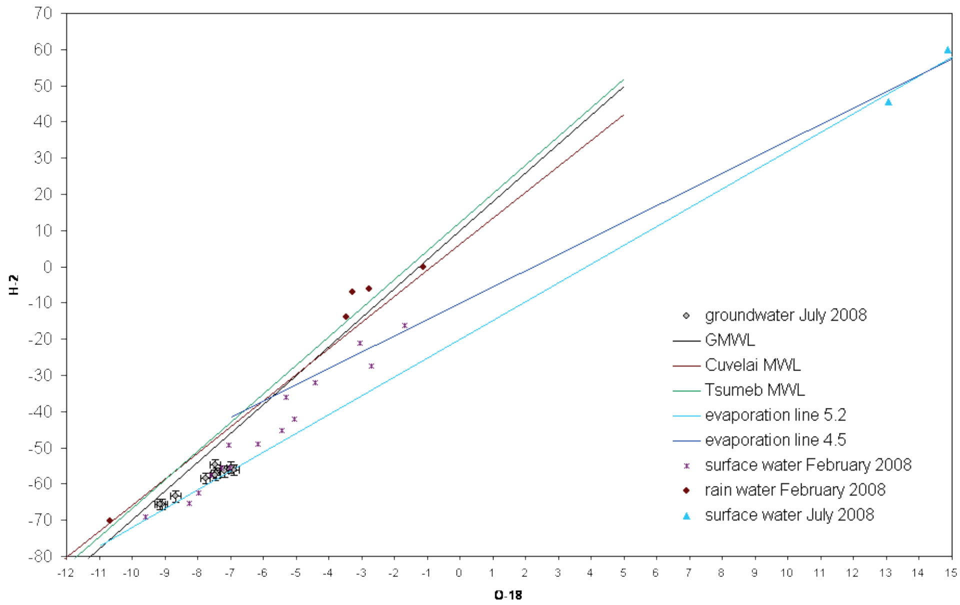


Figure 23: Diagram of stable isotopes of both campaigns.

7.2.2 Altitude effect correction

Concerning the stable isotopes H-2 and O-18 corrections for the “altitude effect” as suggested by Geyh (1997) have not been used. The altitude effect causes a depletion of heavy isotopes in recharge from rainfall at higher elevations due to the lower temperatures. Since the difference in elevation between the main recharge area, the Angolan highlands (mountains SE of Huambo), to the Etosha Pan is approximately 600 m, this effect may be considerable. Geyh (1997) estimates an altitude effect of ~ -0.25‰/100 m for the flow component from Otavi Mountain Land to the Etosha Pan. However, neither the present-day nor the past isotopic composition of the rainfall in the potential recharge area can be currently assessed or sufficiently well estimated. It seems therefore better not to use an altitude correction but to keep in mind that such an effect may still be relevant. The altitude effect for the flow from the Angolan highlands has not to date been studied.

7.3 Interpretation

7.3.1 Stable Isotopes

Plotting δH-2 (deuterium) versus δO-18 values (Figure 23) it becomes evident that most values for groundwater do not plot on the Global Meteoric Water Line (GMWL; $\delta D = 8^* \delta^{18}O + 10$) but on an evaporation line. The suggested evaporation lines for the kinetic fractionation by secondary evaporation have a slope of 5.2 and 4.5 respectively as suggested by Geyh (1997). Both lines meet the evaporated surface water samples taken in July 2008, tracing them back to either a middle part of the Meteoric Water Lines (in the case of the 4.5 slope) or to the far "light", negative end of the diagram (with the 5.2 slope). Nevertheless it can be clearly seen that kinetic fractionation by evaporation takes place in the surface water reservoirs making the water "heavier" from February to July 2008. Unless no further, weighted rainfall samples are analysed from the Cuvelai Etosha Basin and from the surface waters of Angola, where the floods originate from, an interpretation of this data is speculative. With the few, un-weighted rainfall samples from February 2008 and the assumed fact that rainfall and discharge in Angola is lighter due to an altitude effect, the isotopic signal of the surface water ponds sampled in February 2008 underlines the assumption that pond water in most cases is a mixture of local rainfall and discharge from Angola.

According to the diagram the groundwater samples, clearly plot in the negative corner, indicating that little to no evaporation had taken place before the water infiltrated beyond the evaporation-influenced zone. The signals are scattered as they originate from very different depths (the known figures range from 42 m to 400 m). However, three samples are even lighter than the rest, and these come from the boreholes WW37070, WW34470 and WW36866 which are 259, 258 and 400 m deep respectively. All of them represent the Ohangwena II Aquifer (formerly called KOH). The sample of borehole WW36865 (300 m deep) is assumed to be contaminated, as neither stable isotopes resemble the signal of neighbouring borehole WW36866 nor does the tritium (H-3) content fit into the picture (2.3 TU indicates recent water), thus it is excluded from the interpretation. It needs to be mentioned that while borehole WW37070 and WW36866 show fresh water with EC-values below 1000 µS/cm, borehole WW34470 has an EC of more than 4000 µS/cm and TEM-measurements did not respond positively for a freshwater/ saltwater interface.

