A Stable Isotope Study of the Hydrological Systems in the Naukluft Region in Namibia

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Abstract

The Naukluft Region is situated ± 200 km southwest of Windhoek in Namibia. The region includes the Naukluft Nappe Complex (NNC), a series of nappe stacks of severely thrusted and folded limestones and dolomites of Neoproterozoic Damara orogen. Although it is a very arid (<200 mm /yr) part of the country, it is also one of the most important tourist destinations, because of its varied geomorphology, spectacular scenery and fragile vegetation biomes. It is the availability of fresh water that that will limit the growth and development of both the agricultural and tourism industries in the region. In this detailed stable isotope study ($\delta^{18}O$, δD and $\delta^{13}C$) of the precipitation, surface- and ground- water in the region, numerous possibilities for recharge and aquifer characterization are provided. The river, stream and groundwater in the Naukluft have average $\delta^{18}O$ and δD values of between -7.0‰ and -5.0‰ and between -45‰ and -30‰ respectively, with all values plotting close to the Global Meteoric Water Line. Most of the borehole data for both seasons plot at the negative end of GMWL ($\delta^{18}O$ between -8.0‰ and -6.0‰ and δD between -40‰ and -50‰), whereas surface waters and rivers in March 2008 and February 2009 had higher δD and $\delta^{18}O$ values. It is suggested, based on the large variability between groundwater and precipitation stable isotope values, that there is a significant amount effect and only large rain events infiltrate the aquifers in the Naukluft. Spatial distribution of the stable isotope values throughout the Naukluft region, indicate that the boreholes in the NNC tap water from at least two distinct aquifers. The ^{14}C data (Bernhard, 2009) suggest that an entirely separate, confined source is present at the edge of the Namib Desert. The aquifers are proposed to be homogenous, characteristic of large, well-mixed sources.

Foreword

The Naukluft Water Project is an NRF-SADC funded project (2008-2009), with Dr Jodie Miller (University of Stellenbosch) and Dr Benjamin Mapani (University of Namibia) as grant co-chairs. The project was a collaborative project involving the University of Cape Town (UCT), the University of Stellenbosch (US), the University of Namibia (UNAM) and the University of Lausanne, Switzerland (UNIL). The project involved numerous aspects of the hydrogeology of the Naukluft.

The water from the Naukluft was analysed at UCT, US and UNIL. At US, two honours students (2008) under the supervision of Dr Jodie Miller, Shane Turner and Alet Terblanche focussed on the water geochemistry, specifically the cations and anions of the Naukluft water presented here. At UNIL, under the supervision of Prof Torsten Vennemann (UNIL), two master's students: Caroline Reymond and Claude Bernhard analysed the nitrate content and the ^{14}C of the water. At UCT, Kate Naudé (author) under the supervision of Prof Chris Harris analysed the stable isotopes of the waters in the Naukluft. Two honours students, Fabian May (from US under the supervision of Dr Jodie Miller) and Winnie Kambinda (from UNAM under the supervision of Dr Benjamin Mapani), performed pump tests on boreholes in the Naukluft.

Dr Christie Rowe (UCT) headed a structural research project (2009) in the Naukluft with two UCT honours students: Carly Faber and Fernando Sylvester.

A water usage aspect to the project was also explored by an honours student, Marion van Dorssen at the US under the supervision of Prof Ronnie Donaldson and Dr Jodie Miller.

All fieldwork for this specific study (*A Stable Isotope study of the hydrological systems in the Naukluft region in Namibia*) was under the supervision of Dr Jodie Miller and all analysis under the supervision of Prof Chris Harris.

Table of Contents

Figures

Tables

Symbols and Acronyms

%cc	Percentage calcium carbonate (Percentage DIC as calcite equivalent)
%cc	
‰	Per mil
a.s.l	above sea level
b	Intercept
CO_2	Carbon dioxide
DCW	Digital Chart of the World
DIC	Dissolved Inorganic Carbon
EC	Electrical Conductivity
Fm	Formation: A lithostratigraphic term for a unit ranked below a Subgroup
GMWL	Global Meteoric Water Line
HDPE	High Density Polyethylene
He	Helium
HNO_3	Nitric Acid
IAEA	International Atomic Energy Agency
K/Ar	Potassium/Argon
L	litre
LMWL	Local Meteoric Water Line
m	slope
m	metres
Ma	millions of years
Mbr	Member: A lithostratigraphic term for a unit ranked below a Formation
mg	milligrams
mg/dm^3	milligrams per litre
mm/yr	millimetres per year
$NaCO_2$	Sodium bicarbonate

NK	Naukluft
NNC	Naukluft Nappe Complex
O_2	Oxygen
°C	Degrees centigrade
PDB	Pee Dee Belemnite
pH	Acidity/basicity
PP	Polypropylene
ppm	parts per million
r	Pearson's Product Moment Correlation Coefficient
RMA	Reduced Major Axis
s	Standard deviation
SLAP	Standard Light Antarctic Precipitation
SMOW	Standard Mean Ocean Water
Std. dev.	Standard deviation
T	temperature
TDS	Total Dissolved Solids
UCT	University of Cape Town
UNIL	University of Lausanne
US	University of Stellenbosch
VSMOW	Vienna Standard Mean Ocean Water
δ	Per mil (‰) deviation from the standard
$\delta^{13}C$	$[(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{reference} - 1] \times 1000$
$\delta^{18}O$	$[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{reference} - 1] \times 1000$
μmol	micro-moles
μS/cm	Micro-siemens per centimetre (a measure for EC)

1 INTRODUCTION

The availability of fresh water is becoming a significant problem as the Earth's ever-increasing population continues to put pressure on its natural resources. The concern is not only in finding potable water, but is in finding it in sufficient quantities. In this current age of uncertain and unstable economies, there is an urgent need to find sustainable water sources and manage these appropriately into the future. Southern Africa is vulnerable to changes in the hydrological cycle because of the large proportion of the population living below the poverty line and the high proportion of semi-arid and arid regions. Management of limited resources in these environments can only be achieved with a detailed understanding of the source of the water and recharge processes at work. The use of isotopes in achieving this understanding lies in the fact that all water has a naturally occurring isotope signature and water recharged at different times or locations, or water that has followed different flow paths might be isotopically distinct. Thus, as water becomes the main priority in planning for the future, so the use of isotopes as tracers in hydrological systems is becoming a more important and established tool.

The Naukluft Region is situated ± 200 km southwest of Windhoek in Namibia and forms part of the Namib-Naukluft Park (**Figure 1**). This park is one of the most important tourist destinations in Namibia, because of its varied geomorphology, spectacular scenery and fragile vegetation biomes. In this very arid (<200 mm/yr) part of the country, the availability of fresh water limits the growth and development at the current rate and scale of both the agricultural and tourism industries in the region. The Naukluft Mountains form a nappe complex that consists mainly of karstic dolomites and limestones and represents the most significant freshwater catchment in the area, which sustains the needs of the surrounding population and the economies on which they depend. However, there is no water management scheme in the area, no monitoring of borehole drilling, which occurs regularly, and no plans for the future seem to have been put in place. In order for the growth of the agricultural and tourism industries to continue, the sustainability of the water currently being exploited needs to be assessed and a plan constructed in order to manage the use of the water effectively.

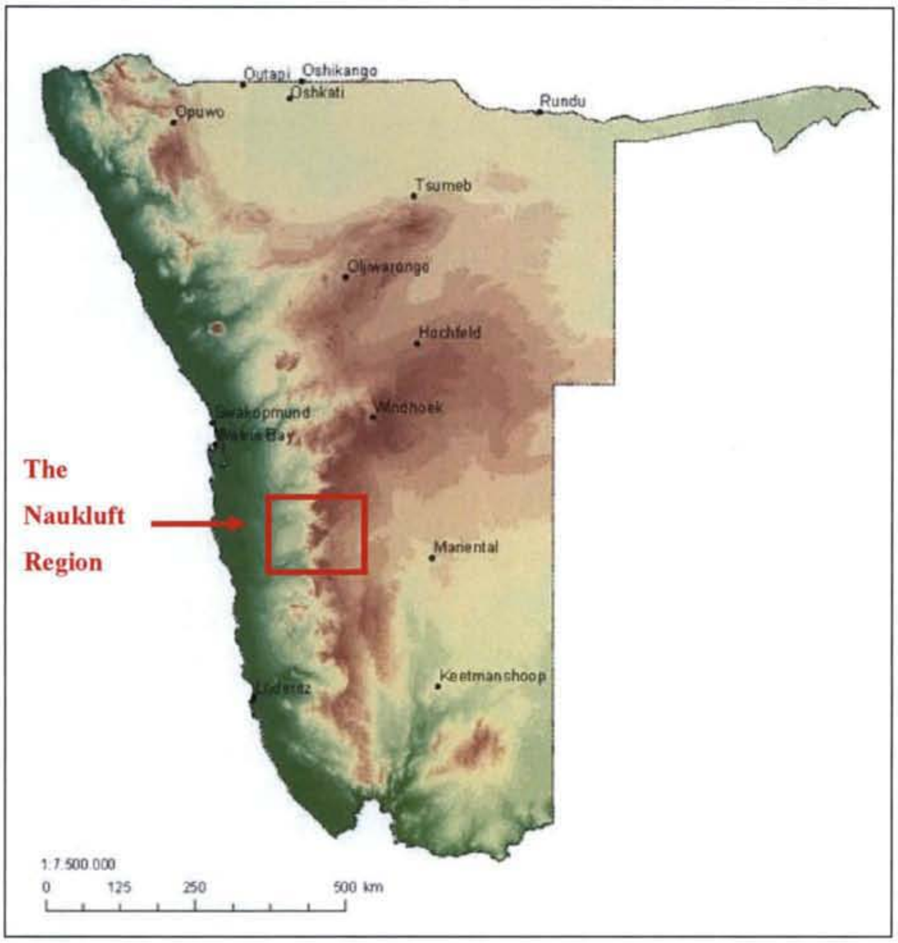


Figure 1: Map of Namibia showing location of the Naukluft with respect to the capital city of Windhoek. High elevation areas are in brown and lower elevation areas are in green. (SFB 389 ACACIA, subproject E1, Atlas of Namibia project, 2002) Red square denotes location of the Naukluft.

Several recent studies of groundwater in semi-arid to arid regions and other karstic environments have used stable isotopes as tracers to effectively establish and understand the water processes at work. In the semi-arid Granada Basin in Southern Spain, Kohfahl *et al* (2008) used stable isotopes and hydrogeochemistry to establish the source of the abundant spring water and the source of the water that recharges the basin watershed. The spring water showed isotope signatures relating to recharge from both the western Mediterranean and Atlantic, whereas the quaternary aquifer showed spatial separation of recharge sources relating to bankfiltration of rivers (Kohfahl *et al*, 2008). Barbieri *et al* (2005) used the spatial variation of $^{18}O/^{16}O$ and D/H ratios to trace groundwater sources to mean isotope elevations and used $^{87}Sr/^{86}Sr$ ratios to show seasonal variations in springs in the carbonate karst aquifers of Gran Sasso in central Italy. Although central Italy has a Mediterranean climate, the study did emphasise the contribution of isotope variations both spatially and temporally, to groundwater flow-paths in karstic environments. In another karst dominated environment, although of subtropical/savannah climate, Marfia *et al* (2004) used stable isotopes (δD, $\delta^{18}O$ and $\delta^{13}C$) and major ions to show the rapid recharge rate and influence of groundwater geochemistry on surface water in Belize in Central America in order to assess what may affect the water quality of the drinking water. In the semi-arid regions of Israel, stable isotopes were used to assess the rainfall-recharge relationship in its karstic aquifer systems (Ayalon *et al*, 1998). A distinction between fast and slow drips infiltrating into caves was explored and the source of slow-drip water was attributed to water that remained for several decades in the upper vadose zone, whereas fast-drip water recorded an isotope signature that was related to heavy rainfall events and a minor component of slow-drip water (Ayalon *et al*, 1998).

In northern Chile, Aravena (1995) studied isotope hydrology and geochemistry of the groundwater in order to establish groundwater quality, origin and residence time, evaporation times and recharge relationships. The most important conclusion of this study was that the groundwater in Northern Chile should be considered a non-renewable resource. Aravena (1995) established that there was a multi-aquifer system associated with recharge at different altitudes and showed that many $\delta^{18}O$ ratios showed values indicating precipitation at low altitudes, where rain was no longer relevant, establishing that recharge must have occurred in wetter climates. It was also established that precipitation in Chile was affected greatly by evaporation on its way down, with the groundwater data plotting below the local meteoric water line (Aravena, 1995). Through an examination of isotopes in soils after flooding, it was established that many of the rivers in the area, which were expected to recharge aquifers, did in fact lose most of their water to evaporation (Aravena, 1995). In an arid climate such as Chile, these sorts of results are not unexpected but are essential to future growth and planning.

Locally, Vogel and van Urk (1975) found groundwater samples in southern Africa's semi-arid regions to have reasonably constant isotope compositions within the same district and have become a distinguishing feature of an area. They also used isotopes to indicate that infiltration only occurred during periods of heavy precipitation (Vogel and van Urk, 1975). The IAEA (International Atomic Energy Agency), as a part of their water resources project, used stable isotopes to assess the Oshivelo artesian aquifer (NAM8004) and Southeast Kalahari basin (RAF8029-NAM) to prevent over-exploitation and better management of water resources. The Oshivelo aquifer borehole water showed a mean $\delta^{18}O$ of -8.0 ± 1.2‰ and δD of -59 ± 6‰, while the Southeastern Kalahari basin borehole water has a mean $\delta^{18}O$ of -6.6 ± 1.0‰ and δD of -48 ± 5‰ (IAEA, water resources programme).

Although there is an understanding of fresh water processes and sources in other arid regions, there is very little recent knowledge on the origin and recharge relationships of the groundwater in Southern Africa, particularly in and around the Namib-Naukluft region. Stable isotope analysis of the water in the region will help to establish whether an abundance of fresh water will be available in the future, as currently this water resource is unmanaged.

Stable isotope analysis of natural water is particularly useful as oxygen and hydrogen isotopes make up the molecules of water and are thus built-in tracers (e.g. Sharp, 2007). Original isotope compositions of water can change by physical processes and by chemical reactions with other fluids and rocks at high temperatures (e.g. Sharp, 2007). The wide range in $\delta^{18}O$ and δD of meteoric waters are fundamentally related to phase changes during freezing and evaporation (ie. ocean evaporation and cloud circulation) (e.g. Sharp, 2007). Meteoric water originates as atmospheric precipitation in the form of rain, fog, hail, sleet and snow (e.g. Sharp, 2007, Criss, 1999). In the Naukluft, rain can be considered the primary source of meteoric water. Meteoric water resides in the Naukluft in groundwater systems and rivers. The use of ^{13}C as a tracer for carbonate evolution in water systems has been used by Aucour *et al* (1999),Bouchaou *et al* (2009) and Gonfinatini and Zuppi (2003), among others. Specifically, the analysis of $\delta^{13}C$ of dissolved inorganic carbon (DIC) is of particular importance as it reflects possible sources of carbon and therefore can help to assess recharge pathways of the groundwater. The effect of the dissolved CO_2 in the soil on the $\delta^{13}C$ of the DIC in the groundwater would vary considerably, depending on the amount of soil and the flow-path of the infiltrating water.

The objective of this study is to determine the stable isotope composition (δD, $\delta^{18}O$ and $\delta^{13}C$ of the DIC) of the precipitation, surface, spring and borehole water in the Naukluft area as well as to determine the spatial variation in isotope composition within the region. In distinguishing specific isotope characteristics for different sources, as has been done successfully in many other arid and karstic regions, one can establish to what degree the prevailing precipitation mixes with groundwater and surface water. The spatial variation of isotope compositions of the groundwater, which contributes to the understanding of underground flow-paths, might determine whether the groundwater is sourced from different areas and if the aquifers being tapped are inter-connected and rechargeable.

1.1 Aims and key questions

The following aims and key questions have been outlined for this study:

1) To determine the stable isotope characteristics of the water in the Naukluft

- What is the range of $\delta^{18}O$ and δD and $\delta^{13}C_{DIC}$ for the groundwater, surface water and precipitation?
- Do the $\delta^{18}O$ and δD values of the precipitation, surface- and groundwater in the Naukluft define a LMWL (Local Meteoric Water Line) and how does this compare to the GMWL (Global Meteoric Water Line)?
- What is the spatial distribution of $\delta^{18}O$ and δD and $\delta^{13}C_{DIC}$ in the Naukluft and does this vary seasonally?

2) To compare the O- and H- isotope composition of the water to other arid regions and karstic environments

- Do the isotope values lie along a similar Meteoric Water Line (MWL) as other arid regions?
- Are the stable isotope values of the groundwater samples within a similar range as compared to other arid and karstic environments?
- Are the $\delta^{13}C$ values of the groundwater samples similar to those in other dolomite-dominated areas?

3) To determine the recharge processes in the Naukluft

- What is the relationship between the stable isotope values of the two end-members, groundwater and precipitation?
- To determine the amount of recharge per year by establishing the shift in δD between groundwater and precipitation and the frequency of the recharge by looking at seasonal variation and radiogenic isotopes.
- To determine the origin of the groundwater in the Naukluft recharge and whether recharge is as a result of normal rainfall/specific episodic rainout events or other processes.

4) To determine to what extent can the stable isotope values of groundwater be used to identify and characterise aquifer systems in the Naukluft region

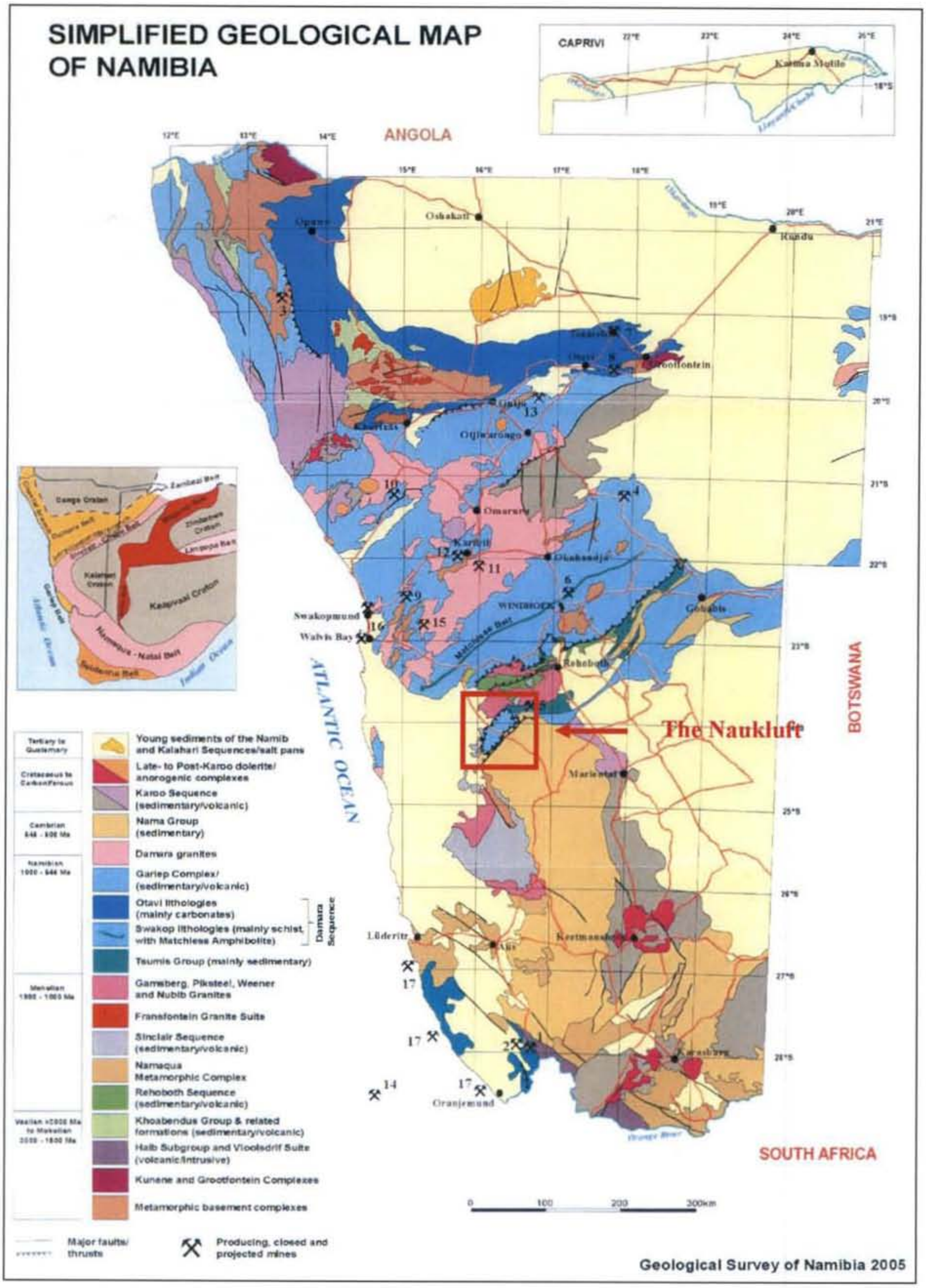
- Do the stable isotope values of the groundwater fall into any distinct compositional groups?
- How and to what extent might radiogenic isotopes and elemental concentration data help in order to characterize source/s and/or aquifer/s?
- From this information, what kind of aquifer system is present in the Naukluft?

2 GEOLOGICAL AND GEOGRAPHICAL SETTING

2.1 Regional geology

The Naukluft mountains, in and around which the study area lies, are situated southwest of Windhoek in Namibia and emerge as a series of nappe stacks of thrusted and folded sediments of the Neoproterozoic Damara orogen in an otherwise relatively flat landscape (e.g Viola *et al*, 2006; Miller *et al*, 2008) (**Figure 2**). Namibia's Damaran orogenesis is due to Pan African deformation that formed a mobile belt that trends in a southwesterly direction, separating the Congo Craton from the Kalahari Craton (e.g. Viola *et al*, 2006). The Naukluft Nappe Complex (NNC) lies at the southern end of this, at one of the corners of Africa's great escarpment (Korn and Martin, 1959).

The lithologies present in the Naukluft area consist of: (1) the granitic pre-Damaran basement, (2) the Damaran Nappe sequences, (3) Nama sediments that crop out mainly in the south, (4) recent tufa deposits throughout the NNC and (5) desert sands to the west (**Figure 3**). The stratigraphy and the structure of the Naukluft area play equally important roles in present day hydrological processes and therefore the main characteristics of each are summarised below.



Figures 2: Geological Map of Namibia (Geological Survey of Namibia, 2005).

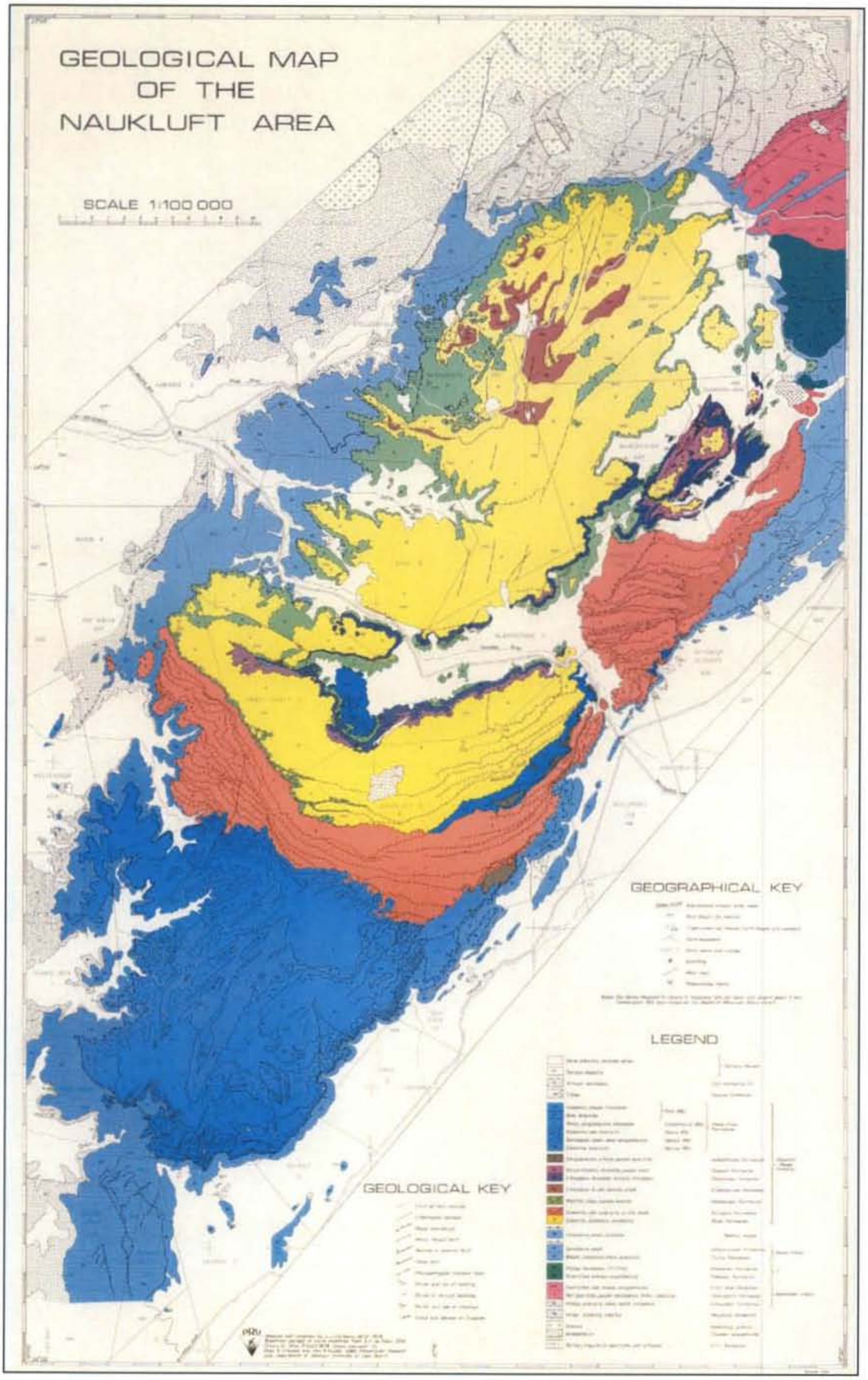


Figure 3: Geological Map of the Naukluft (Hartnady, 1978).

2.1.1 Stratigraphy

Pre-Damara Basement

The Pre-Damaran basement to the NNC consists of Paleoproterozoic high-grade granites and gneisses of the Marienhof Series overlain by the mainly acidic and andestic extrusive rocks as well as meta-sediments of the Sinclair Sequence (Korn and Martin, 1959; Viola *et al*, 2006). The Gamsberg, Piksteel, Weener and Nubib Group granites are also present in the North and occasionally crop out on the edge of the desert to the west of the NNC.

Damara Sequence: Naukluft Nappe Complex

The NNC itself is an allochthonous unit of Neoproterozoic Damaran metasedimentary rocks with its north and south ends lying unconformably on the Sinclair Sequence and in the west and northwest on the Marienhof Series (Viola *et al*, 2006, Korn and Martin, 1959).

Eight lithostratigraphic formations make up the NNC (Miller, 1983) (**Table 1**). The oldest units, the Noab and Büllsport formations, appear to represent tidal flat and dune beach facies (Hartnady, 1978, Miller, 1983). These units seem to have equivalents 70 km north-east of the NNC confirming their Damaran age (Saylor *et al*, 1995; Martin *et al*, 1983). All younger units in the NNC have no known equivalents in the Damaran sequence and appear to have been deposited from the north during deformation (Hartnady, 1978).

There is a sequence of five major nappes from south to north, the Kudu Nappe, Northern Pavian Nappe, Southern Pavian Nappe, Eastern Dassie Nappe and Western Dassie Nappe, which in the east overlies a still lower allochthonous unit, the Rietoog Nappe and Nama sediments. This sequence of nappes however is currently under revision and the number of nappes and terminology may change in the near future.

Table 1: Pre-emplacement chronostratigraphic succession forming the allochthonous part of the NNC, overlying the Sole Dolomite (re-drawn from Miller, 1983)

	Formation	Member	Lithology
Syntectonic	Zebra River Fm	Onis Mbr	Dolomite, bituminous limestone Grey dolomite
		Lemoenputs Mbr	Shale, conglomerate, limestone
		Tsams Mbr	Dolomite, quartzite
		Ubisis Mbr	Sandstone, shale, local conglomerate
		Neuras Mbr	Dolomite, quartzite
	Aubschlucht Fm		Conglomerate, arkose, purple quartzite
	Tsabisis Fm		Volcaniclastics, dolomite, purple slate
Pretectonic	Blasskranz Fm		Limestone-dolomite breccia, limestone
	Remhoogte Mbr Klipbokrivier Fm		Klipbokrivier-limestone, limestone-dolomite breccia, shale Remhoogte-phyllite, slate, marble, breccia
	Büllsport Fm Noab Fm		Büllsport-dolomite, calcerous quartzite, purple shale Noab-dolomite, dolomitic sandstone

Unconformity

______ Conformable contact

The Naukluft Thrust

The entire NNC was thrust along a near planar thrust zone. This thrust zone consists of distinct lithological units and, when all are present, shows a series with a massive yellow dolomite , gritty "Sole Dolomite", foliated and folded calcmylonites and an upper massive dolomite unit (Viola *et al*, 2006, Miller *et al*, 2008) (**Table 2**). The entire sequence varies in thickness from 0-30m throughout the Naukluft (Behr *et al*, 1983).

Table 2: Naukluft Thrust Zone stratigraphic units (drawn from Viola *et al*, 2006) Component five (the planar fault) can be found at any horizon within the the thrust zone. Not all units are always present and the thickness of each component varies considerably throughout

	Lithological Units	Notes
5	Discrete Planar Brittle Fault	<50 mm thick, can occur at any level in this sequence
4	Massive Dolomite	Upper unit in thrust zone
3	Foliated and folded Calcmylonites	Isoclinal Folding
2	Polymict, Gritty Dolomite	"Sole Dolomite" (See Figs. 3 and 4)
1	Massive Dolomite	Yellow-weathering

The "Sole Dolomite" is a gritty layer (**Figure 5**) that seems to correlate well with the basal thrust of the nappe system, but it is not clear that this is always the case. The gritty dolomite can be observed as injections into calcmylonite, clasts within the massive dolomite and as clasts within itself and is thus probably an indicator of numerous pulses of brecciation (Viola *et al*, 2006).

The laterally persistent Sole Dolomite unit throughout the Naukluft is likely to have some effect on the flow-paths of the groundwater. It may provide an impermeable layer, separating deep aquifers from shallow ones, or it may provide a porous layer in and around which water can flow. Fracturing is evident through out the Sole Dolomite and is likely to provide conduits for water to be transported through the Sole Dolomite (**Figure 4**). Further investigation of the Sole Dolomite layer as a flow regulator should be made in the future.

Figure 4: Seep beneath gritty dolomite

Figure 5: Close-up of texture of Sole Dolomite

Nama Foreland Basin sediments

The Damaran NNC rocks overlie autochthonous Nama sediments that belong to a platform area adjacent to the mobile belt (Behr *et al*, 1983). The Nama Group was deposited during the assembly of Gondwana in a foreland basin on the craton edge of the Damara, Gariep and Saldahna belts, formed because of lithospheric flexure in response to thrust loading (Gresse and Germs, 1993). There are three subgroups of the Nama; the Kuibis, Schwarzrand and Fish River, the older and lower two units: the Kuibis and Schwarzrand Subgroups crop out in the Naukluft area. The Schwarzrand Subgroup generally overlies the Kuibis Subgroup conformably (Germs, 1983). Sedimentation in the basin was largely controlled by orogenic pulses in the flanking belts. The main sediment contribution to the Kuibis and Schwarzrand Subgroups was from the East with only the topmost portion of the Schwarzrand being contributed from uplift of the Damaran orogen to the north and west (Germs, 1972; Germs, 1974). The Kuibis Subgroup consists of dark blue grey bituminous limestones with interbedded dark grey marly shales and the Schwarzrand Subgroup consists of dark green grey slates and thin dark limestone beds, dark grey limestone, yellow dolomite and brown weathering quartzites near the top (Viola *et al*, 2006).

The K/Ar ages of white micas in the folded slates of the Nama, yield ages of 532-537 Ma with 535 Ma determined as the age of peak metamorphism (Weber and Ahrendt, 1983). Detrital micas dated at 635 Ma in lower Kuibis and up to 567 +- 12 Ma in the upper Schwarzrand and Fish River subgroups of the Nama group confirm metamorphism and uplift in the Damara and Gariep belts during the foregoing 650- 570 Ma events (Horstmann *et al*, 1990).

Tufa

The most recent deposits in the NNC are the often-imposing tufa formations (**Figure 6**). These tufas precipitate out of the waters originating from the extensive network of springs throughout the region. Tufa is a calcium carbonate precipitate formed from ambient temperature water containing calcium that is then exposed to CO_2 in the atmosphere (Ford and Pedley, 1996) (**Figure 7**). In the Naukluft, tufa formations are prolific, forming large cascade types (waterfall type setting), barrage types (dam wall type setting) and pool types (Viles *et al*, 2007; Ford and Pedley , 1996). The tufa formations in the Naukluft are sizeable and can reach a thickness of approximately 120 m (Blasskopf tufa) (**Figure 6**). Viles *et al* (2007) did a sedimentalogical study on the tufas in the Naukluft and showed evidence of hydroclimatic shifts over the last few thousand years by looking at the layers and size of the tufa deposits.

There seems to be evidence from observations in the field, that the massive tufa deposits throughout the Naukluft are positioned along large faults and that these faults in the nappe complex act as conduits for the calcium carbonate fluids to flow. This could explain the prevalence of tufa deposits in certain areas particularly on Blasskranz Farm along the C 14 road.

Figure 6: Blasskopf tufa deposit on Blasskranz farm (Photo: Duane Fourie)

Figure 7: Close-up of Tufa growing on roots (Photo: Duane Fourie)Desert Sands

To the west of the Naukluft, the vast Namib Desert stretches out towards and along the coast. This vast (80 900 km^2) sand-sea has its origins dating back to the Tertiary when the climate was becoming increasingly arid. During this dry phase, the reddish sand dunes of the Tsondab Sandstone Formation were deposited with slightly consolidated sandstones found from south of the Kuiseb river in the North all the way down to the Orange River (Christelis and Struckmeier, 2001). In the subsequent semi-arid phase, the degree of erosion was diminished and calcerous soils formed on stable surfaces covering most of the plains and valleys in the Namib (Christelis and Struckmeier, 2001). Then between 10 to 7 Ma with the development of the cold Benguela Current, the accumulation of wind-blown deposits of the Sossus Sand Formation formed what is known today as the Namib sand-sea (Christelis and Struckmeier, 2001).

2.1.2 Structure

The NNC is present as a separate structural klippe with an estimated displacement around 50-80 km to the southeast, which overlies the Schwarzrand layer of the Nama sequence (Behr *et al*, 1983; Christelis and Struckmeier, 2001, Hartnady, 1978) (**Figure 8**). Its final uplift and internal imbrication probably occurred around 480 Ma ago based on the 495 Ma age of the mylonites of the Naukluft Thrust which is significantly after peak metamorphism (Behr *et al*, 1983, Weber and Ahrendt, 1983). The sediments of the NNC are severely folded and deformed consisting mainly of low-angle lystric thrust faults (**Figure 9**). The entire nappe stack is thrust along a near planar, sub-horizontal "Naukluft Thrust" (Behr *et al*, 1983; Hartnady, 1978; Viola *et al*, 2006) (**Figure 8**).

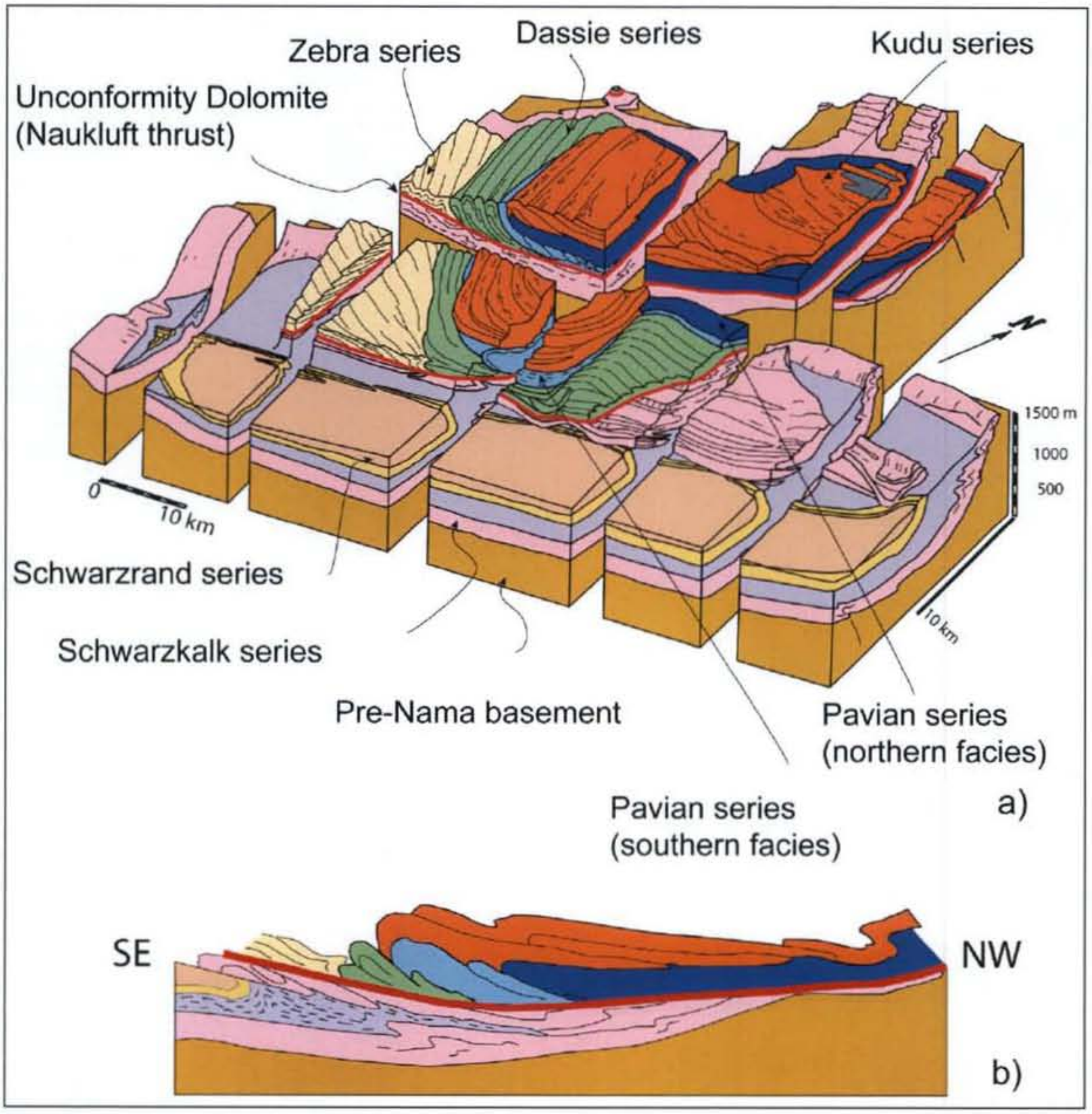


Figure 8: The Naukluft Nappe Complex (Viola *et al*, 2006). Diagram shows Nappe Complexes as well as the Naukluft Thrust. The direction of thrust is evident from the profile of the NNC

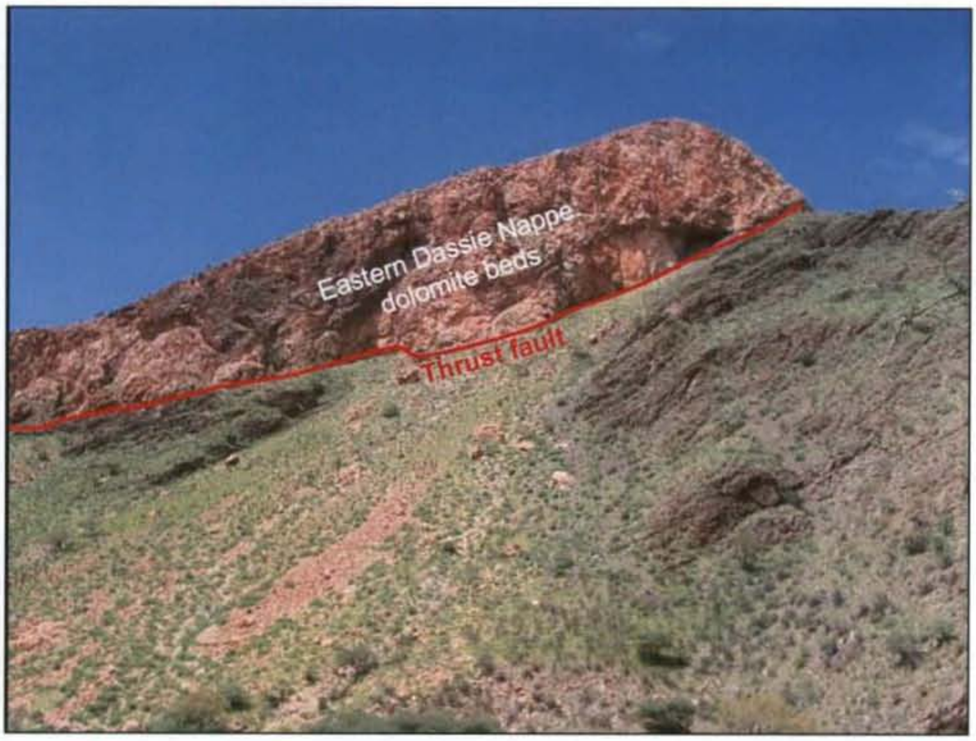


Figure 9: Unconformity and thrusted dolomite beds.

According to Hartnady (1978), there are six major nappe units (**Table 3**) and there were five deformational events in the structural evolution of the NNC. The first deformational event resulted in the emplacement of Northern Pavian Nappe at approximately 547±17 Ma (Weber *et al*, 1983). D_2 then resulted in the emplacement of the Kudu-Dassie Nappes onto Northern Pavian Nappe at around 434±17 Ma (525-537) (Weber *et al*, 1983; Ahrendt *et al*, 1983). At around the same time, the folding of the Nama Group along edge of the Damara Orogen began with the formation of slaty cleavage at the syntectonic peak of metamorphism (Ahrendt *et al*, 1977, 1983). Post D_2 and pre D_3 the lower Zebra River Fm was deposited onto the Büllsport Fm forming the imbricated toe of Kudu-Dassie Nappe. During D_3, the Kudu-Dassie Nappe and the lower Zebra River Fm dismembered into the Kudu and the Eastern and Western Dassie Nappes and the Southern Pavian Nappe, allowing for tilting of the lower Zebra River Fm to occur. During D_4, the Upper Zebra River Fm (the Onis Mbr) was deposited and folded (Miller, 1983). From around 535 to 480 Ma, the movement of the Nappe stack over a lubricating layer, the "Sole Dolomite", began (Miller, 1983). D_5 resulted in the final emplacement of allochthonous NNC on Sole Dolomite at about 480 Ma (Miller, 1983). The Nama Group is overlain by the rigid NNC causing overturning of the Nama beds at the toe (Ahrendt *et al*, and Weber *et al*, 1983).

Table 3: Tectonic and Stratigraphic units of the NNC (redrawn from Miller, 1983)

	Tectonic Unit	Lithostratigraphic unit	
Allochthonous	Kudu Nappe	Klipbokrivier Fm	
		Noab Fm	
	Northern Pavian Nappe	Tsabisis Fm	
		Blasskranz Fm	
		Remhoogte Fm	
	Southern Pavian Nappe	Zebra River Fm	
		Aubslucht Fm	
	Western Dassie Nappe	Onis Mbr	Zebra River Fm
		Lemoenputs Mbr	
		Tsams Mbr	
		Ubusis Mbr	
		Neuras Mbr	
		Büllsport Fm	
	Eastern Dassie Nappe	Zebra River Fm	
		Büllsport Fm	
Par-autochthonous	Rietoog Nappe	Kuibis Subgroup	

Tectonic boundary

Unconformity

Conformable contact

2.2 Physical and climatic setting

The water samples collected in this study were from both the Naukluft Nappe Complex (NNC) and the surrounding farmlands in a study area that extends north to 23° 49' and south to 24° 43' and is bounded in the east at 16° 35'and west at 15° 39' (**Figure 14**). The Naukluft Mountains are approximately 80 km along the length, from northeast to the southwest and approximately 35 km along the width, from the northwest to the southeast. The top of the mountain terminates in an extensive peneplain, and rises from east to west, to a height of 2000 m (Korn and Martin, 1959). To the west of the NNC lies the Namib Sand Sea where most dune types, from barchan to transverse, are present. Most of the older dunes on the edge of the sand-sea are more stabilised and in some areas they are fossilised. These arid climatic conditions started in the Tertiary, becoming even drier in the late Tertiary (between 10 and 7 Ma ago) with the full development of the cold Benguela Current (Christelis and Struckmeier, 2001). Since then, the climate has remained arid and only interrupted by short wet periods during the ice ages in the Pleistocene (Christelis and Struckmeier, 2001).

In the summer season (Jan-March), temperatures on average reach highs of 30°C with lows of 15°C (**Figure 12**). In winter (June-August), the temperature on average reaches highs of 20°C and the lows drop to around 6°C. The Naukluft area is considered an arid to semi-arid region towards the east, with very low rainfall, on average 200 mm/yr (**Figures 10 and 11**), and very high evaporation rates around 2000 mm/yr resulting in a net deficit of water (Viles *et al*, 2007). Although this is generally the capacity of rainfall expected in the region, the third field season had anomalously high rainfall. In the month of February 2009, the area had already received over 180 mm of rainfall (Solitaire rainfall data collected and measured on Solitaire farm pers comm. 2009).