Isotopic signals are nonetheless very similar. Samples that are derived from the south-western part of the CEB (WW200231, WW200705, WW35500, WW35502) cluster with the highly saline, artesian water samples from the north-eastern part of the Etosha Pan, boreholes WW10276 and WW8190.

7.3.2 Tritium

The distribution of tritium values (Figure 23) indicates that little to no recent recharge has occurred. The highest value is 0.9 TU, except for the unlikely value of 2.3 TU for borehole WW36865 as the Tritium values in the Ohangwena II Aquifer (KOH) are below 1. The elevated value of WW36866 (0.9 TU) and WW36865, however, might indicate that some mixing with younger water occurs within these boreholes. It could be both possible, that filtered areas of higher and lower aquifers are connected by the borehole or through leakage from the Ohangwena I towards the Ohangwena II aquifer.

7.3.3 C-14

The Radiocarbon age was determined by the *Leibniz Labor für Altersbestimmung und Isotopenforschung of the Christian-Albrechts University Kiel* (Table 9). A short report of the procedure is available in German. The data has not been further interpreted due to missing information with regard to the filter in the boreholes. Mixed waters also give mixed ages and hence do not represent the real information. A video capturing of these boreholes is recommended. Results show that the last ice age might have re-set the information derived from the C-14 samples. Also, maximum detection level is about 50 000 years for C-14 so that possibly the detected ages are less precise.

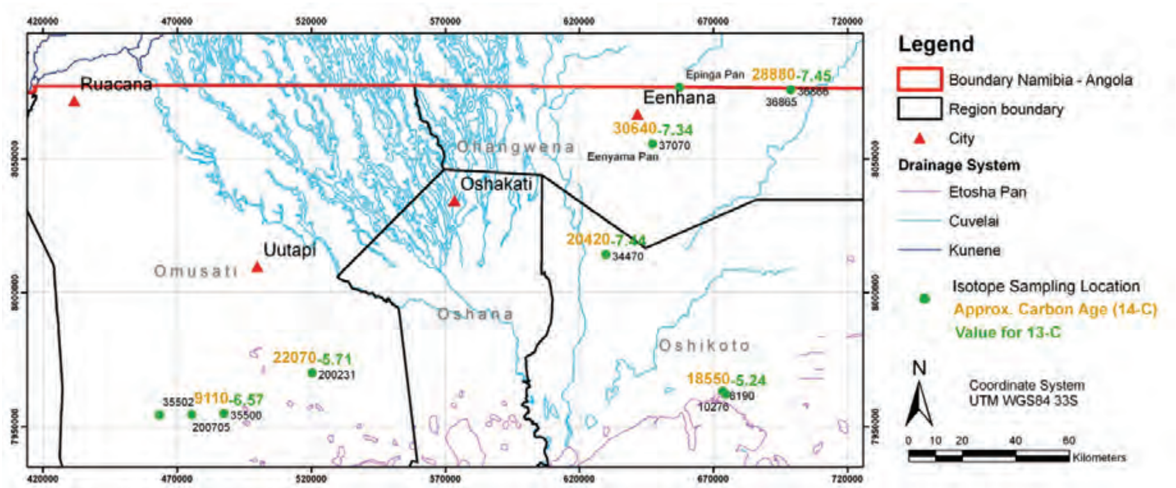


Figure 24: Spatial distribution of carbon ages and stable carbon values (13-C).

Table 9: Results from radiocarbon age determination.

Borehole sampled	**WW10276**	**WW34470**	**WW37070**	**WW36866**	**WW200231**	**WW35502**
Date of sampling	11.07.2008	11.07.2008	12.07.2008	12.07.2008	13.07.2008	13.07.2008
Region	Oshikoto	Oshikoto	Oshikoto	Ohangwena	Omusati	Omusati
Lat	18.42321	17.95572	17.58127	17.394	18.3588	18.5003
Log	16.65483	16.22803	16.38986	16.874	15.1938	14.513
RWL (m)	Artesian	4.14	18.37	52.76	7.1	-
EC [mS/cm]	14.62	4.74	0.995	0.645	31.2	-
PH	8.93	9.8	9.3	10.03	7.46	-
Temp	29.0	27.1	19.2	27.7	-	-
Fraction [mg C]	27.7	22.4	11.8	7.8	11.5	11.5
PMC (corrected)*	9.94	7.87	2.21	2.75	6.41	32.18
error	± 0.11	± 0.11	± 0.10	± 0.10	± 0.11	± 0.18
Radio carbon age	**18550**	**20420**	**30640**	**28880**	**22070**	**9110**
error BP	± 90	± 110	+ 360 / -340	+ 290 / -280	+ 140 / -130	± 45
δ^{13}C (‰)	-5.24	-7.44	-7.34	-7.45	-5.71	-6.57
error	± 0.18	± 0.17	± 0.30	± 0.33	± 0.22	± 0.22