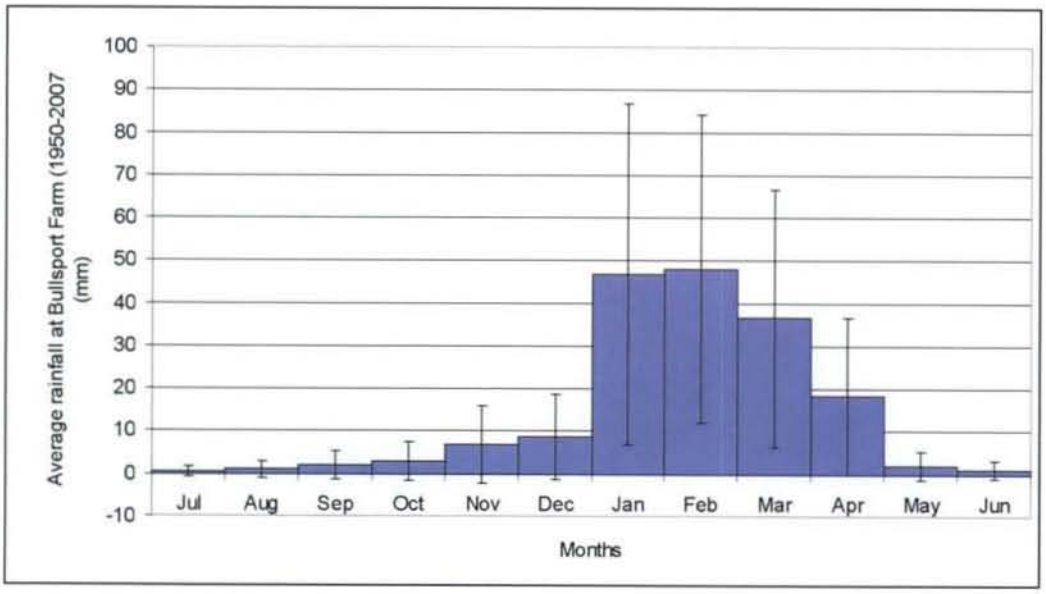
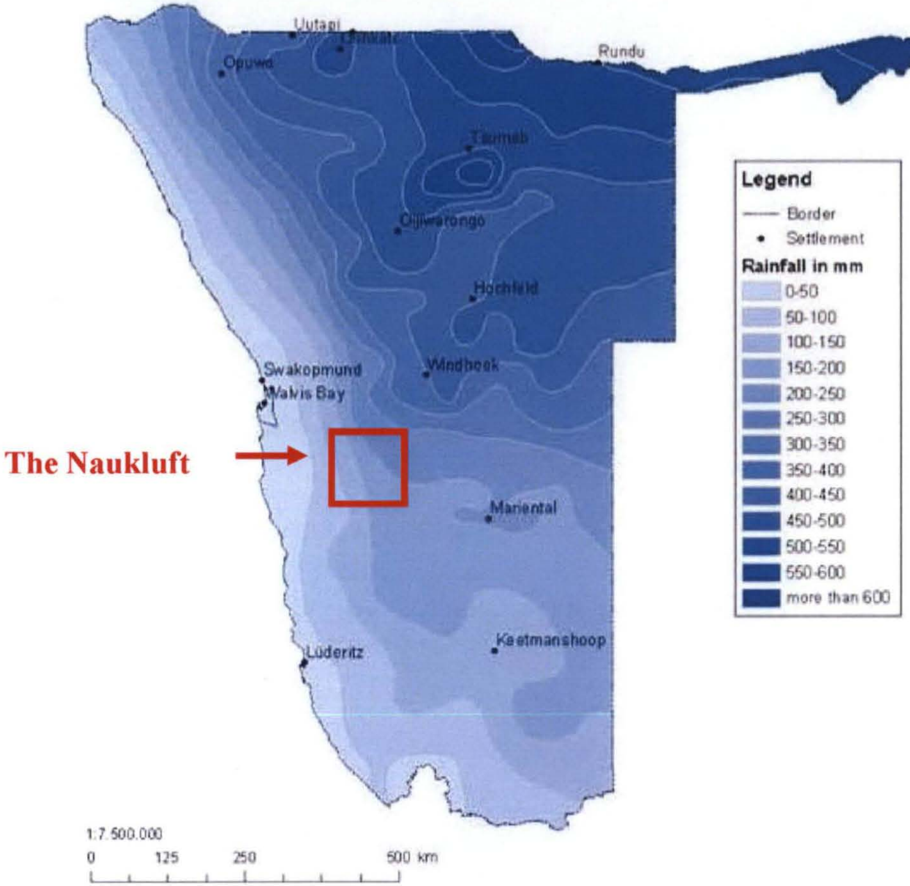


Figure 10: Average annual rainfall (mm) measured monthly at Büllsport Farm from 1950-2007. Error bars show average deviation from the mean. The annual average rainfall calculated to be 175.3 mm at the farm. (Source: E. Sauber, pers. comm., 2008)

The study area is the catchment area for the two large rivers in the region, the Tsauchab River in the South and the Tsondab River in the North. It is these rivers, their underground paleochannels and the karstic aquifers that are essential for providing fresh water to the local population particularly on the outskirts of the Namib Desert in the west. These two main rivers flow from east to west into the desert, although it is only on occasion that one can witness the water reaching the two vleis, the Tsondab vlei and Sossusvlei, in the desert.

The vegetation is very sparse in the west of the study area on the edge of the Namib Desert and it is only shortly after rains that one will see grass sparsely distributed among the red dunes. The grass distribution increases eastwards, reflecting the increasing rainfall gradient towards the east (Gunster, 1995). The vegetation changes include the introduction of low-lying shrubs and sporadic trees. Large wild fig trees are occasionally present and are most often indicative of a year-round water source such as a natural spring or an artesian well. The sparse vegetation means that in most areas, the geology is well exposed and only the bottoms of valleys are alluviated (Korn and Martin, 1959).



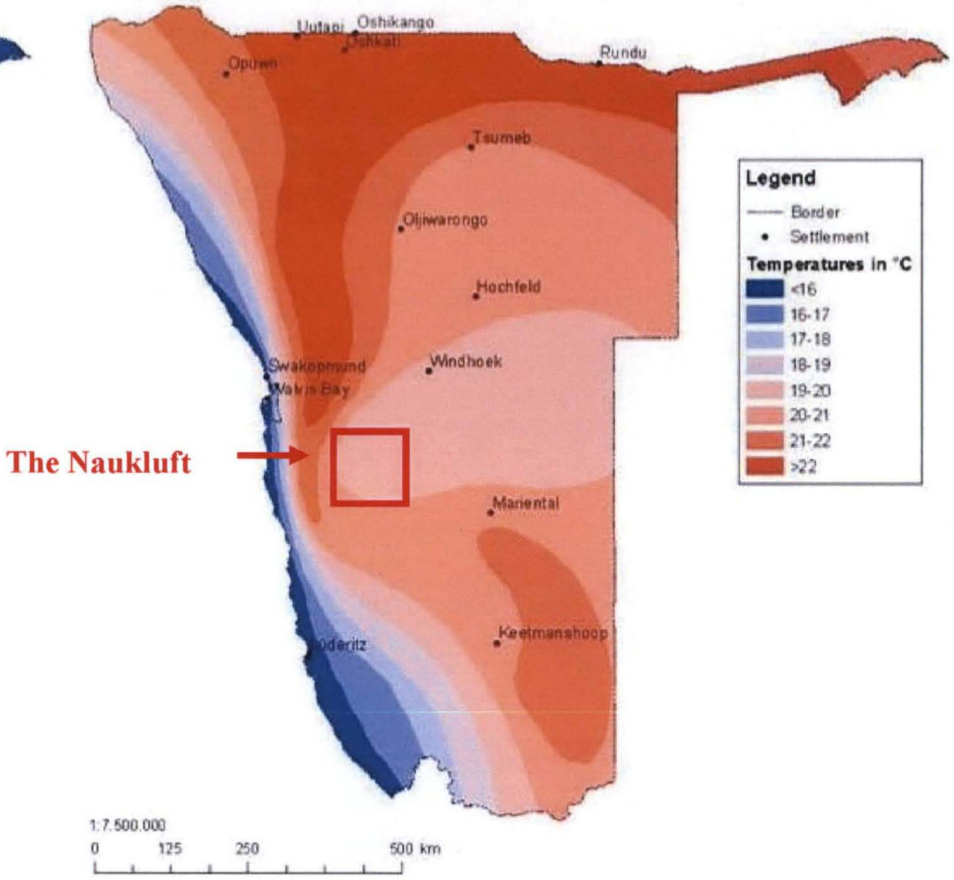


Figure 11: Average annual rainfall map of Namibia. (SFB 389 ACACIA, subproject E1, Atlas of Namibia project, 2002) Red square denotes location of the Naukluft.

Figure 12: Average annual temperature map of Namibia. (SFB 389 ACACIA, subproject E1, Atlas of Namibia project, 2002) Red square denotes location of the Naukluft.

2.3 Land use

Land-use varies substantially throughout the region due to vegetation, geomorphology and historical legacies. Subsistence farms dominate the north of the region above the Büllsport-Solitaire east-west road (the C 14, **Figure 1**). Larger farms, farming mainly livestock, are located in the south and northwest, these farms often incorporate a guest farm component in order to provide the inhabitants with another income, which becomes particularly important during periods of extended drought. Establishments that are exclusively for tourism (guest farms, desert retreats, campsites, hotels etc) occur throughout Namibia, but are primarily located on the edge of the Namib Desert in the west of the study region. Large hotel groups have bought out and continue to buy out many sub-divided farms in the area, as the area becomes better known and tourism becomes one of most important industries in Namibia. This change in land-use has also changed the water-usage patterns in the area. Instead of water being used solely for human consumption and for their livestock, it is now also being used to fill-up swimming pools, water lawns, and wash cars. Considering urban households consume three times as much water as rural households in Namibia (Lange, 1998), this change in water usage will most certainly put pressure on the current sources in and around the Naukluft.

2.4 Hydrogeology

Namibia is one of the driest countries in Southern Africa and an understanding of its hydrogeological processes is therefore essential for future development. In general, the hydrology of Namibia reasonably well understood (**Figure 13**). However, detailed knowledge on specific regions is lacking, and even less is known about water/rock interactions and hydrological flow-paths in relation to the local geology. It is widely accepted that the Naukluft Mountains form the catchment area for the surrounding region and provide the edge of the Namib Desert with an important water source that drains towards the west (Korn and Martin, 1959). However, the hydrological processes at work and the relationship between the rain falling in the mountains in the east and the extraction of water from aquifers to the west, is not well known.

As the geology of the NNC is dominated by limestone and dolomite units, the region is particularly favourable to the formation of large karstic aquifers. The presence of such aquifers provide an excellent source for groundwater above the low permeable Nama sediments (Christelis and Struckmeier, 2001). A karstic terrain as defined by Ford and

Williams (2007) has a distinctive hydrology and the landforms that develops do so because of a combination of high rock solubility and well-developed secondary (fracture) porosity. The structure and lithology of the rocks is also important with dense, massive, pure and coarsely fractured rocks developing the best karsts (Ford and Williams, 2007). Discharge of the groundwater in karsts is usually through springs back to the surface routes (White, 2002). Although not all these characteristics have been documented in the Naukluft, the current extensive network of springs and the historical knowledge of the exploitation of groundwater in the area support the interpretation of a karstified landscape and it is prudent in carbonate terrains to assume karst exists unless proved otherwise (Ford and Williams, 2007).

Karsts in semi-arid and arid regions tend to form slightly differently to those in humid regions although usually the same principles involved. The first major difference lies in the lack of, and often-patchy nature of soil. This means it is less influential as an infiltration governor and as a moisture store (White, 2002 and Ford and Williams, 2007). Since the soil supports only a small biomass, it also has reduced significance as a source of CO_2 (Ford and Williams, 2007). Consequently, the production of solution dolines (downward solution of limestone in form of a bowl, cone or depression) is rare and collapse dolines (shafts formed by the collapse of a cave roof) are of greater importance although still not common (Ford and Williams, 2007). Precipitation in arid regions occurs mainly in short, violent convectional storms, favouring flash flooding (Ford and Williams, 2007). This rapid delivery of rain followed by the loss of runoff through evaporation, limits the development of epikarsts (sub-cutaneous zone forming at the top of the vadose zone, immediately below the soil) and often results in the morphology of the landscape taking on a more fluvial character (Ford and Williams, 2007). The other important factor to remember when considering the development of karsts in arid regions is whether one can ascribe the landscape to sporadically repeated modern events or more humid periods in the past when karst formation was more favourable (Jennings, 1983a). In the Naukluft, little is known about the morphology of underground caves, but the geomorphology above ground exhibits the above characteristics. Based on Ford and Williams (2007), description of karsts in arid environments, the Naukluft karst displays arid formation characteristics. However, this may have over-printed an earlier karst system formed during the more humid periods before the Tertiary.

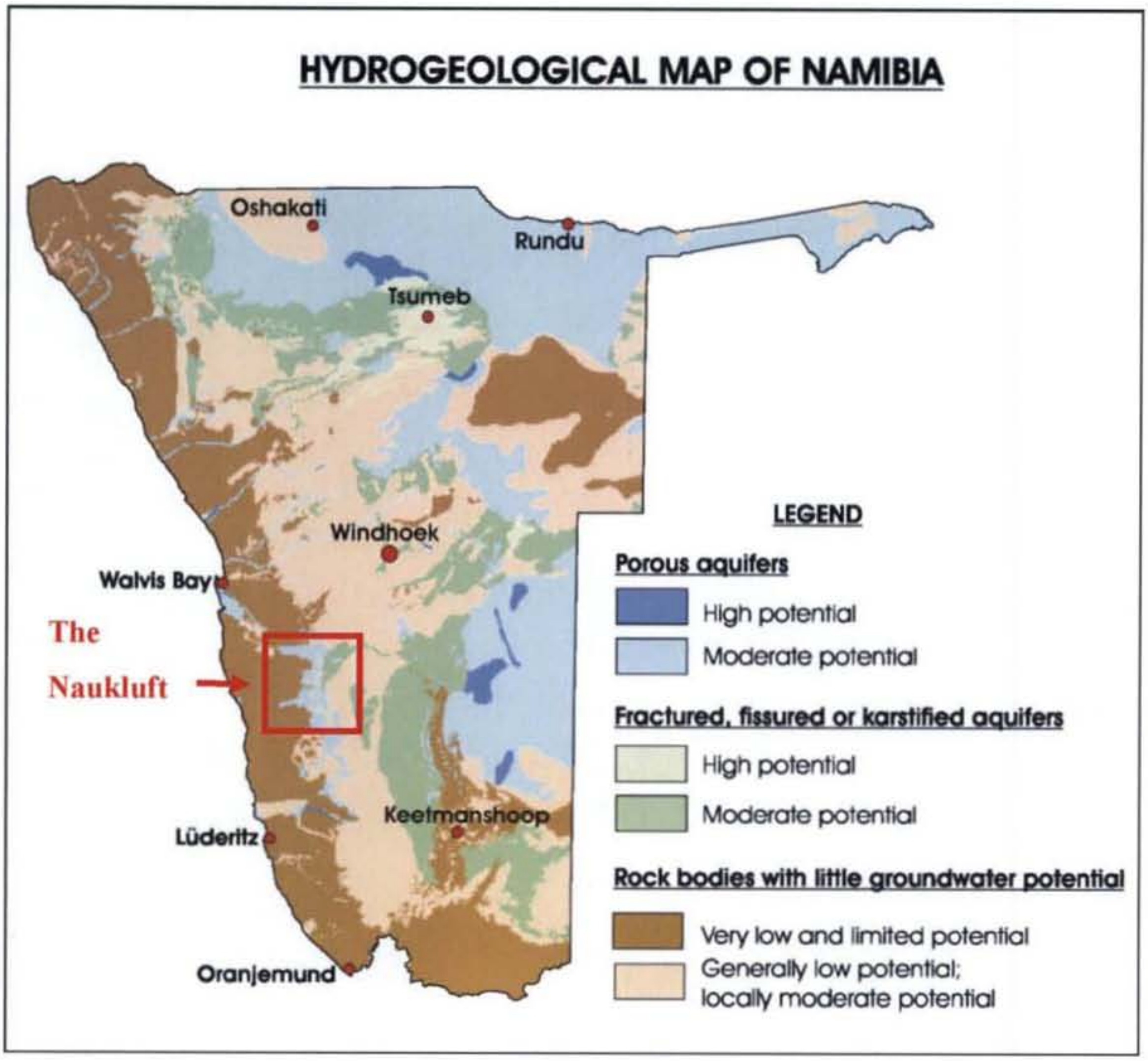


Figure 13: Simplified hydrogeological map of Namibia (1:100 000) (Department of Water Affairs and Geological Survey of Namibia, 2001)

3 METHODOLOGY

3.1 Sampling rationale, locations and distribution

Water samples were collected from the following sources (**Figure 14**):

- Precipitation (in summer)
- Groundwater
    - Springs
    - Boreholes
    - Wells (Hand dug wells)
- Surface water
    - Rivers (the two main rivers, the Tsauchab and Tsondab Rivers)
    - Surface water (smaller tributaries and streams)

Sample sites were identified by observation and by personal communication with the local community and residents. These sources were then investigated and sampled if possible. In order to achieve the greatest coverage and best spatial distribution throughout the sampling area, as many water sources as possible were sampled in the Naukluft region from as many varied locations as possible.

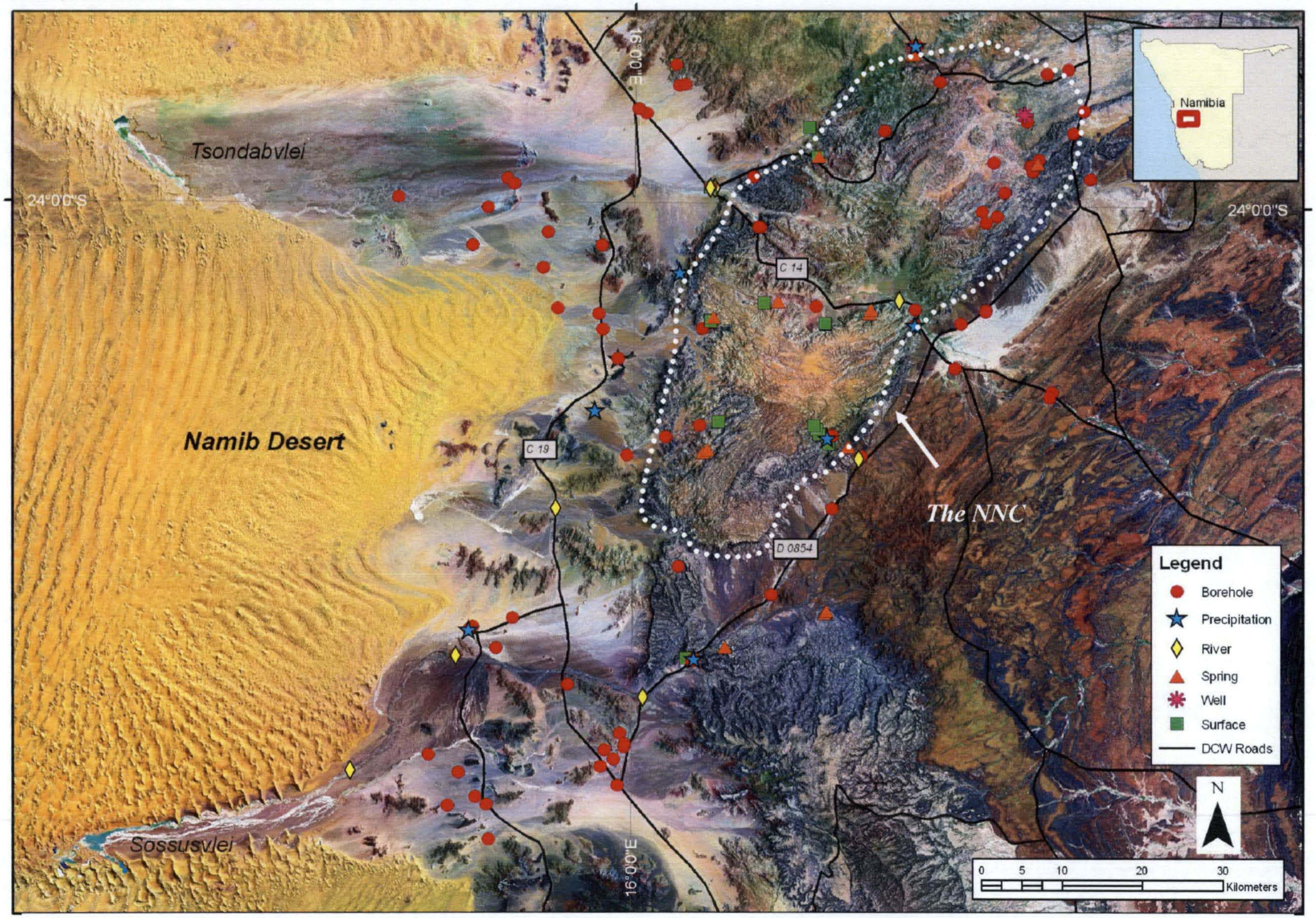


Figure 14: Sample site distribution in the Naukluft [Map]. 1:500000. Roads: DCW (Digital Chart of World), Nasa Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab, University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: Environmental Systems Research Institute, Inc.

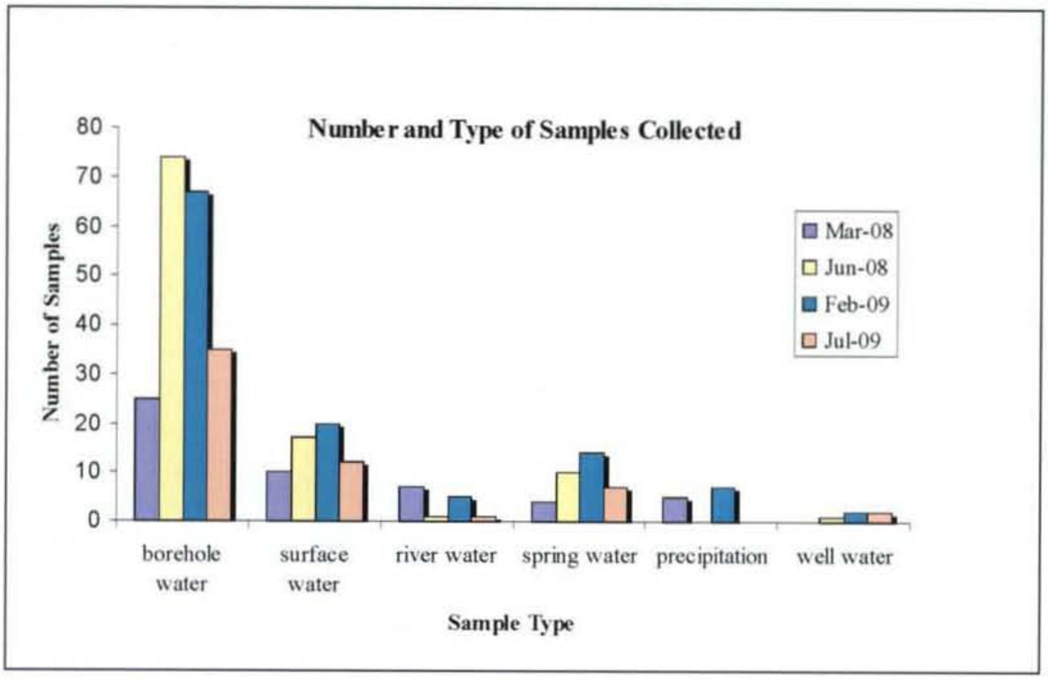


Figure 15: Type and number of samples collected.

Samples were collected in four field camps in both the wet and dry seasons over two years in order to assess any seasonality in water composition and amount of water present. The samples were collected in March 2008 (rainy season), June-July 2008 (dry season, season 2), February 2008 (rainy season, season 3) and July 2009 (dry season, season 4) (**Figure 15**).

The samples were labelled according to the type, location and sample season in which the sample was collected. The sample name begins with the location (NK=Naukluft), followed by the year of sample collection (08/09), the field season it was collected in (2, 3,4), the sample type (B=Borehole, S=Spring, W=Well, R=Tsondab/Tsauchab River, A=Surface water , P=Precipitation) and then it is ended with a small letter to denote what analysis the sample was being collected for (a=oxygen and hydrogen, b=DIC, c=cations, d=anions, g=carbon dating and h=nitrates). An example would be NK08-2B45a, this sample was collected in the Naukluft in 2008 in the second field season from a borehole numbered 45 (numbers do not relate to any specific borehole numbers but were allocated in order of collection) and is collected for oxygen and hydrogen analysis. Some samples were also indexed according to the farm or lodge name. Instead of NK, a few samples were prefixed with an abbreviated version of the property name. An example is NNL09-3B10a, NNL being an acronym for Namib-Naukluft Lodge. This was done on occasions when samples were collected by two groups at the same time in order to prevent duplicated sample numbers.

3.2 Sampling methods

Where samples were collected from each location for different purposes, the protocols followed for each were slightly different (**Figure 16**). All collection vessels for samples intended for dissolved inorganic carbon (DIC) isotope analysis were acid washed with 1% HNO_3 and allowed to stand overnight. These bottles were then rinsed with de-ionised water and allowed to stand overnight before final rinsing with de-ionised water and drying. All collection vessels were rinsed with the water sample that was about to be collected prior to filling and sealing the vessels.

Water samples for oxygen and hydrogen isotope analysis were collected directly from the source and added straight to 25 ml glass bottles using a sterile 60 ml syringe. In the third season, a duplicate was collected in a clear 60 ml high-density polyethylene (HDPE) nalgene bottle for oxygen and hydrogen analysis at the University of Lausanne (UNIL). Water samples for DIC analysis were filtered through 0.45 µm cellulose acetate filters into the acid washed 25 ml glass bottles. Bottles were filled so that no air was present and then sealed with tape and stored at ~4 °C until analysis. In the third field season, one amber 60 ml HDPE nalgene bottle and two 25 ml glass bottles were collected for DIC analysis for triplicates to be analysed at the University of Cape Town (UCT) as well as at the UNIL. The HDPE nalgene bottles were used in the third season for ease of transport to Switzerland, preparation and storage of the vessels was the same as for the glass bottles. Samples for cation and anion analysis were collected in blue-capped 50 ml polypropylene (PP) sterile bottles. Samples for both cation and anion analysis were filtered using a 0.45 µm cellulose acetate filter and then 1 ml of 65% HNO_3 was added to the sample for cation analysis. The anion samples were stored at ~4 °C until analysis.

In situ alkalinity analysis at the source of the water was done by titrating with bromocresol green-methyl red indicator and adding H_2SO_4 (1.6 molar for groundwater samples and 0.16 molar for rainwater samples) using a Hach digital titrator. Bromocresol green-methyl red indicator was used instead of Phenolphthalein, as the bicarbonate alkalinity was equivalent to the total alkalinity for Phenolphthalein. Alkalinity is determined by titration to an end-point of pH 8.3 and indicates the total hydroxides and one-half the carbonate present (Hach digital titrator manual). *In situ* measurements of pH, T (temperature) and EC (electrical conductivity) were measured using an ExTech instrument probe (Waterproof ExStik® II pH/Conductivity Meter) and salinity and TDS (total dissolved solids) were calculated digitally by the probe, using the known relationship between salinity and EC, and TDS and EC at 25 °C. The TDS value is determined by multiplying a conductivity reading by a known ratio factor. The meter allows for selecting a conversion ratio in the range of 0.4 to 1.0. The ratio varies with the application, but is typically set between 0.5 and 0.7 (Extech, Waterproof ExStik® II pH/Conductivity Meter, User's guide). For salinity, this ratio is fixed at 0.5.

Table 4: Table showing precision of ExTech ExStik probe (Waterproof ExStik® II pH/Conductivity Meter, product data sheet)

	Range	Max Resolution	Basic Accuracy
Conductivity	0 to 199µS/cm, 200 to 1999µS/cm, 2.00 to 19.99mS/cm	0.1µS/cm	±2%FS
TDS/Salinity	0 to 99.9ppm (mg/L), 100-999ppm (mg/L) 1.00 to 9.99ppt	0.1ppm (mg/L)	±2%FS
pH	0.00 to 14.00pH	0.01pH	±0.01pH
Temperature	23° to 194°F (-5 to 90°C)	0.1°F/°C	±1.8°F/1°C

Two ExStick probes were in circulation throughout the sampling seasons and therefore in order check their accuracy, *in situ* comparative analysis was conducted on a number of samples in our third season using both probes. Our inter-probe correlation showed that out of 27 tests, pH showed an average standard deviation of 0.1pH, EC σ=34.02µS/cm (All EC values to follow are µS/cm, reported in the text as µS) , temperature σ=0.29°C, TDS σ=30.47mg/L and salinity σ=14.22ppm.

Samples collected from boreholes or wells were collected as close to the source as possible, through taps or pipes, or directly from the borehole itself, if possible. Where possible, the depth to water of the water in the borehole or well was measured using a dip meter. This reading also was used to determine drawdown as the water was bailed from depth using a Teflon bailer. Where a pump was connected to the borehole, the water was purged equivalent to twice the borehole volume or until a steady state (pH, EC) was achieved, after which a sample would be collected. Windmills, solar powered electrical pumps and pumps connected to generators were all encountered and sampling strategy varied according to the set-up at any particular borehole or well. Samples collected from springs were collected as close to the source as possible and at depth. Rainwater was collected in large, shallow plastic 10 L buckets placed at height to prevent soil splash back. The water was collected immediately after the rainfall event and bottled and stored appropriately. Rivers were sampled when possible (mostly in summer) when they were flowing and in the deepest channels. For samples with high sediment load, samples were collected in 500 ml nalgene bottles, the water was syringed from the top of the bottle, and filtered as soon as possible thereafter.

3.3 Analytical procedures

Analysis of all the samples was completed as soon as possible after collection at UCT using the extraction lines in the stable isotope laboratory. The samples collected in the third season were also analysed at UNIL in Switzerland.

At UCT, the CO_2 equilibration method of Socki *et al* (1992) of evacuating 7 ml glass vials was employed for oxygen isotope analysis. About 0.5-atmosphere medical grade CO_2 was equilibrated with 2 ml of water for two hours at 25°C. For hydrogen isotope analysis, reducing the water to H_2 requires using 2 mg of water in a micro-capillary tube in a glass break-seal tube containing a 100 mg of "Indiana Zinc" (Schimmelmann and DeNiro, 1993; Coleman *et al*, 1982). The tube is then attached to the vacuum line and the sample is frozen with liquid nitrogen and then evacuated and sealed with a torch. Once a number of samples have been prepared, the tubes are placed in a furnace at 450°C to reduce water to H_2. Stable isotope analysis of DIC had never been processed at UCT prior to this study. The method involved the addition of 100% phosphoric acid to 2 ml of water and allowing it to react for two hours at 25°C and then extracted using the carbonate line using the method of McCrea (1950). Isotope ratios of CO_2, H_2 and $\delta^{13}C$-DIC were measured using a ThermoFinnigan DeltaXP mass spectrometer in dual inlet mode, and the fractionation factor between CO_2 and O_2 was assumed to be 1.0412 (Coplen, 1993). Data are reported in the familiar δ notation relative to SMOW (standard mean ocean water) (oxygen and hydrogen) and PDB (Pee Dee Belemnite) (carbon) where δ = (Rsample/Rstandard- 1)*1000, and R = 18O/16O, D/H or $^{13}C/^{12}C$.

The standards VSMOW (Vienna standard mean ocean water) and SLAP (standard light Antarctic precipitation) have previously been analysed to determine the degree of compression of raw data and the equations of Coplen (1993) were used to convert the raw data to the SMOW scale. The CTMP3 internal water standard, which had been calibrated against VSMOW and SLAP, and independently analysed, was run with each batch of samples and used to correct for drift in the reference gases, its δD= -7‰ and $\delta^{18}O$= -1.95‰. Evian water, which has δD and $\delta^{18}O$ values of -73.1‰ and -10.2‰ respectively (Spangenberg and Vennemann, 2008) was used as a secondary standard. The vast majority of samples had isotope compositions between that of Evian Water and CTMP3. The average deviation between duplicates of the UCT internal water standard CTMP3 run throughout was 0.04‰ for O (n=16) and 1.03‰ for H (n=18). For the secondary internal standard Evian, the average deviation between duplicates was 0.07‰ for O (n=14) and 0.64‰ for H (n=20). The internal standard for DIC was dissolved $NaCO_3$ of known $\delta^{13}C$ value measured at UCT with an accepted value of -4.68‰ for C of DIC (C. Harris pers. comm., 2008). The standard was prepared fresh with each batch of samples, with a known and constant concentration of $NaCO_3$. It was run throughout and had an average deviation between duplicates of 0.08‰ for C of DIC (n=40).

The samples from the third field season were primarily analysed at the UNIL, Switzerland. Oxygen isotope analysis was analysed on the continuous flow Gas Bench and then measured using a ThermoFinnigan Delta^{plus}XL mass spectrometer. The sample block was kept at room temperature and approximately 0.8 ml of water was pippetted into glass vials. A combination of He-CO_2 flushed the vials with 30 ml/min flow (0.5% CO_2 in He for 4 minutes, displacing air) and was allowed to equilibrate for 24 hours. Hydrogen isotopes were analysed using the H-Device and measured with the Finnigan MAT Delta V plus dual inlet mass-spectrometer. The reactor was pumped out under vacuum and heated up in steps of 100 °C, up to 800 °C. Water samples were pipetted into 1.5 ml crimp-top vials, closed and then analysed. DIC was analysed on the continuous flow Gas Bench and measured with the ThermoFinnigan Delta^{plus}XL continuous flow mass spectrometer (Spötl and Vennemann, 2003). The sample block was once again kept at room temperature. Approximately 5 drops of 100% H_3PO_4 was pipetted into the glass vials and the vials were flushed with 100 ml/min flow of He for 4 minutes to displace the air. The water samples were then added with a 5 ml syringe and allowed to react for 1 hour. The majority of the samples required between 0.8 ml to 1 ml of water, however for precipitation samples, with very low DIC content, approximately 3 ml of water was required.

At UNIL, a pure carbonate Carrara Marble standard was interspersed throughout DIC analysis and had a standard deviation of 0.08 for $\delta^{13}C_{DIC}$ (n=32). Oxygen and hydrogen analysis required three in-house standards to be used throughout, INH (tap water) ($\delta^{18}O$=-

17.0‰, δD=-114.0‰), LIPE (bottled water) ($\delta^{18}O$ =-8.5‰, δD=-54.8‰), and MOW (Mediterranean Ocean Water) ($\delta^{18}O$ =0.4‰, δD=3.4‰), an additional standard SCH (bottled water) (δD =-123.7‰) was also used for hydrogen. INH had a standard deviation of 0.11‰ for O (n=30) and 0.3‰ for H (n=36). LIPE's average deviation was 0.06‰ for O (n=20) and 0.4‰ for H (n=36) . The average deviation of MOW was 0.03‰ for O (n=18) and 0.2‰ for H (n=36). SCH had an average deviation of 0.4‰ for H (n=9).

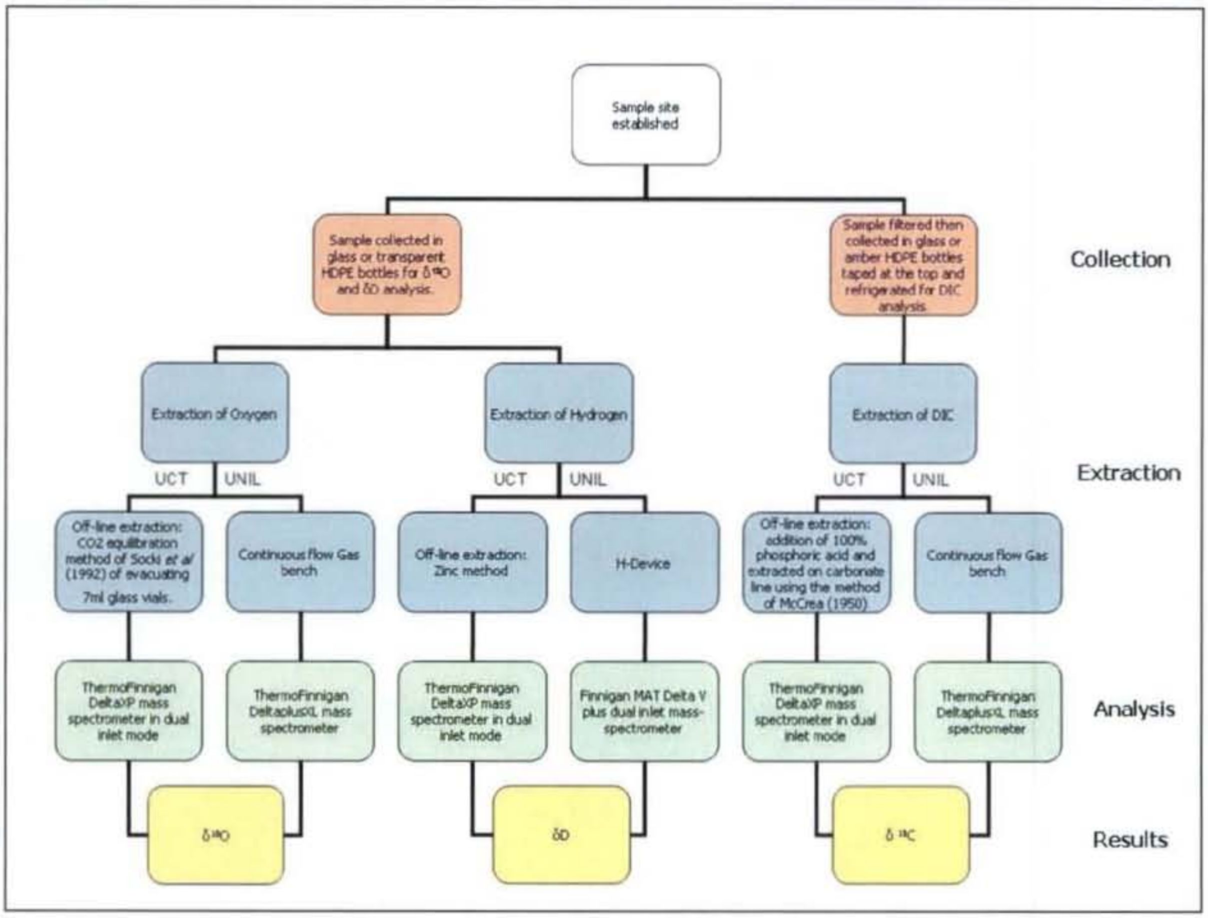
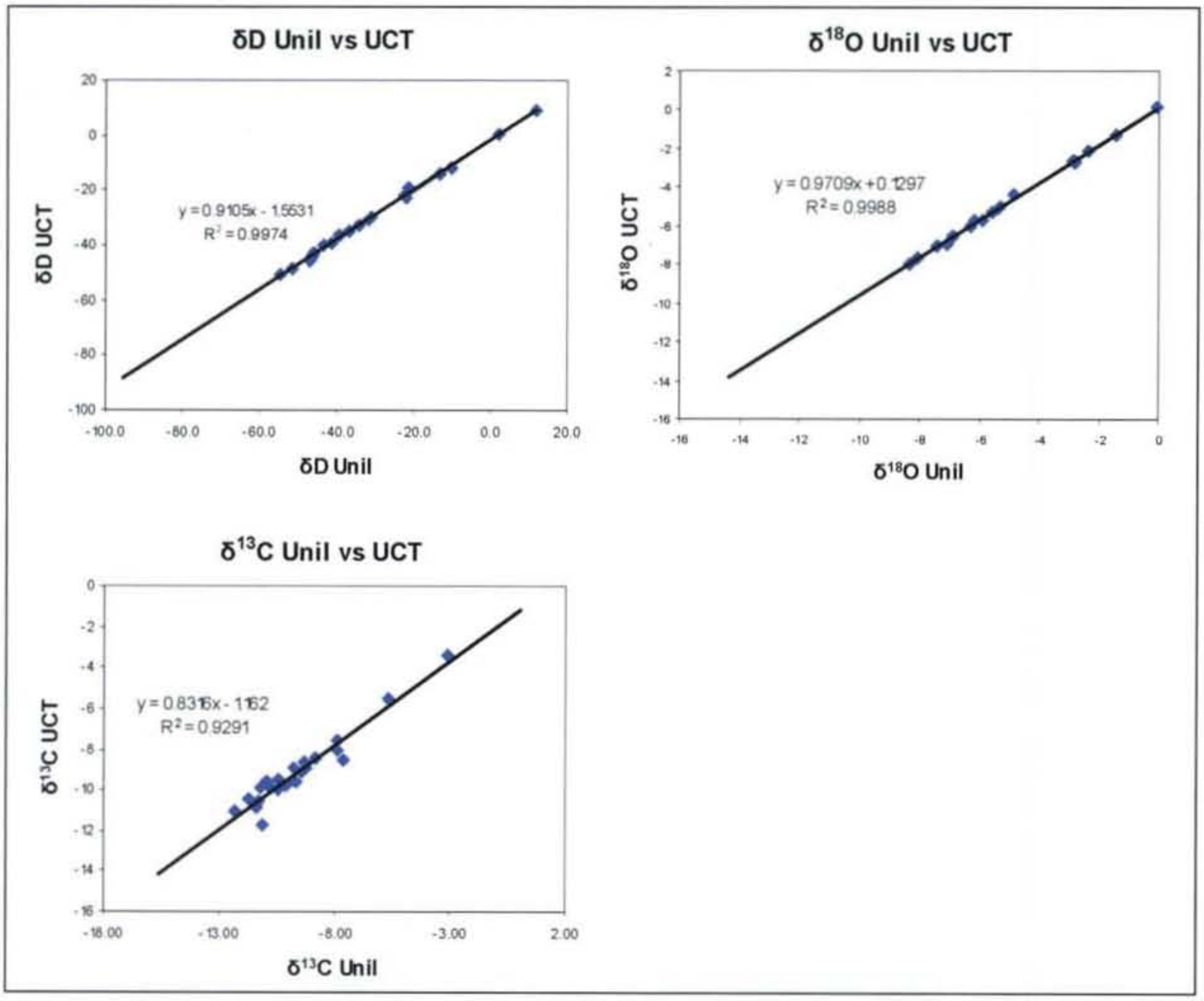


Figure 16: Methodology flow chart

3.3.1 Comparison between UCT and UNIL data

The samples collected in the third season were analysed on the gas bench at UNIL and 20 samples were chosen at random to be duplicated at UCT to determine the agreement between the differing laboratories. This assessment was vital as samples were collected from four different seasons and in order to compare data from the different seasons, the different analytical approaches had to be comparable. The samples analysed in both laboratories showed a very good correlation indicating a high confidence in the accuracy of the results in the study. For $\delta^{18}O$ and δD of UCT and UNIL the Pearson's Product Moment Correlation Coefficient (r) was 0.999 and for $\delta^{13}C$ was 0.96. This indicates the strength of the correlation. The significance of this correlation then had to be tested. An **F-test** was then performed to determine if the variances were equal or not, so the appropriate t-test for that data could be used to determine the significance of the correlation. The F-test showed equal variances between the two data sets ($F_{calc}<F_{crit}$, therefore accept null hypothesis of equal variances). Then a **t-test** for equal variances was performed and $t_{calc} <t_{crit}$ therefore the null hypothesis, that the correlation was statistically significant, was accepted for $\delta^{18}O$, δD and $\delta^{13}C$ from the two laboratories. In **Figures 17-19**, δD, $\delta^{18}O$ and $\delta^{13}C$ from UCT was plotted against the δD, $\delta^{18}O$ and $\delta^{13}C$ from UNIL. Not only is the correlation good (δD: r^2=0.9974, δ18O: r^2=0.9988, $\delta^{13}C_{DIC}$: r^2= 0.9291), but the offset is also small. The correlation is slightly worse for the DIC as carbon is much less abundant than oxygen and hydrogen in water and therefore inherently less precise.



Figures 17, 18 and 19: Plots of δD UCT vs. δD UNIL, $\delta^{18}O$ UCT vs. $\delta^{18}O$ UNIL and $\delta^{13}C$ UCT vs. $\delta^{13}C$ UNIL. A linear trendline shows the correlation between the samples analysed at UCT and UNIL

4 RESULTS

A linear relationship exists between $\delta^{18}O$ and δD values of the majority of waters of meteoric origin. Craig (1961) characterized the Meteoric Water Line (MWL) which defined all modern meteoric water, with an equation of $\delta D = 8\delta^{18}O + 10$. The "deuterium excess" produced by kinetic effects during the evaporation of an individual sample, can be defined by an equation '$d' = \delta D - 8\delta^{18}O$.(Criss, 1999). Local Meteoric Water Lines (LMWL) can have different intercepts and slopes, due to differing kinetic effects during evaporation of individual samples (Criss, 1999). In arid regions, where waters undergo intense evaporation, kinetic effects are stronger and the deuterium excess in each sample is thus much higher (Sharp, 2007).

The $\delta^{18}O$ and δD values for all four seasons from all sources have values that are between -8.0‰ and -4.0‰ and between 25‰ and -95‰, respectively (**Figure 20**). All the samples collected during the wet and dry seasons have values that plot close to the Global Meteoric Water Line (GMWL) with an equation of $\delta D = 7.07\delta^{18}O + 4.28$ (the 'local MWL') (**Figure 20**). The LMWL (ie. the line of best fit) was calculated using the Reduced Major Axis (RMA) regression method (used in order to account for errors in both variables) from the mean values of each sample site. The slope was calculated by $\boldsymbol{m} = \boldsymbol{s}_x \div \boldsymbol{s}_y$ and the y-intercept calculated from $\boldsymbol{b} = \overline{\boldsymbol{Y}} - \boldsymbol{m}\overline{\boldsymbol{X}}$. The similarity of this LMWL to the GMWL allows a comparison with the GMWL to be utilised from this point forward.

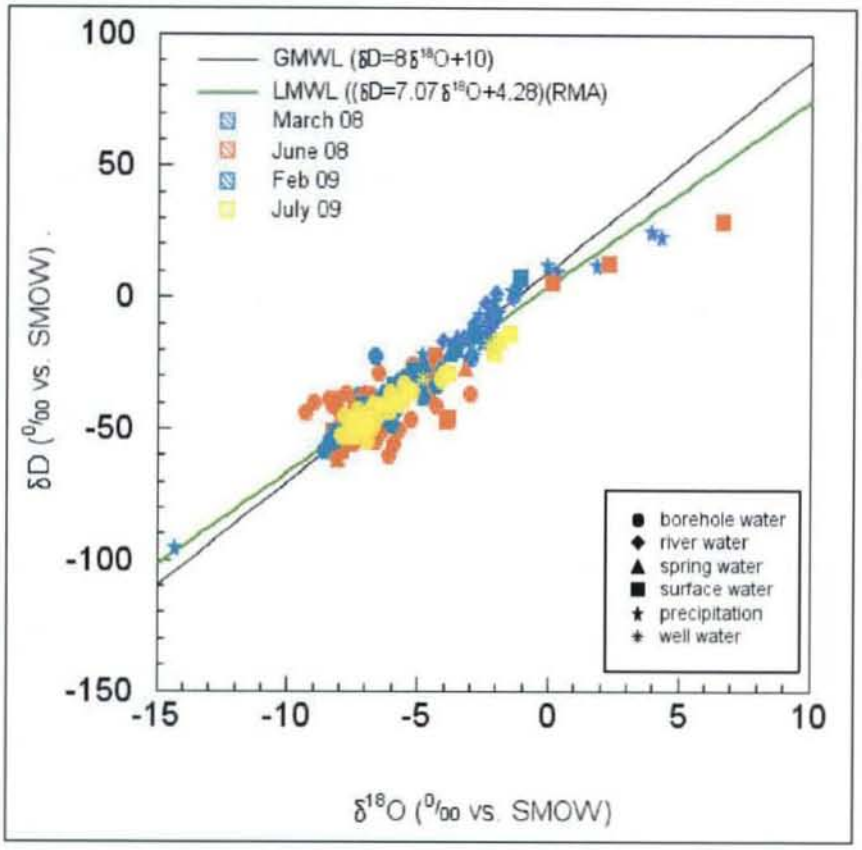


Figure 20: δ^{18}O vs. δD for all samples. Graph shows relationship of the LMWL to the GMWL

4.1 Precipitation

A total of 15 precipitation samples were collected from the two summer (wet) field seasons (March 2008 and February 2009). Although all the samples were analysed for DIC, the CO_2 values were too low (<1μmol CO_2) in the precipitation samples to measure the DIC accurately. The average δ^{18}O for all the precipitation samples was -2.2‰ (n=15), but there was one anomalously negative δ^{18}O value of -14.5‰ and δD value of -95‰ (**Figure 21**). This sample (P130) was collected in February 2009, during a torrential rainstorm and was the most northerly rain sample collected. The δD average was -9‰ but the total range was very large from 25‰ to -95‰, although δD is naturally variable. The precipitation samples show the highest δ^{18}O and δD average values of all the samples collected.