*PMC is the percentage of modern carbon (1950), corrected on the mass fraction of the C-13 measurement.

7.4 Outlook

As the need for a local MWL has been recognized, sampling of rainfall for stable isotope analysis was agreed to be an activity carried out throughout Phase 2 of the DWA-BGR project. The sampling will be done systematically at four weather stations (Ruacana, Tsumeb, Ondangwa and Okongo) through the support of Meteorological Service of Namibia (weather station Tsumeb and Ondangwa) and the Directorate of Water Supply and Sanitation Coordination (Ruacana and Okongo). The analysis will be covered by the IAEA in cooperation with iThemba Labs in South-Africa. Sampling has started during the rainy season of 2008/2009 while results will only be available to the project in Phase 2.

Statements

- Isotope study is ongoing but needs additional samples before a sound interpretation is possible.

Recommendations

- Sampling should only be done when well construction is available to avoid the sampling of mixed waters of different aquifers.

8 Conclusion

The TEM sounding proved to be a successful method for the determination of deep seated freshwater aquifers within the Ohangwena Region, namely the Ohangwena II Aquifer. A three dimensional model of the TEM soundings within the vicinity of the most promising area for deep freshwater resources gives help in interpreting the groundwater body and its boundaries. A boundary towards brakish water extending south-east to north-west is delineated which likely corresponds to lake levels of Paleolake Etosha.

The almost basin-wide TEM sounding campaign also showed interesting and promising results in the Ishana and Omusati Regions. However, additional calibrations with drillings are necessary there. An exploratory drilling in the Omusati region was not successful so far.

Three drilling campaigns proved the extension of the deep seated freshwater body of Ohangwena II aquifer. Freshwater is found in between a depth of approximately 200-300 meters (WW201047) further up the Cubango Megafan and 250-300 meters (WW201045) towards the center of the Cuvelai-Etosha depression. A thick confining layer caps the highly pressurized aquifer. Vertical hydraulic conductivity measurement of undisturbed cores show very low values for the confining layer (10^{-8} to 10^{-13} m/s) and satisfying values for the aquifer itself, 10^{-6} m/s for vertical and 10^{-5} m/s for general hydraulic conductivity derived from pump tests). Water quality is fresh with increasing values for salinity towards the center of the Cuvelai-Etosha depression. According to Namibian and international standards, Fluoride and Arsenic concentrations are mainly too high for drinking water use. A treatment or mixing of water is recommended before using as drinking water. A more detailed investigation of water quality is needed and not within this report.

Concerning the Ohangwena region, a complex sedimentological evolution is expected for the geological structure of the Cubango Megafan. An almost 400 m thick layer consisting of sand with low silt and clay content (10-20 wt.% in average with few thin clay layers) is encountered in the drillings. It is difficult to define hydrogeological layers only on drill cuttings. Hence detailed core investigation and especially gamma and conductivity geophysical borehole logs proved to be very helpful for the interpretation of hydrogeological and sedimentological layers. This also showed that TEM soundings are not fully able to distinguish between confining and non-confining layers as the clay content differences are too low to be seen in the TEM exploration. The interpolated TEM sounding profiles are not exactly representing sedimentological or hydrogeological layering in all parts. It rather shows an almost clear distinction of salt- and freshwater distribution (Figure 8).

A preliminary Isotope investigation campaign was successful but needs further intensification.

Major recommendations for further investigations are:

- A refinement of TEM measurements for the Ohangwena II aquifer would prove successful
- Re-calibration and further exploration with additional drillings would be required in Ishana and Omusati Regions
- Borehole geophysical logging before the construction of boreholes should be made mandatory for the Cuvelai-Etosha Basin, especially for the Cubango Megafan. In combination with detailed sedimentological description after specific standards this is the **only** possibility for high quality interpretation of aquifers and aquitards within this region. Construction of boreholes without geophysical logging would lead to an improper setting of filters and casing and hence to the short cut of possibly brackish and freshwater aquifers.

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