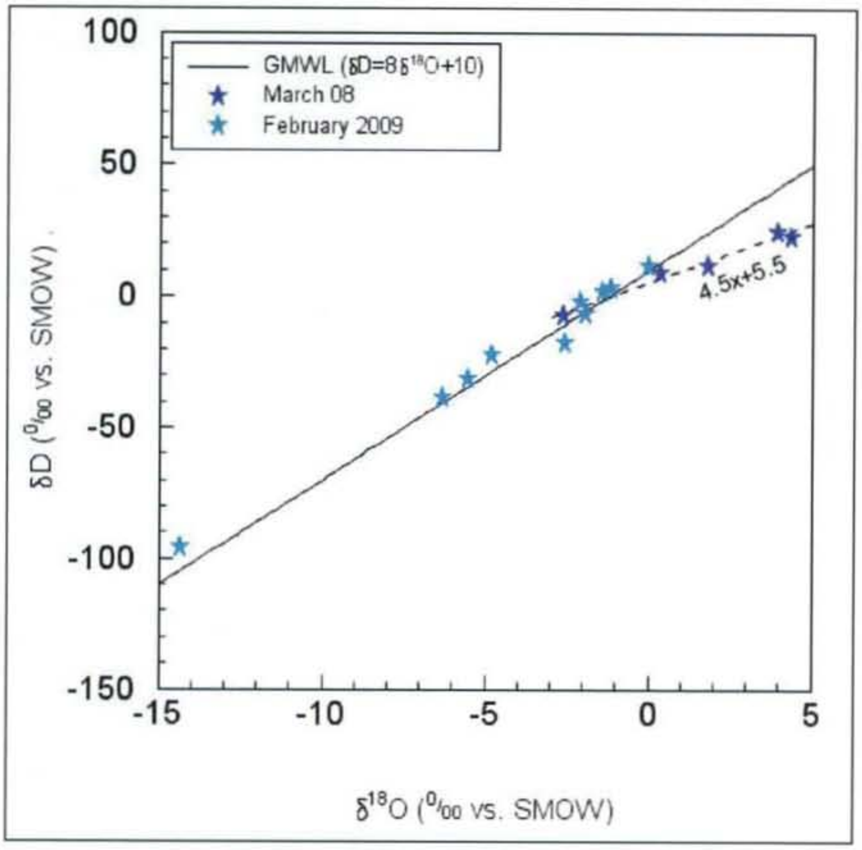
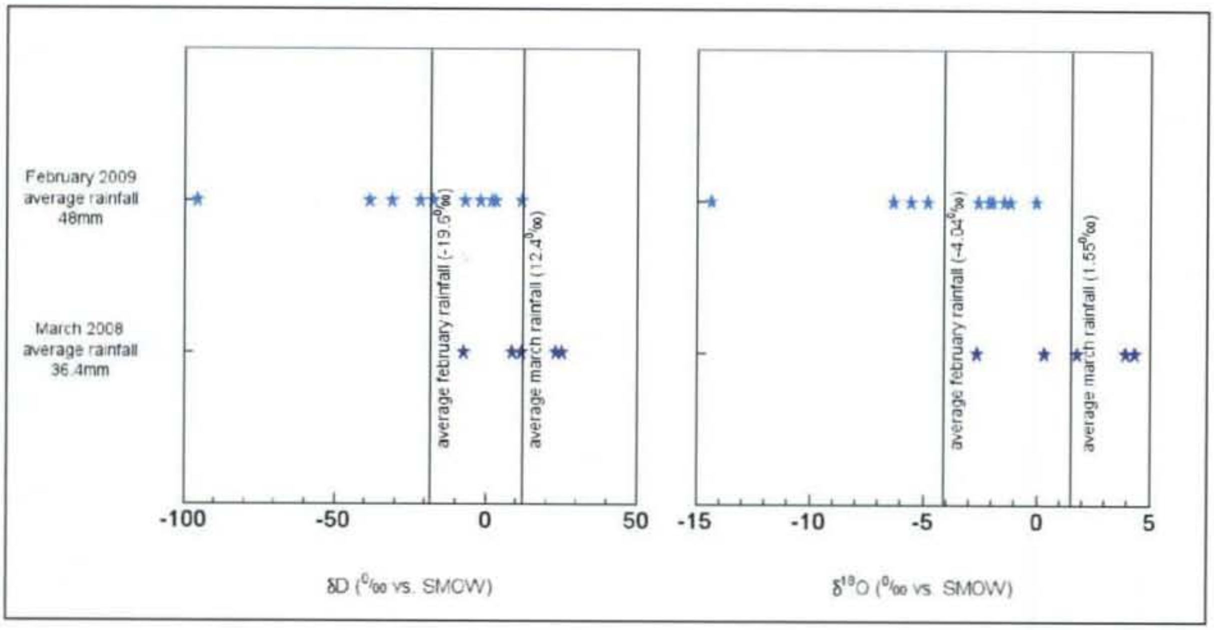


Figure 21: δ^{18}O vs. δD for all precipitation samples. March 2008 data falls on an evaporation trend with an equation δD=4.5δ^{18}O+5.5. February 2009 data lies along the GMWL

The δ^{18}O and δD data of the precipitation samples collected in March 2008 show correlation with a shallower slope (δD= 4.5δ^{18}O + 5.5), compared to the GMWL (**Figure 21**). However, this trend is not seen in the data from February 2009, where the data follows the GMWL closely.

Actual daily temperatures and amount of rainfall in any one event were not recorded during this study. It is suggested that any future studies in the area should definitely consider these measurements as vital. A more comprehensive knowledge of precipitation in the area will help in gaining a better understanding of the fractionation effect affecting the isotope values and in turn, help to distinguish rainfall that is recharging the aquifers from rainfall that is not. Average monthly amounts of rainfall (mm) were however, used to establish any variations in δ^{18}O and δD as a result of the amount of rain in any month (**Figures 22 and 23**). It is evident that both δ^{18}O and δD values are significantly less negative when there was less rain. The average δ^{18}O value was 1.6‰ in March 2008 (average March rainfall=36.4 mm). This value was significantly more negative in February 2009, with an average value of -4.0‰ (average February rainfall=48 mm). The δD values showed a similar trend, with an average value of 12‰ in March 2008 and -20‰ in February 2009. This is in-line with an understanding of isotope fractionation, where an increase in rainfall would result in a decrease in the heavier isotopes relative to the lighter isotopes resulting in more negative delta values of hydrogen and oxygen. .



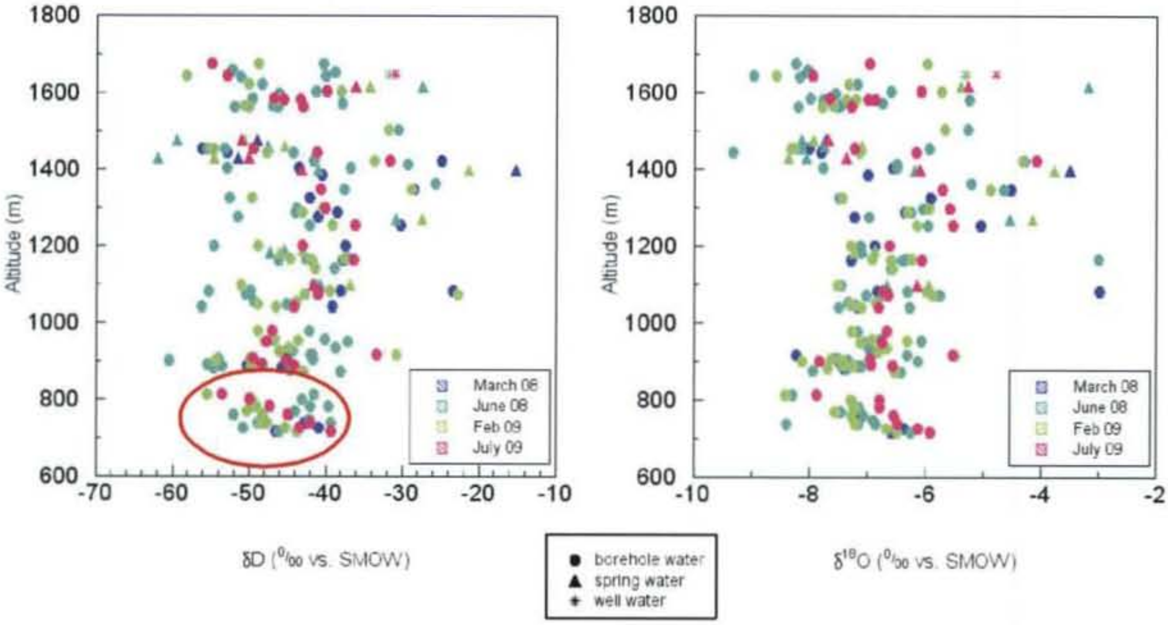
Figures 22 and 23: Plot of average rainfall for February and March against δD (Figure 22) and $\delta^{18}O$ (Figure 23) (average monthly rainfall sourced from E Sauber, pers. comm., 2008)

4.2 Groundwater

Groundwater samples made up by far the bulk of the samples collected (235 over all four field seasons). Boreholes, wells and natural springs were collection points. Boreholes were more frequently sampled, as they were often more accessible, wells were far fewer and often too contaminated by organic matter to sample. Spring samples were sought out, as finding a year-round water source in an arid region such as the Naukluft is rare and it is therefore important to identify its properties and to define its source.

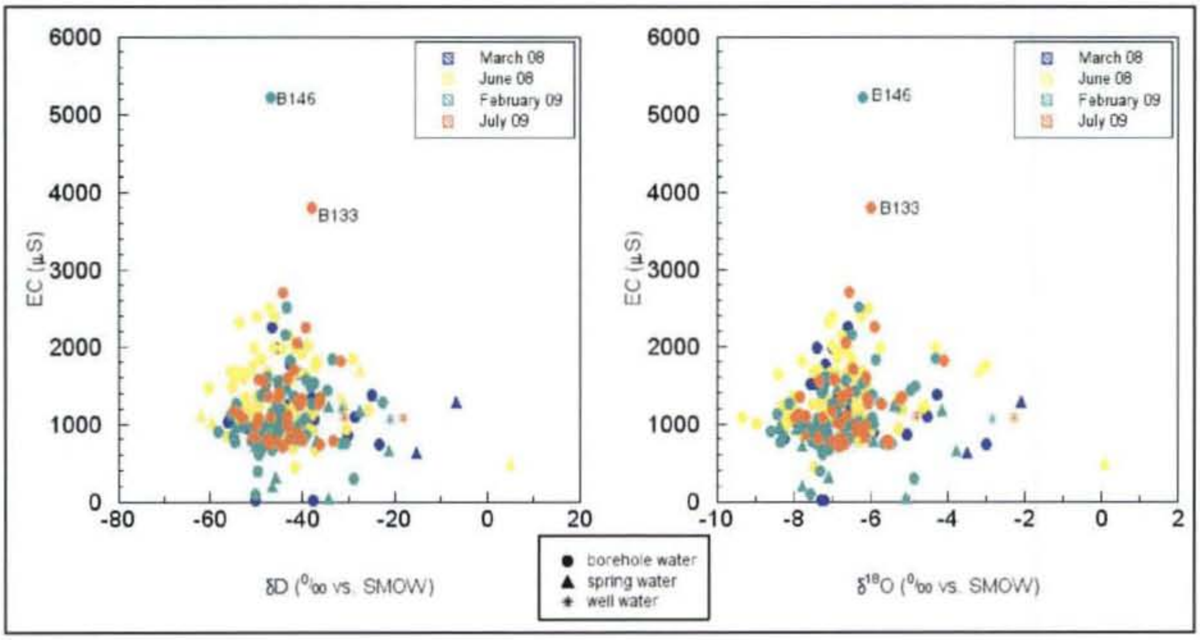
The $\delta^{18}O$ values of all the groundwater samples over all four seasons showed very little variation with most values between -9‰ and -4‰. All $\delta^{18}O$ values from all underground sources were negative. δD values of the groundwater over the two years also varied little with the majority of samples having values between -60‰ and -30‰.

There is very little evidence for any change in delta values of the groundwater samples with topographical height (measured with GPS). **Figures 24 and 25** show no discernable correlation with altitude, except for a few discrete samples encircled in red (**Figure 24**). The Pearson's **r**-values were more significant for this sample set in all seasons of all stable isotopes analysed, the strongest correlation was in the δD values from July 2009 with an r-value of -0.97 indicating a strong negative linear relationship as indicated in **Figure 24**. A significance test, with a null hypothesis assuming no linear relationship, was then performed on the r-value. It was established that $t_{calc} > t_{crit}$, therefore rejecting the null hypothesis and accepting that the linear relationship is statistically significant.These samples, collected in July 2009; B33, B34, B32, B35, B69, B70, B65, in order of increasing altitude (**Figure 24**), are all samples that were collected from the edge of the Namib Desert.



Figures 24 and 25: Plot of δD (Figure 24) and $\delta^{18}O$ (Figure 25) vs. altitude (m) of all groundwater samples. The red circle in Figure 23, indicates a set of samples showing a good correlation between δD and height

The groundwater oxygen and hydrogen delta values show no correlation with EC (μS) (**Figures 26 and 27**). The majority of samples cluster between 500 and 2500 μS with very little variation in $\delta^{18}O$ and δD. There are two samples (B133 and B146) with anomalously high EC values of 3790 μS and 5210 μS, respectively. Sample B133 was collected in July 2009 from a site on the road into Sossusvlei (**Figure 14**), where the water was reported to have a funny taste. Interestingly, this sample site was tested in prior field seasons and although the EC values were high, this was by far the highest they had been. Sample B146 was collected in February 2009, from the construction site of a new guest farm, the water was particularly murky and had a nitrate value of >50 mg/dm^3 (measured using nitrate test strip). As salinity and TDS were calculated from EC (see methodology), it is only necessary to compare delta values to EC.



Figures 26 and 27: Plot of δD (Figure 26) and $\delta^{18}O$ (Figure 27) vs. EC (µS) of all groundwater samples. Two anomalously high EC values B133 and B146 have been labelled

The $\delta^{13}C$ of DIC for all groundwater samples throughout the seasons also had only negative values, the majority falling between values of -13‰ and -7‰ (**Figure 28**). The very small variation of all three stable isotopes from the distinct groundwater sources over the different seasons is important in helping to define the source.

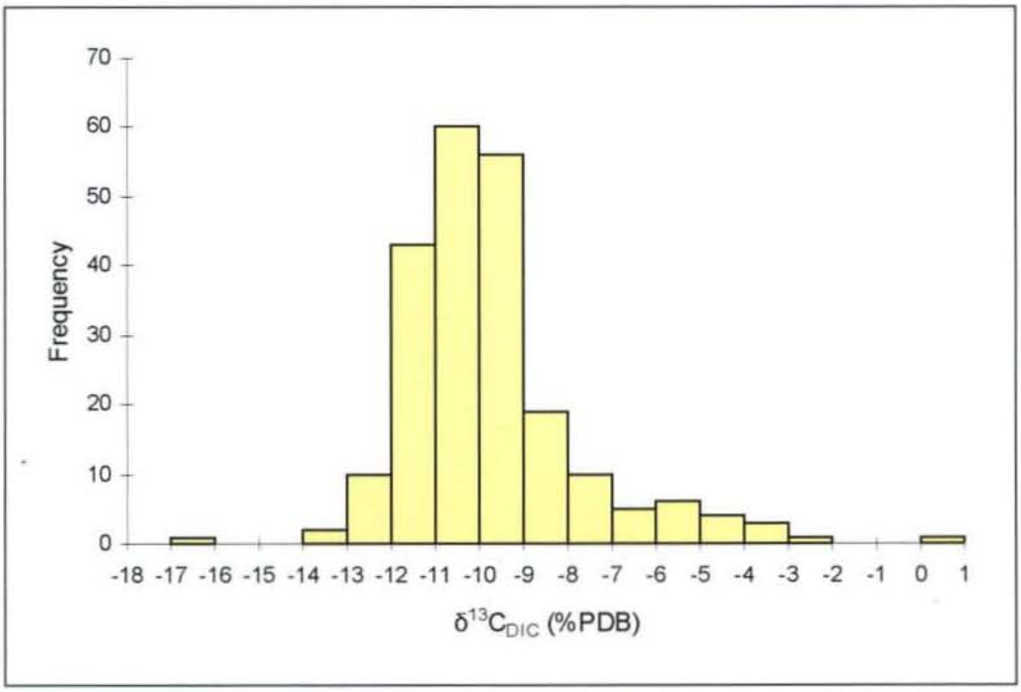


Figure 28: Histogram of $\delta^{13}C$ values of DIC in all groundwater samples. As with all the histograms that follow the frequency denotes the number of values within a certain bin range

4.2.1 Boreholes

Borehole water had the most negative $\delta^{18}O$ and δD values of all the samples collected, with average values and standard deviations of -6.8‰±1.0 and -45‰±7, respectively (n=199) (The mean and standard deviation of all samples collected throughout the project duration). The average values of all stable isotope values from all four seasons do not vary much (<0.17‰ for O and <2‰ for H), with no distinct seasonal changes (**Figure 29**). All standard deviations for the borehole samples were low (1.0‰ for O and 7‰ for H). The $\delta^{13}C$ of the DIC of the borehole water had an average value of -9.7‰ (n=199), which is on par with all the rest of the samples collected. No distinct seasonal variations in $\delta^{13}C$ values were noted.

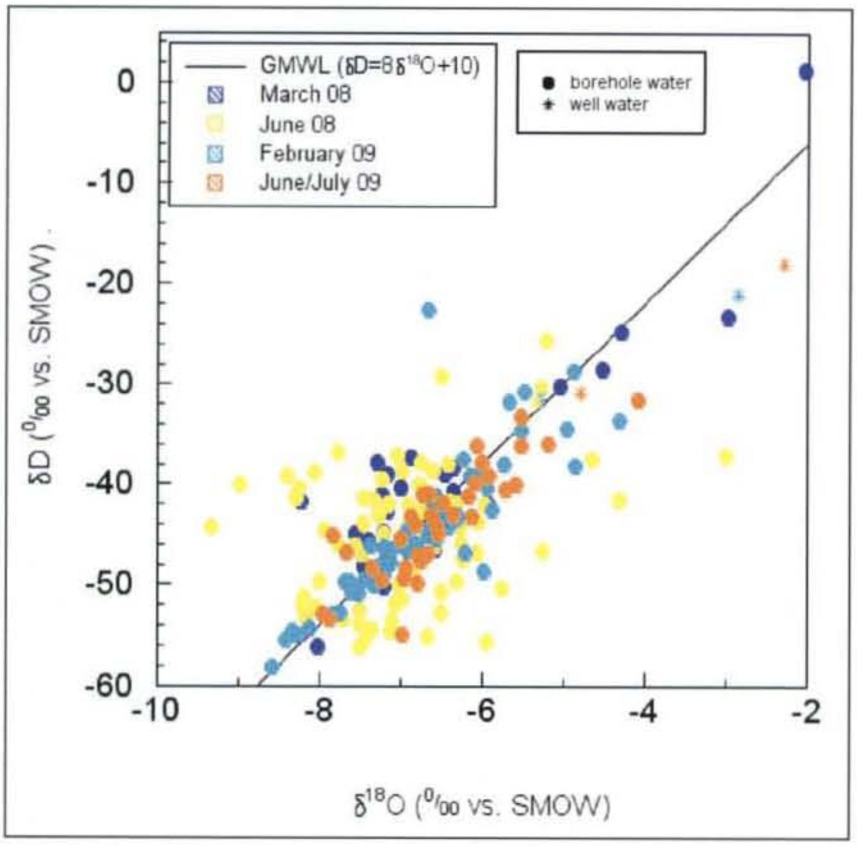


Figure 29: $\delta^{18}O$ vs. δD for all borehole and well samples

4.2.2 Wells

Due to the very small number of well point samples collected (n=5), very little significance can be attached to the data. The average $\delta^{18}O$, δD and $\delta^{13}C$ values from both June/July 2008 and February 2009 are reasonably similar, however July 2009 data has markedly less negative values for $\delta^{18}O$, δD and $\delta^{13}C$ than all prior field seasons. The average values and standard deviations were $\delta^{18}O$ =-4.5‰±1.4, δD =-28‰±6 and $\delta^{13}C$ =-9.3‰±1. The $\delta^{18}O$

and δD values of the wells (**Figure 29**), are less negative than both the borehole and spring water data.

4.2.3 Springs

The spring water collected (n=31) had similar values to the borehole data, with negative $\delta^{18}O$ (-6.5‰±1.5) and δD (-42‰±10) average values. The δD means of June/July 2008 (-44.6‰±11.5) and July 2009 (-43.8‰±5.8) (winter seasons) showed similarly more negative values than the summer season means (-38.6‰±20.2 and -40.9‰±9.5 for 2008 and 2009 respectively), although this seasonality was not evident in the $\delta^{18}O$ values (**Figure 30**). The $\delta^{13}C_{DIC}$ values showed values that are more negative in the summer seasons as compared to the winter seasons (See Appendix 1). The average $\delta^{13}C$ and standard deviation was -10.2‰±1.7, which is slightly more negative than all other samples collected.

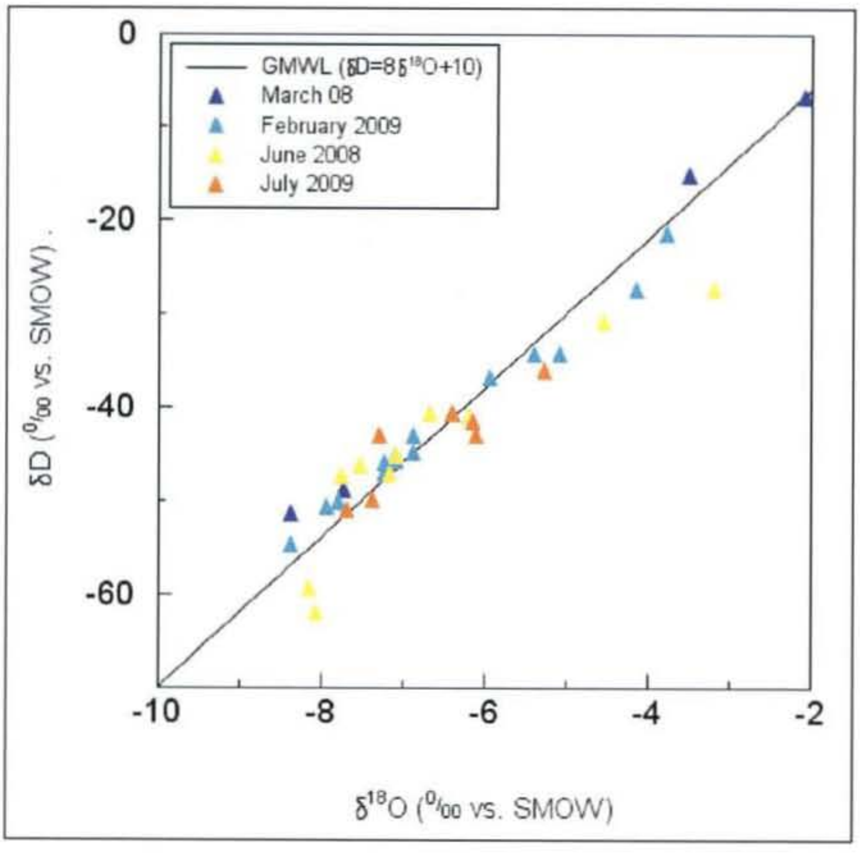


Figure 30: $\delta^{18}O$ vs. δD for all spring water samples

Groundwater samples on a whole, showed the least variability over seasons and between sample sites. The average $\delta^{18}O$, δD and $\delta^{13}C$ values for all the groundwater sampled over all four seasons was -6.7‰±1.1, -44‰±8 and -9.8‰±2.1 respectively.

4.3 Rivers and Streams

River and stream water samples collected refers to the two main rivers in the area, the Tsondab and the Tsauchab Rivers (labelled Rivers) as well as the smaller tributaries (labelled Surface Water) that run throughout the region. The total sample numbers are often very low in the case of the Tsondab River, as throughout the dry winter seasons (June/July 2008 and July 2009) this ephemeral river dried up and it was not possible to collect any samples. The Tsauchab is however, at a certain point in its course, supplemented by a natural spring, which allows one river sample to be collected in the dry, winter season although its isotope signature is likely to be closer to that of spring water. The surface water collected that is not from the two main rivers also dwindles in the dry season. However, sample locations within the Naukluft mountains often provide a year-round source, even if the source is significantly smaller than in the wet, summer months.

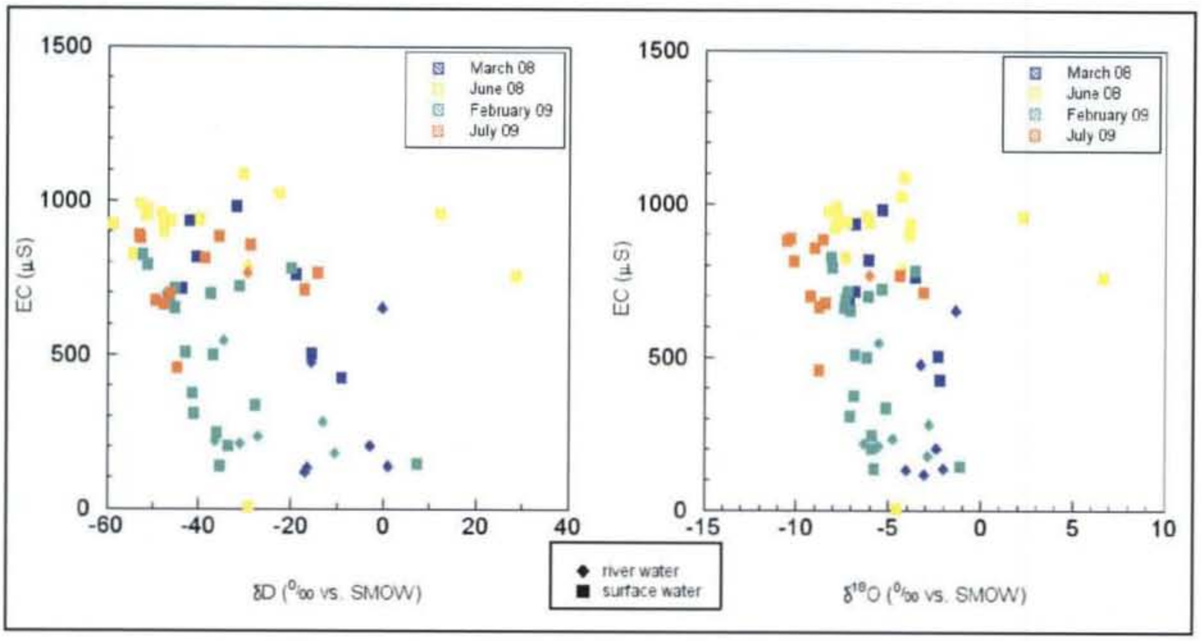
A total of 69 river and stream water samples were collected over the field seasons, the smaller tributaries (surface water) making up the bulk of this total.

The $\delta^{18}O$ and δD of all the river and stream water samples collected showed a greater variation in values compared with groundwater samples, as one would expect with sources in open systems (standard deviation for all rivers and streams = 2.7‰ for O and 18‰ for H). The $\delta^{18}O$ values were also grouped between -9‰ and -1‰, however three positive outliers were also observed. These outliers were all collected from discrete sources (2A57, 2A22, 2A97) and all collected during the second field season. They all plot on the evaporative fractionation line. The δD values spread from -55‰ to -10‰, again with a few positive outliers.

Table 5: Table of stable isotope statistics of all river and stream samples.

	$\delta^{18}O$	δD	$\delta^{13}C$
Average	-5.0	-32	-9.4
Std dev	2.7	18	2.9
Max	6.6	29	0.3
Min	-8.2	-59	-18.5
Count	73.0	73	62.0

The EC values from all the river and stream water samples in the dry winter seasons showed very little variation with varying oxygen and hydrogen delta values. In the wet summer months, this variation was much greater (**Figures 31 and 32**). The summer season data seems to show a weak correlation, indicating increasing EC values with more negative δD and δ^{18}O values.



Figures 31 and 32: Variation in EC (µS) vs. δD (Figure 31) and δ^{18}O (Figure 32). Very weak correlation, the more negative the delta values become the greater the EC values become. This graph clearly indicates a greater variation in EC in the rainy summer months, March and February

The δ^{13}C values varied much less throughout the sampling seasons. The bulk of the samples have values between -12‰ and -4‰ (**Figure 33**). There is one anomalous positive value (0.3‰) which was collected during the second field season from a waterfall (A22). This sample was collected in three sample seasons and in all three it yielded hugely varied δ^{13}C values of the DIC. It is likely that this is a natural anomalous value, its variable values are indicative of its location, i.e. water taken from a waterfall where the amount of water varies and the source of the water may vary.

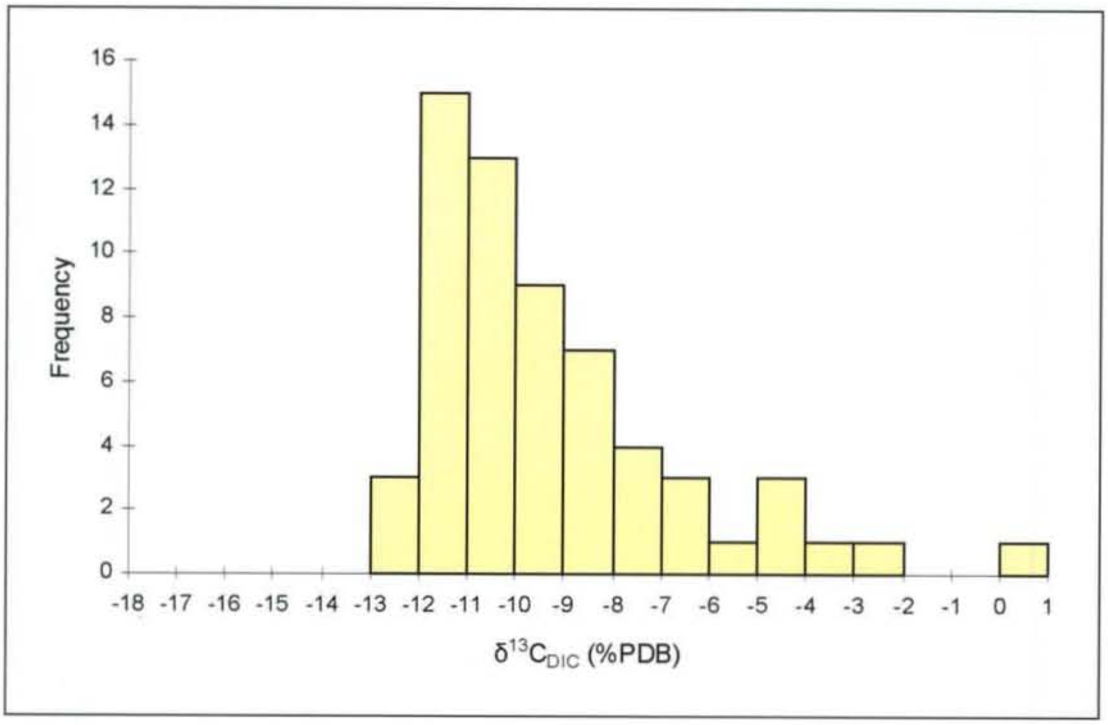


Figure 33: Histograms of $\delta^{13}C$ values of all surface water samples

4.3.1 Tsauchab and Tsondab Rivers

The Tsondab and Tsauchab Rivers have significantly less negative $\delta^{18}O$ and δD values in comparison to groundwater, but are still more negative than the local precipitation at the time they were sampled (**Figure 34**). The values were also higher than other surface water samples taken from the smaller tributaries. It is difficult to draw any conclusions with regard to seasonality as only one sample was collected during each of the dry, winter seasons. When specifically examining this sample site (R38: located in the south of the study area, mid-course along the Tsauchab river), it shows extremely similar values in June/July 2008 and July 2009. Whereas the samples collected during the wet summer, seasons show far more variation. The average values of the two rivers over the three seasons was $\delta^{18}O$ = -3.7‰, δD =-19‰ and $\delta^{13}C$ =-9.5‰, respectively.

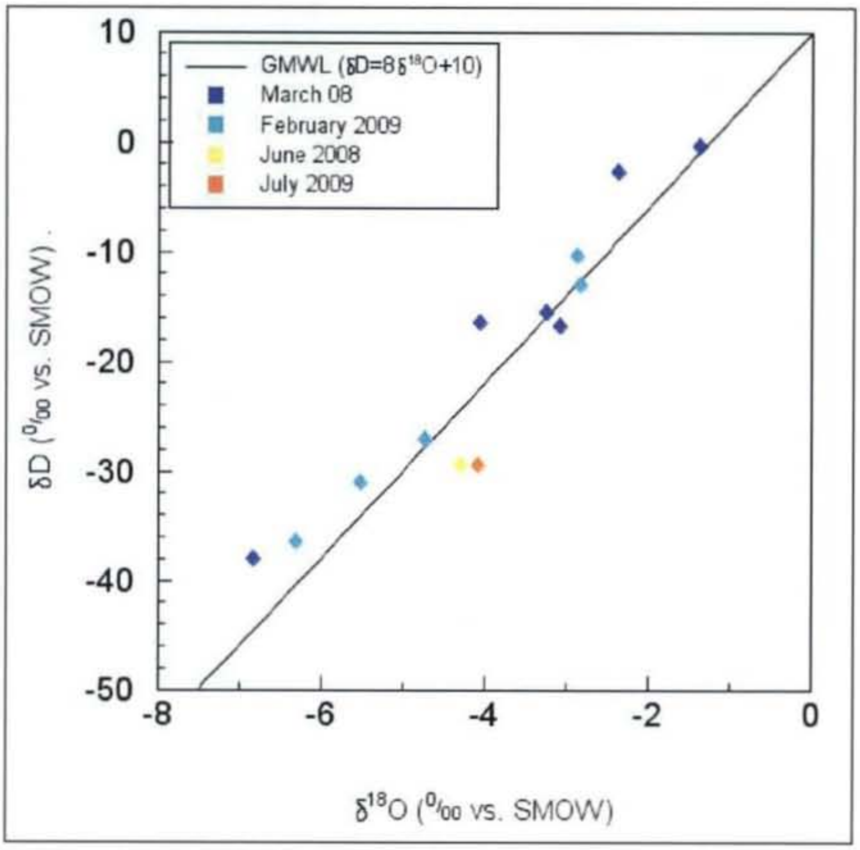


Figure 34: δ^{18}O vs. δD for all river water samples

4.3.2 Small tributaries

The smaller tributaries (surface water samples) (n=59) are most commonly located in the NNC and were often year-round water sources. The surface water samples show by far more variability between sample types and sample sites than the groundwater samples showed. The data show more negative average values than that of the two major rivers with an average and standard deviation of δ^{18}O = -5.3‰±2.8 and an average and standard deviation of δD = -35‰±18 however, the data falls in a range of -8.2‰ and 6.7‰ for δ^{18}O and -59‰ and 29‰ for δD. δ^{18}O values are on average less negative in the winter months; however, this is not seen in average δD values. δ^{13}C values are also less negative in winter than in summer (See Appendix 1).

Table 6: Table indicating statistics form all the smaller tributeries sampled.

	Season	n	ave δ18O (‰)	stdev δ18O (‰)	ave δD (‰)	stdev δD (‰)	ave δ13C-DIC (‰)	stdev δ13C-DIC (‰)
1	**Summer (Rain)** **March 2008**	10	-4.9	2.11	-29.8	15.59	-9.5	2.16
2	**Winter (Dry)** **June/July 2008**	17	-4.6	4.10	-34.6	26.05	-8.8	4.22
3	**Summer (Rain)** **Feb 2009**	20	-6.1	1.81	-36.3	14.12	-10.9	1.36
4	**Winter (Dry)** **July 2009**	12	-5.3	2.39	-37.6	13.95	-8.0	2.48
	All Surface water data:	**ave δ18O (‰)**	**-5.3**	**ave δD (‰)**	**-35**	**ave δ13C-DIC (‰)**	**-9.4**	
	59	**stdev δ18O (‰)**	**2.8**	**stdev δD (‰)**	**18**	**stdev δ13C-DIC (‰)**	**3.0**	

In June/July 2008, a few surface water samples plot on a shallower slope ($\delta D = 3.6\delta^{18}O + 4.4$) as compared to the GMWL, in much the same way as precipitation samples from March 2008 plotted on $\delta^{18}O$ vs. δD graph (**Figure 35**). Samples from July 2009, plot on a much steeper slope ($\delta D = 5.8\delta^{18}O - 6.6$) but show a similar evaporative trend (**Figure 34**).

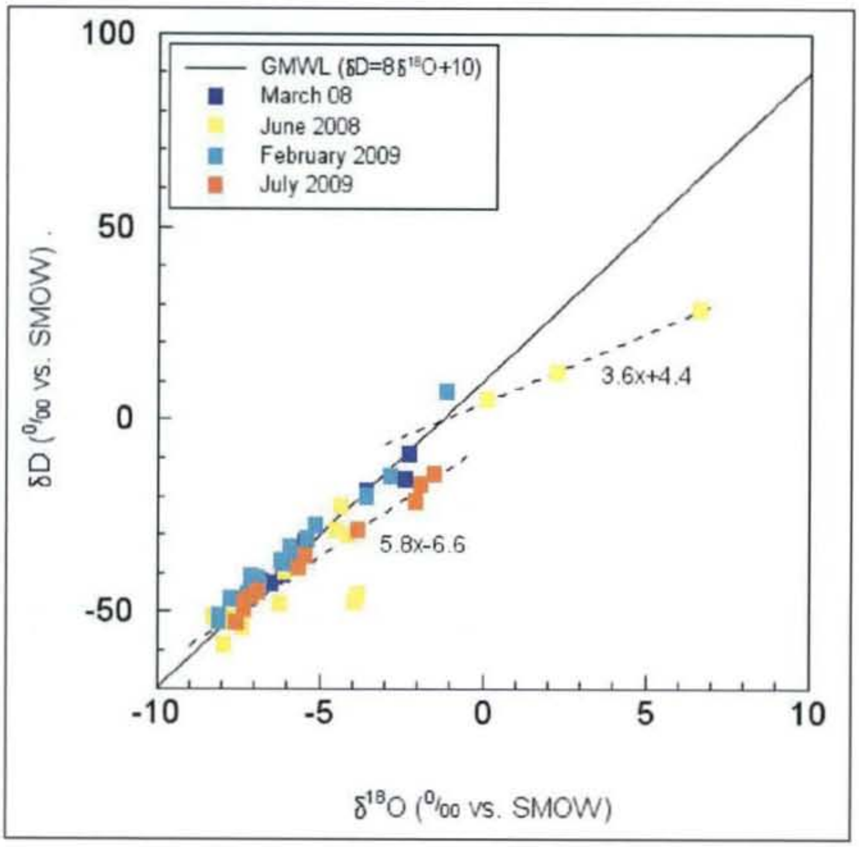
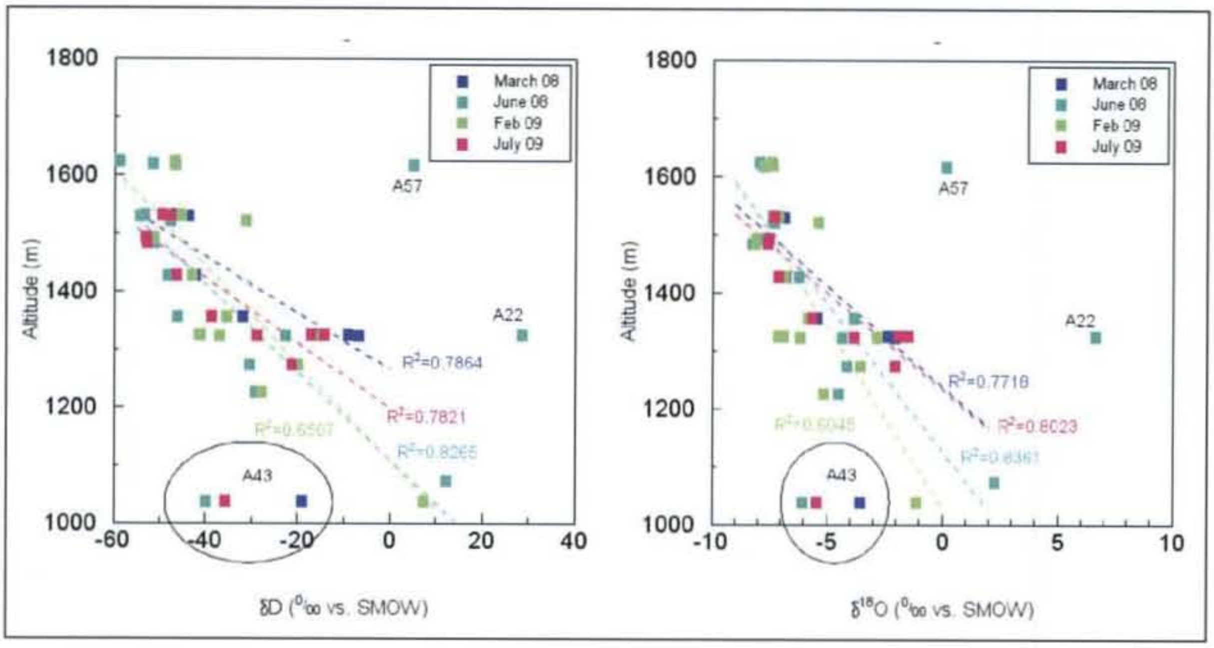


Figure 35: $\delta^{18}O$ vs. δD for all stream water samples from small tributaries

The majority of surface water samples from all four seasons show $\delta^{18}O$ and δD values decreasing with increasing altitude (**Figures 36 and 37**). This trend would most likely be echoed in the precipitation values collected, but not enough altitude measurements were taken with precipitation samples.

A few samples are observed to have interesting δD and $\delta^{18}O$ values when plotted with altitude. Sample A43 collected in the south, from the Tsauchab River is fed by a natural spring that allows the river to flow all year. In all the seasons, except during the heavy rainfall in February 2009, sample A43 has significantly more negative δD and $\delta^{18}O$ values with very little variation between seasons. Samples A57 and A22 both come from Die Valle area. A57 was collected high on the plateau from a pool feeding the waterfall and A22 was collected on the same watercourse at the waterfall at the bottom of the valley. Although they have less negative δ values ($\delta^{18}O$ of 0.1‰ and 6.6‰ and δD of 5‰ and 29‰ for A57 and A22, respectively) they too correlate well with altitude. The Pearson r-value for $\delta^{18}O$ and δD values from all seasons indicated a strong negative linear relationship all values <-0.77 and the t-test showed that these relationships were indeed significant.



Figures 36 and 37: δD (Figure 36) and δ^{18}O (Figure 37) vs. altitude of surface water samples in the Naukluft. Labelled samples indicate samples that do not show any correlation

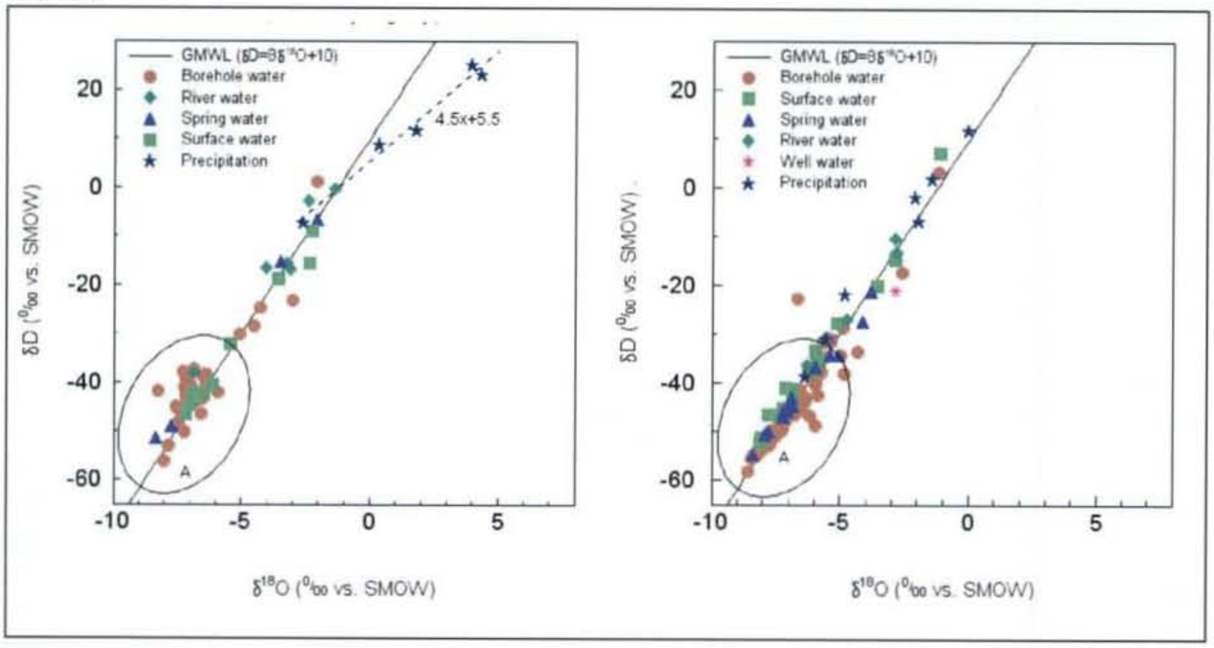
The river and stream samples show far more variability between sample types and sample sites than the groundwater samples showed. River and stream water samples show no significant relationship to the precipitation data.

4.4 Seasonal Variations

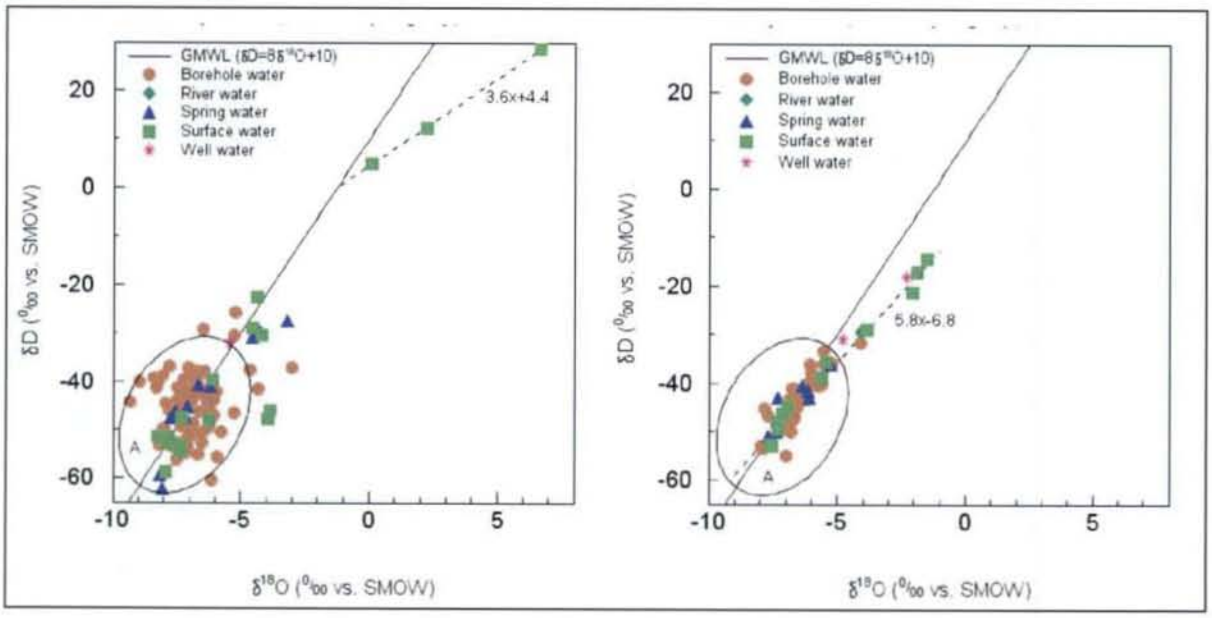
Seasonality might be expected in an area with a climate such as is experienced in the Naukluft. The stark contrast between the dry winters and the wet summers is gloriously observed in the field when the brown, tough grasses miraculously turn delicately green. This onset of the rains however does not seem to affect the isotope values of the Naukluft aquifer/s as might be expected, in fact, groundwater samples overall showed the least variation over the seasons.

4.4.1 δD vs. δ^{18}O

Two groups of samples can be observed in the data from all four seasons. A group labelled 'A' for ease of comparison, lies on the negative end of the GMWL and contains the majority of groundwater samples, with the bulk of boreholes and spring water samples plotting values of δ^{18}O between -8.0‰ and -6.0‰ and δD between -40‰ and -50‰ **(Figures 38-41)**. Outside of 'group A', at higher δD and δ^{18}O values, the majority of river and rain water samples and a number of surface water samples spread out along the GMWL. In both dry seasons (June and July) of 2008 and 2009, only group 'A' seems to be present, with all samples clustering at the negative end of the GMWL and only a limited few with higher δ values.



Figures 38 and 39: δD vs. $\delta^{18}O$ from the rainy seasons (Figure 37: March 2008 and Figure 38: February 2009). Group A is labelled in the circle. An evaporation trend with a slope of 4.5 is observed in precipitation samples in March 2008

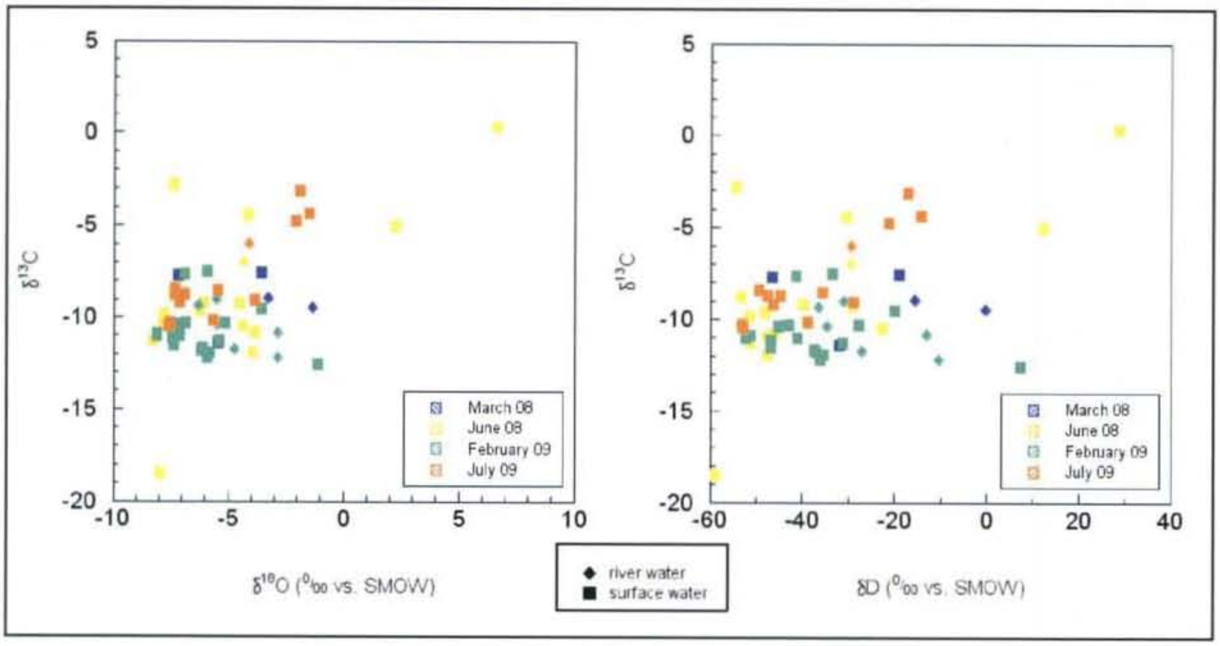


Figures 40 and 41: δD vs. $\delta^{18}O$ from the dry seasons (Figure 39: June 2008 and Figure 40: July 2009). Group A is labelled in the circle. An evaporation trend with a slope of 3.6 is observed in surface water samples from June 2008. An evaporation trend with a slope of 5.8 is observed in surface water samples form July 2009

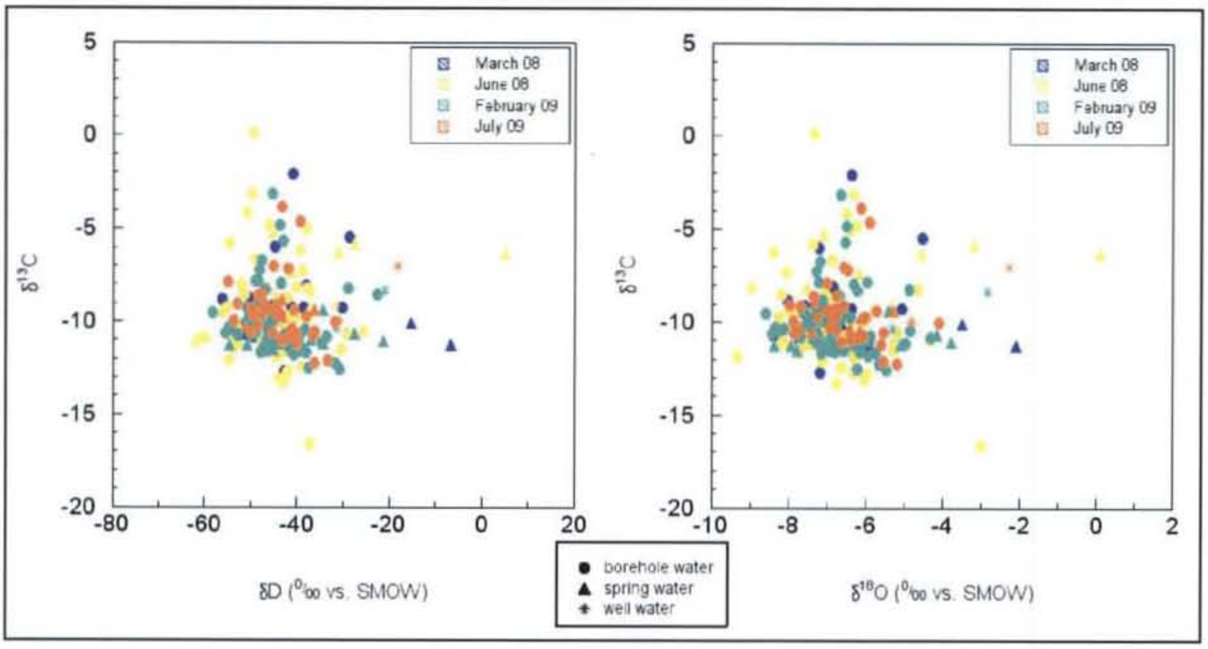
4.4.2 $\delta^{13}C$ vs. $\delta^{18}O$ and δD

An examination of $\delta^{13}C$ values compared with δD and $\delta^{18}O$ values shows no strong correlation (**Figures 42-46**), with Pearson r-values close to zero. Variation in $\delta^{13}C$ from season to season seems to be very small. Larger variations are seen in δD and $\delta^{18}O$, particularly in the wet summer seasons. Spring water samples indicated more negative δD values in the winter season and more negative $\delta^{13}C_{DIC}$ in the summer season, however the variations between the seasons are not significant (δD stdev=3‰ and $\delta^{13}C_{DIC}$ stdev=0.9‰).

The first field season data in particular indicates that the highest percentage DIC occurs in water that has low δD and $\delta^{18}O$ values. No distinct trends are prominent with $\delta^{13}C$ of the DIC.



Figures 42 and 43: $\delta^{13}C$ vs. δD and $\delta^{18}O$ for rivers and streams



Figures 44 and 45: $\delta^{13}C$ vs. δD and $\delta^{18}O$ for groundwater

5 DISCUSSION

5.1 Overview

The factors that influence recharge processes will be investigated and an attempt will be made to characterize the aquifer/s in the region. The characteristics of the $\delta^{18}O$, δD and $\delta^{13}C$ values will be examined in detail with the range of values, the spatial distribution and the seasonal variation of these values, all adding to our understanding of the aquifer/s and the recharge processes. The stable isotopes of the water in the Naukluft will then be compared to other karstic and arid regions, establishing whether the $\delta^{18}O$ and δD values lie along the same MWL and whether the data fall within a similar range of $\delta^{18}O$ and δD values. In comparing $\delta^{13}C$ values of the groundwater in the Naukluft to other areas, it is hoped that the water/rock relationship, in the Naukluft can be better understood and the flow-paths and aquifer/s further characterized.

5.2 Stable isotope characterization of Naukluft waters

In order to understand recharge processes in the Naukluft and the aquifer/s involved, it is important to understand the variations in the stable isotopes of the waters identified in chapter 4. The stable isotopes of the surface- and ground- water in the Naukluft Region vary spatially, with altitude and latitude, and seasonally, whereas the precipitation samples, vary with the amount of rainfall. The variation and range of these stable isotopes, a result of the hydrological processes in the Naukluft, may help to understand the recharge processes and characterize the source of the groundwater. Climatic variations are thus critical to an understanding of the role the above variables play in the stable isotope values, and it is important that these are known or approximated.

Although daily temperatures in the Naukluft during sampling were not recorded and the amount of rainfall in each event was not measured however, this information would only provide a short-term picture during the two-year sampling program. In order to give a reasonable idea of expected $\delta^{18}O$ and δD values and their relationship with temperature and amount in the area, the average monthly values of the amount of precipitation and the average temperature and $\delta^{18}O$ and δD values for Windhoek, the nearest region with long-term data (IAEA, 1997; Station 6811000, Windhoek, (1961-1986)) have been used (**Figure 46 and Table 5**). The average monthly amount of rainfall at Büllsport is also plotted for further comparison (E. Sauber, pers. comm., 2008) and the two data sets correlated with a coefficient of 0.97. It is evident that despite the high overall amount of rainfall in Windhoek, the seasonal effect of amount of rain is the same. Temperatures in both Windhoek and the Naukluft are also comparable (**Figure 12**). The $\delta^{18}O$ values of Windhoek rainfall range from -6.1‰ to 2.6‰ and δD from -28‰ to 38‰, whereas the $\delta^{18}O$ values of the Naukluft precipitation, shows a much larger, albeit overlapping, range with $\delta^{18}O$ values from -14.4‰ to 4.3‰ and δD values from -95‰ to 25‰. However, it is important to note that the Windhoek data are the average for 25 years (over 20 years ago), whereas the Naukluft data are a small sample-set (n=15) and is only representative of two rainy seasons. The weighted average $\delta^{18}O$ and δD values for Windhoek, with respect to the amount of precipitation, is -3.7‰ and -18‰, respectively.

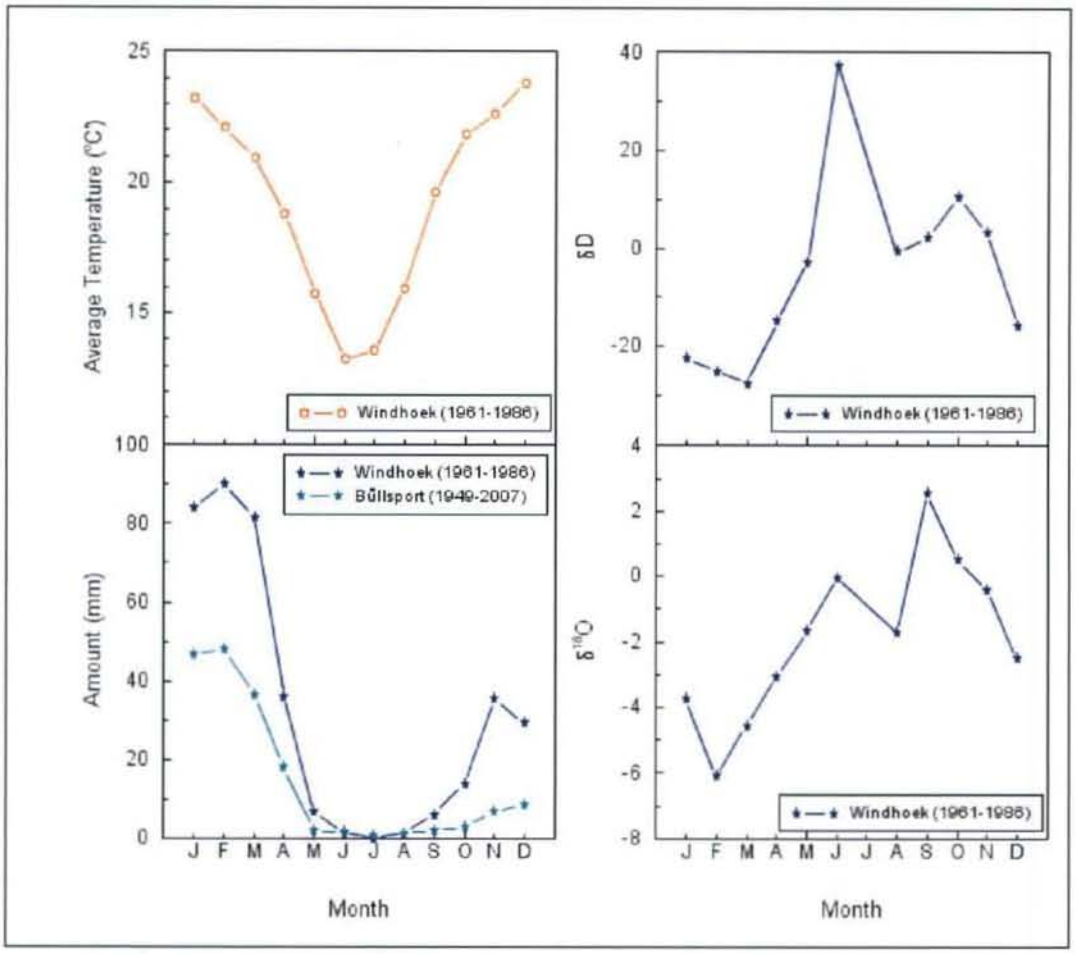


Figure 46: Average monthly values of; amount of precipitation, average temperature and $\delta^{18}O$ and δD values for Windhoek (1961-1986) (IAEA, 1997; Station 6811000, Windhoek). Average monthly amount of rainfall at Büllsport also plotted (E. Sauber, pers. comm., 2008). July $\delta^{18}O$ and δD values were not available as there was not enough rain in this month over all 25 years to analyse, therefore July data point has been excluded

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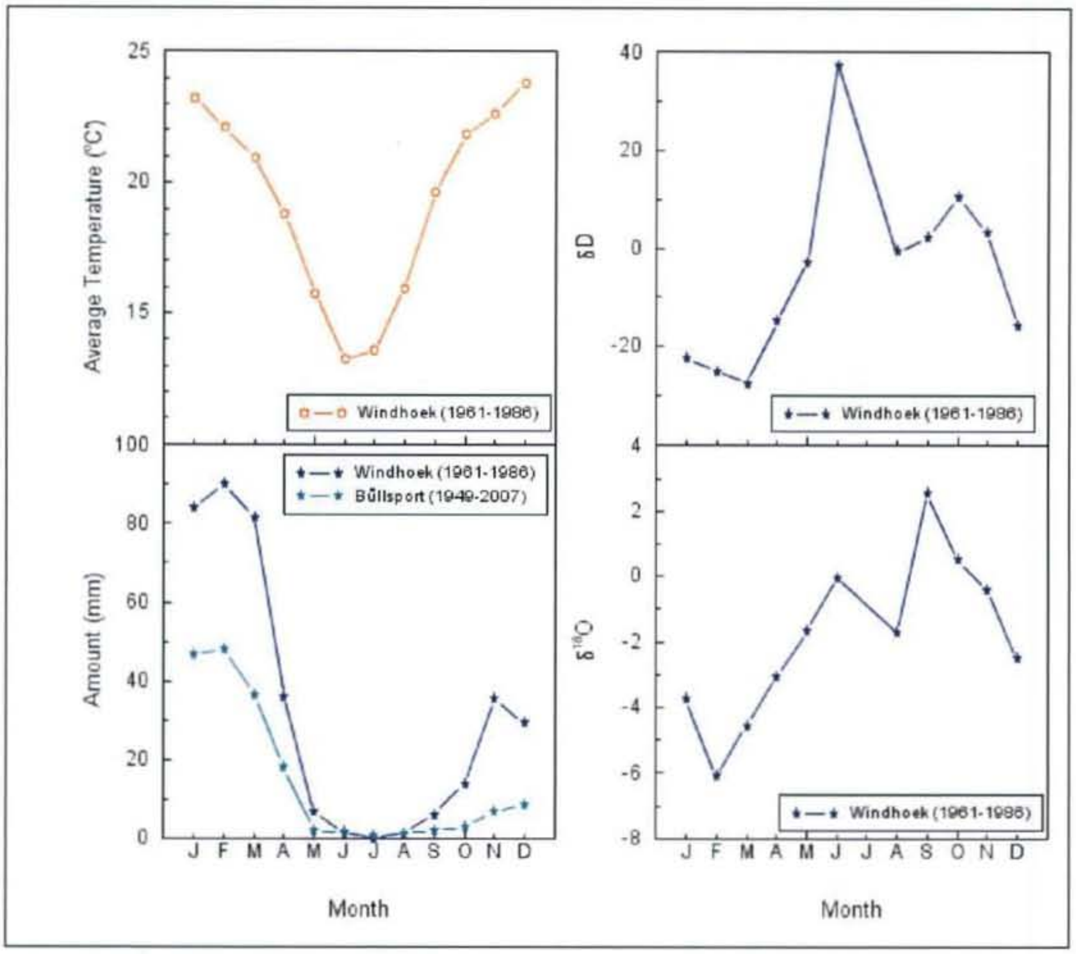


Figure 46: Average monthly values of; amount of precipitation, average temperature and δ^{18}O and δD values for Windhoek (1961-1986) (IAEA, 1997; Station 6811000, Windhoek). Average monthly amount of rainfall at Büllsport also plotted (E. Sauber, pers. comm., 2008). July δ^{18}O and δD values were not available as there was not enough rain in this month over all 25 years to analyse, therefore July data point has been excluded

The precipitation data from Windhoek indicate a decrease in $\delta^{18}O$ and δD values with an increase in the amount of rainfall (**Figure 47 and Table 5**). The correlation of $\delta^{18}O$ and δD with temperature is not as well defined but the data seems to indicate a decrease in $\delta^{18}O$ and δD values with increasing temperature. This is a reversal of the normal temperature effect, possibly a "monsoon effect", where the heavy monsoonal rains show a depletion in ^{18}O as an effect of increased temperature (Cerling, 1984). The proximity and similarity in altitude and latitude of the Naukluft Region to Windhoek (± 200 km), suggest that the Naukluft $\delta^{18}O$ and δD precipitation data would reflect similar relationships with temperature and amount of precipitation. Qualitatively, this amount effect has been observed in the precipitation samples from the Naukluft, although the increased amount of rainfall in Windhoek would result in more negative average $\delta^{18}O$ and δD values than are observed in the Naukluft. The average Windhoek $\delta^{18}O$ and δD values are -6.1‰ and -25‰ for February and -4.6‰ and -27‰ for March, respectively. In the Naukluft, the $\delta^{18}O$ and δD values are -4.0‰ and -20‰ for February and 1.5‰ and 12‰ for March, respectively.

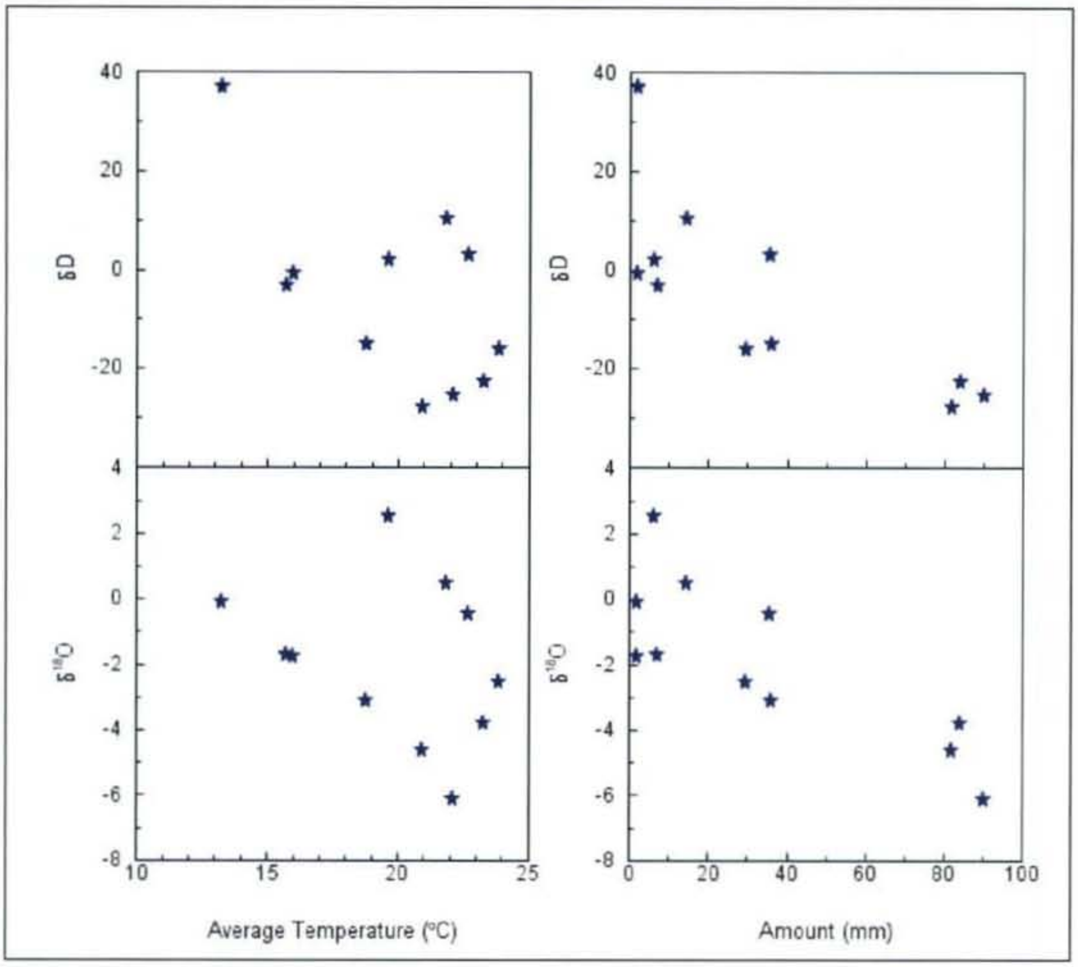


Figure 47: $\delta^{18}O$ and δD vs. average temperature and average amount of precipitation for Windhoek (1961-1986) (IAEA, 1997; Station 6811000, Windhoek).

Table 7: Average monthly amounts of rainfall, δD values, $\delta^{18}O$ values and temperature for Windhoek (1961-1986) (IAEA, 1997; Station 6811000, Windhoek).

Month	Amount (mm)	δD (‰)	$\delta^{18}O$ (‰)	Temperature (°C)
J	84	-23	-3.7	23
F	90	-25	-6.1	22
M	82	-27	-4.6	21
A	36	-15	-3.1	19
M	7	-3	-1.7	16
J	1	38	0.0	13
J	0			14
A	1	-1	-1.7	16
S	6	2	2.6	20
O	14	11	0.5	22
N	35	3	-0.4	23
D	29	-16	-2.5	24

5.2.1 Seasonality

On the overall Naukluft water $\delta^{18}O$ and δD plots (**Figures 39-41**) a group of samples have $\delta^{18}O$ and δD values between -5‰ and -10‰ and -30‰ and -65‰, respectively. This group of samples has been labelled 'group A'. In all four seasons 'group A' was present, with $\delta^{18}O$ values of between -5‰ and -10‰, and δD values of between -30‰ and -65‰. In the dry winter seasons, the samples almost exclusively fall into this group whereas in the summer the samples have a greater variation in $\delta^{18}O$ and δD values and spread out more along the GMWL. It is possible that this variation is as a result of an increased number of surface water samples, precipitation samples and river water samples that are collected in the summer season with less negative values. 'Group A' however, represents the δ-values of the groundwater, or at least samples with a large groundwater component (i.e. more negative $\delta^{18}O$ and δD values) that were collected in both winter and summer. So, although this variation looks like seasonality, it is only observed due to a natural sampling bias.

The average $\delta^{18}O$ and δD values of the borehole samples did not change significantly over all four field seasons (std. dev: 0.18‰ and 2.18‰ for $\delta^{18}O$ and δD, respectively). ANOVA was performed between the groups and showed that the null hypothesis, that the variance between the groups was not significant, had to be accepted. This suggests that the groundwater is either an isolated source, unaffected by local precipitation and/or river water, or the source must be a large, well-mixed body able to homogenize the less negative precipitation and river water $\delta^{18}O$ and δD values. The wells (W97 and W147) that indicated markedly less negative values for $\delta^{18}O$, δD and $\delta^{13}C$ (average values of -3.5‰, -25‰ and -8.5‰ respectively) in July 2009 compared with all other seasons, may be as a result of the increasing rains in Feb 2009, with less negative δ values (average $\delta^{18}O$ = -4.0‰ and average δD = -20‰) that infiltrated these shallow sources in the Naukluft. It is also important to note that many of the wells in the Naukluft were not sufficiently covered to prevent access of rain water directly into the well-point and despite efforts to sample actual groundwater (i.e. not evaporated or directly recharged by rain) from the wells the samples taken may have contained a component of rain water.

The largest seasonal variation occurs in surface water samples (std. dev: 2.8‰ and 18‰ for $\delta^{18}O$ and δD, respectively). It is likely that this is due to recharge in the rainy season. There is large discrepancy between the $\delta^{18}O$ and δD values of the local rainfall (average $\delta^{18}O$ and δD: -2.17‰ and -8.19‰, respectively) and the groundwater (average $\delta^{18}O$ and δD: -6.7‰ and -44‰, respectively). The surface water samples fall in between these ranges (average $\delta^{18}O$ and δD: -5.3‰ and -35‰, respectively). In the main rivers, the $\delta^{18}O$ and δD values are closer to that of the groundwater and are thus likely to be groundwater-fed. Where seasonal differences in the main rivers occurred, they usually had values that are more negative in the summer, rainy months. This variation in summer may be due to the less negative values of the precipitation, although it is uncertain if the precipitation that fell on the Naukluft was responsible for aquifer recharge.

The effect of the dissolved CO_2 in the soil on the $\delta^{13}C$ of the DIC in the groundwater would vary considerably, depending on the amount of soil and the flow-path of the infiltrating water. The $\delta^{13}C$ values of the water showed that limestone CO_2 ($\delta^{13}C_{carbonate}$ ± 0‰) modified the DIC in the Naukluft water to a greater extent than soil CO_2 ($\delta^{13}C_{soil}$ ± 25‰), yielding average $\delta^{13}C$ values of -9.7‰. This is to be expected given that this is an arid, karst region. In the rainy season groundwater samples might be expected to become more negative due to the increased volume of water passing through the soil ($\delta^{13}C$ values of -25‰), thus larger quantities of water with more negative $\delta^{13}C$ values are possibly recharging the aquifer/s.

However, this is not evident in all groundwater samples but it is seen in spring water samples. This may suggest that the rain that falls in the Naukluft is only recharging certain aquifer/s in the region, but this lack of seasonal variation in $\delta^{13}C$ values, is most probably related to the climate. In arid regions like the Naukluft, the soil coverings are thin and therefore would have significantly less of an effect on the groundwater than in a humid region where soil coverings are thicker and the $\delta^{13}C$ values are closer to -25‰.

5.2.2 Altitude

Dansgaard (1964) defined the altitude effect to be the relationship between altitude and δD and $\delta^{18}O$ values. The Naukluft Region ranges from 672 -1674 m a.s.l. However, there is no correlation between altitude and the δD and $\delta^{18}O$ values of the groundwater samples (**Figures 24 and 25**) however; the surface water samples do indicate a reasonably good correlation (**Figures 36 and 37**).

Although no correlation was evident between δD and $\delta^{18}O$ values of the groundwater and altitude, a few samples at low altitudes collected in July 2009 did seem to indicate quite a good correlation between δD and $\delta^{18}O$ values and altitude. Samples B33, B34, B32, B35, B69, B70, B65, in order of increasing altitude (**Figure 24**), are all samples that were collected from the edge of the Namib Desert. Further than that however, their relationship to one another is random and does not follow any distinguishable pattern that might help to define flow-paths or determine if this correlation is indeed due to the altitude effect.

An empirical altitude effect from the western flank of the Sierra Nevada in the United States was worked out to have a change of 0.002 ± 0.001‰ $\delta^{18}O$ with every 100 m in altitude (Criss, 1999, Rose et al, 1996). However, all the surface water samples from all the seasons in the Naukluft show a much greater altitude effect compared to this empirical gradient (2.4 ± 0.6‰ $\delta^{18}O$ per 100 m and 16 ± 5‰ δD per 100 m), indicating evidence of a much greater change in δ values with height. However, this high gradient, may not be entirely due to the altitude effect as defined above, but is perhaps aquifer-related and reflective of the source of water. It may be that the surface water at higher altitudes is recharged by groundwater sources and those at lower altitudes are influenced more substantially by the local precipitation, hence the less negative values at lower altitudes ($\delta^{18}O$ >-5.0‰ and δD >-30‰ at altitudes lower than ~ 1300 m).

Interestingly, sample A43 (Tsauchab River) in all seasons, except during the heavy rainfall in February 2009, does not have this correlation with altitude but has significantly more negative δD and $\delta^{18}O$ values with very little variation between seasons. This sample was collected in the south, from the Tsauchab River and is fed by a natural spring (sample collected a few kilometres from source) that allows the river to flow all year. This supports the theory that very negative δD and $\delta^{18}O$ values are as a result of a greater groundwater component. This sample however, is the only river courses at low altitudes with this apparent groundwater signature. It may be that precipitation in valleys and at lower altitudes is more significant, with possibly more extreme values occurring because of high run-off from higher altitudes.

Samples A57 and A22 (Die Valle) have less negative δ values than all other samples at their altitude ($\delta^{18}O$ of 0.1‰ and 6.6‰ and δD of 5‰ and 29‰ for A57 and A22, respectively). Their δD and $\delta^{18}O$ values also however, correlate well with altitude and considering they are sampled from the top and bottom waterfall, this may indeed be as a result of the true altitude effect as defined above.

5.2.3 Latitude and geomorphology

The lack of seasonal variation between sample sites, particularly with regard to groundwater samples, meant that the average stable isotopes values established from all four seasons could be used in order to examine spatial variations of δ-values of groundwater and surface water in the Naukluft Region. These values were plotted using GIS positioning and contouring was done using an inverse distance weighted interpolation between samples sites, to provide isopleth diagrams (**Figures 48-53**) of both groundwater and river and stream water for all stable isotope data.

Groundwater

The maps of $\delta^{18}O$ and δD for groundwater (**Figures 48 and 49**) show very similar patterns, as is expected, with less negative values ($\delta^{18}O > -6.0‰$ and $\delta D > -38‰$) in the north and central regions and more negative values ($\delta^{18}O < -7.0‰$ and $\delta D < -45‰$) in the northeast and on the edges of the desert in the west. The inverse is observed for $\delta^{13}C_{DIC}$ (**Figure 50**), with the less negative values ($\delta^{13}C > -7.0‰$) in the northeast, southeast and west. The similarity in the $\delta^{18}O$ and δD maps suggests a distinctive water source, possibly related to the catchment area of the Tsondab River (flows into "Tsondabvlei", **Figures 48-51**), which flows from east to the west in this region or one of its paleochannels. The $\delta^{13}C_{DIC}$ values of close to 0‰ indicate a high component of carbon derived from carbonates (as opposed to carbon derived from the soil). The NNC is observed to have the more negative values in the east and the less negative values in the west, suggesting two distinct sources within the nappe complex.

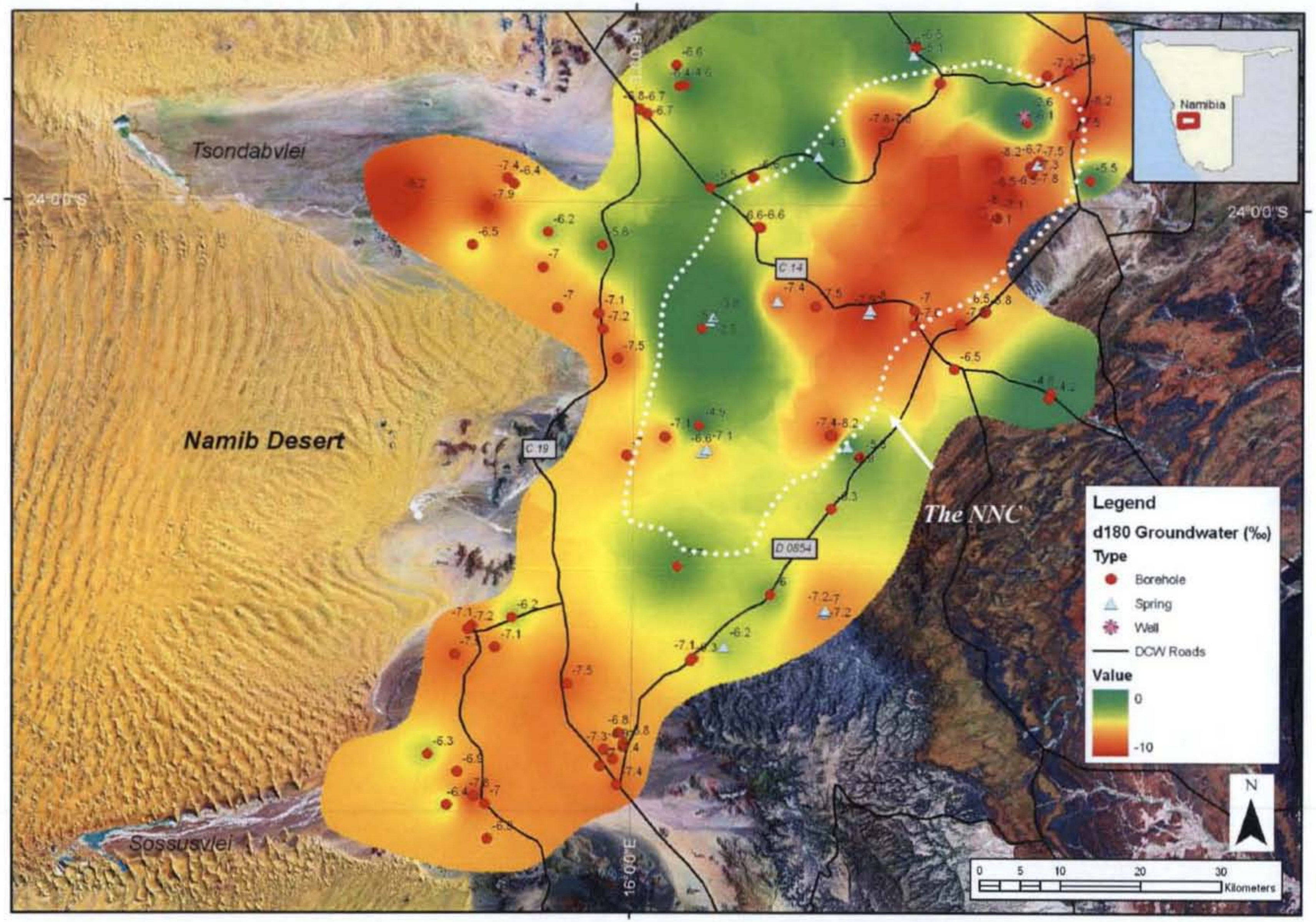


Figure 48: Position of samples with contouring of δ18O values of groundwater in Naukluft (Inversed Distance Weighting interpolation from average values of all four seasons) [Map]. 1:500000. Roads: DCW (Digital Chart of the World), NASA Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab. University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: ESRI, Inc.

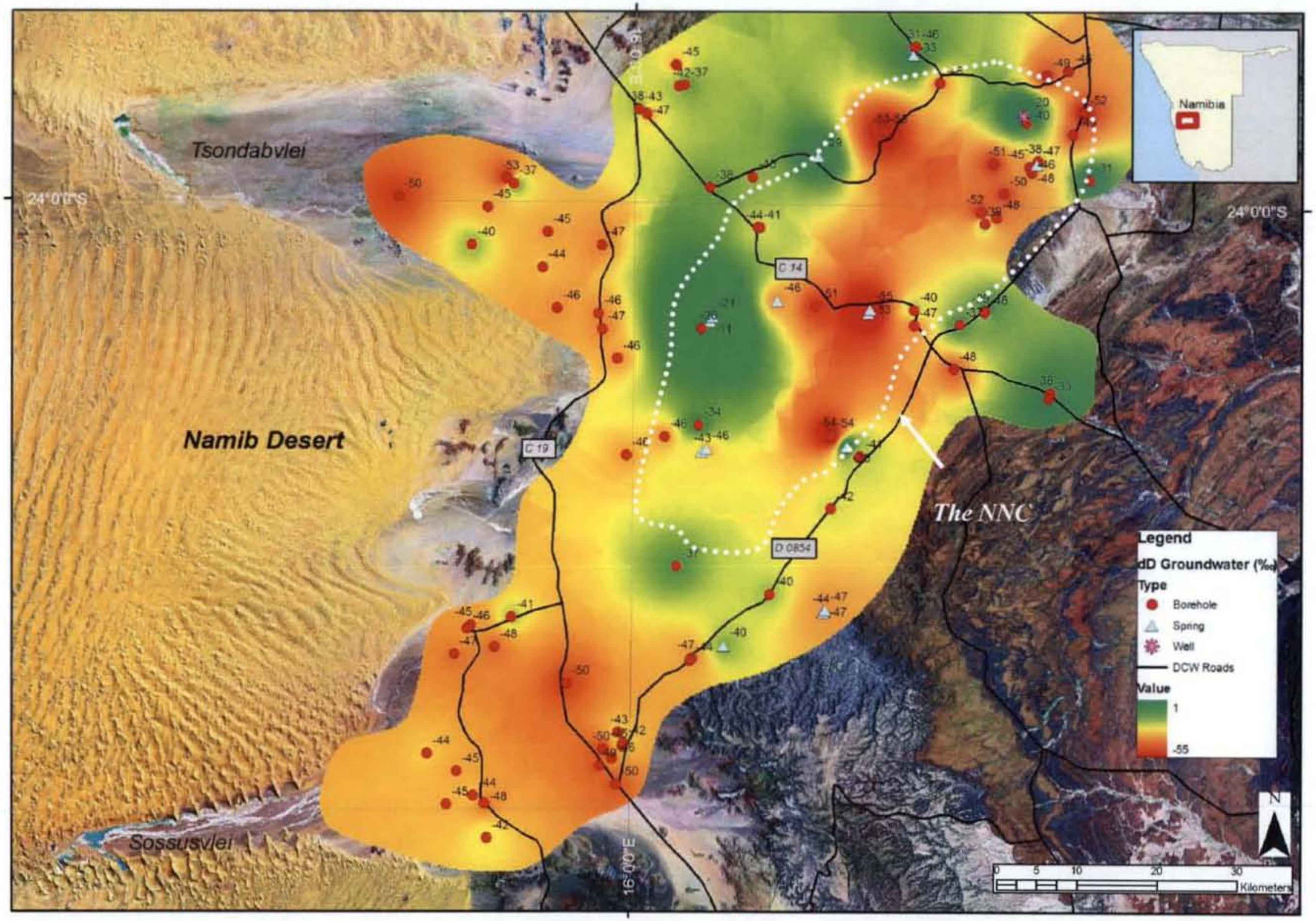


Figure 49: Position of samples with contouring of δD values of groundwater in Naukluft (Inversed Distance Weighting interpolation from average values of all four seasons) [Map]. 1:500000. Roads: DCW (Digital Chart of the World), NASA Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab. University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: ESRI, Inc.

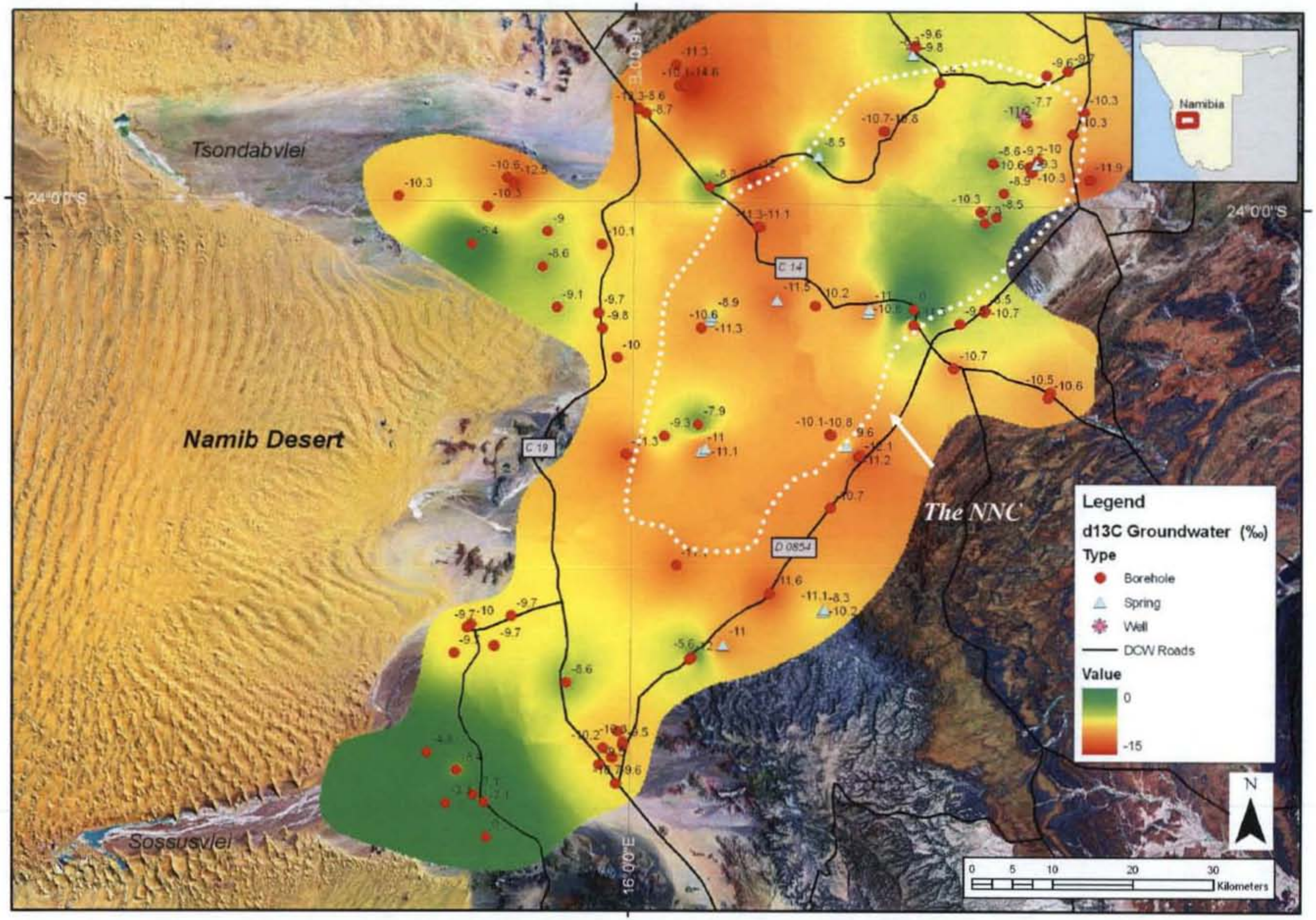


Figure 50: Position of samples with contouring of $\delta^{13}C$ values of groundwater in Naukluft (Inversed Distance Weighting interpolation from average values of all four seasons) [Map]. 1:500000. Roads: DCW (Digital Chart of the World), NASA Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab. University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: ESRI, Inc.

River and stream water

Although the river and surface water maps are less informative than the groundwater maps because of the lower number of river and stream samples collected and the naturally variable nature of open water sources, all three isopleth diagrams show significant regions indicative of the catchment areas in the area (**Figures 51-53**). The rivers in the east, particularly in the east of the NNC, have more negative $\delta^{18}O$, δD and $\delta^{13}C_{DIC}$ values ($\delta^{18}O < -6.0‰$, $\delta D < -40‰$ and $\delta^{13}C < -10.0‰$). The southwest and northwest have less negative $\delta^{18}O$, δD and $\delta^{13}C_{DIC}$ values ($\delta^{18}O > -4.0‰$, $\delta D > -30‰$ and $\delta^{13}C > -9.5‰$). These less negative regions mirror the flow of the main rivers in the area, namely the Tsondab and Tsauchab Rivers (flows into "Sosussvlei", **Figures 51-53**). It is possible that these samples may be recharged by the local precipitation during the summer seasons and hence the less negative values comparable with the positive values of the local precipitation. Interestingly two of these samples (R29 and R31) could only be sampled in March 2008, during a rainy season that was not remarkable in any way, whereas in February 2009 during the torrential rainstorms these sources were dry. It is possible that the similarity in the isotope values of the surface water collected in the NNC is due to the fact that these are often spring-fed tributaries and the springs as mentioned above come from a well-mixed, homogenous source. These spring-fed sources show markedly more negative values indicative of the groundwater δ values in the area.

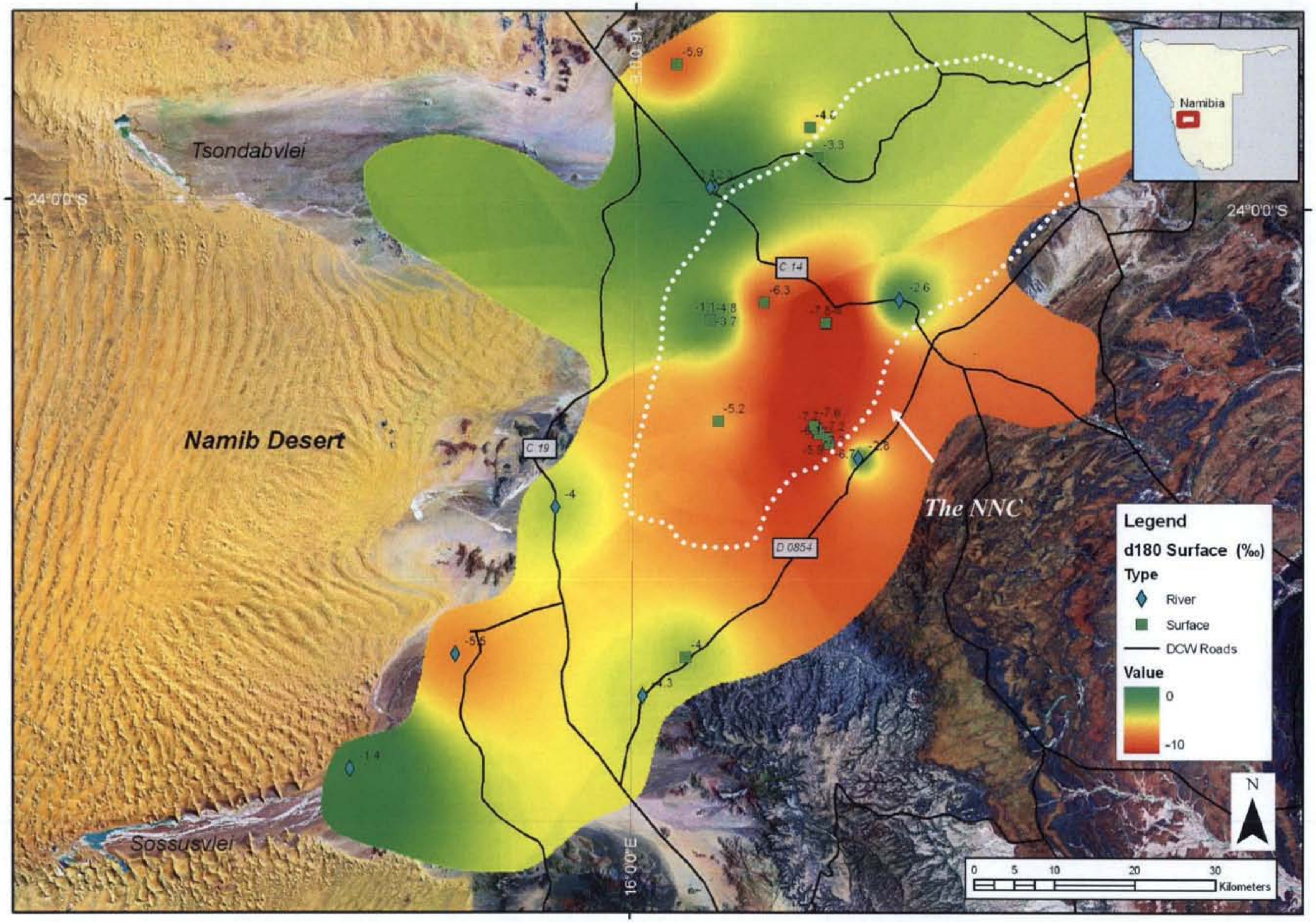


Figure 51: Position of sample sites with contouring of δ18O values of surface water in Naukluft (Inversed Distance Weighting interpolation from mean values of all four seasons) [Map]. 1:500000. Roads: DCW (Digital Chart of World), NASA Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab. University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: ESRI, Inc.

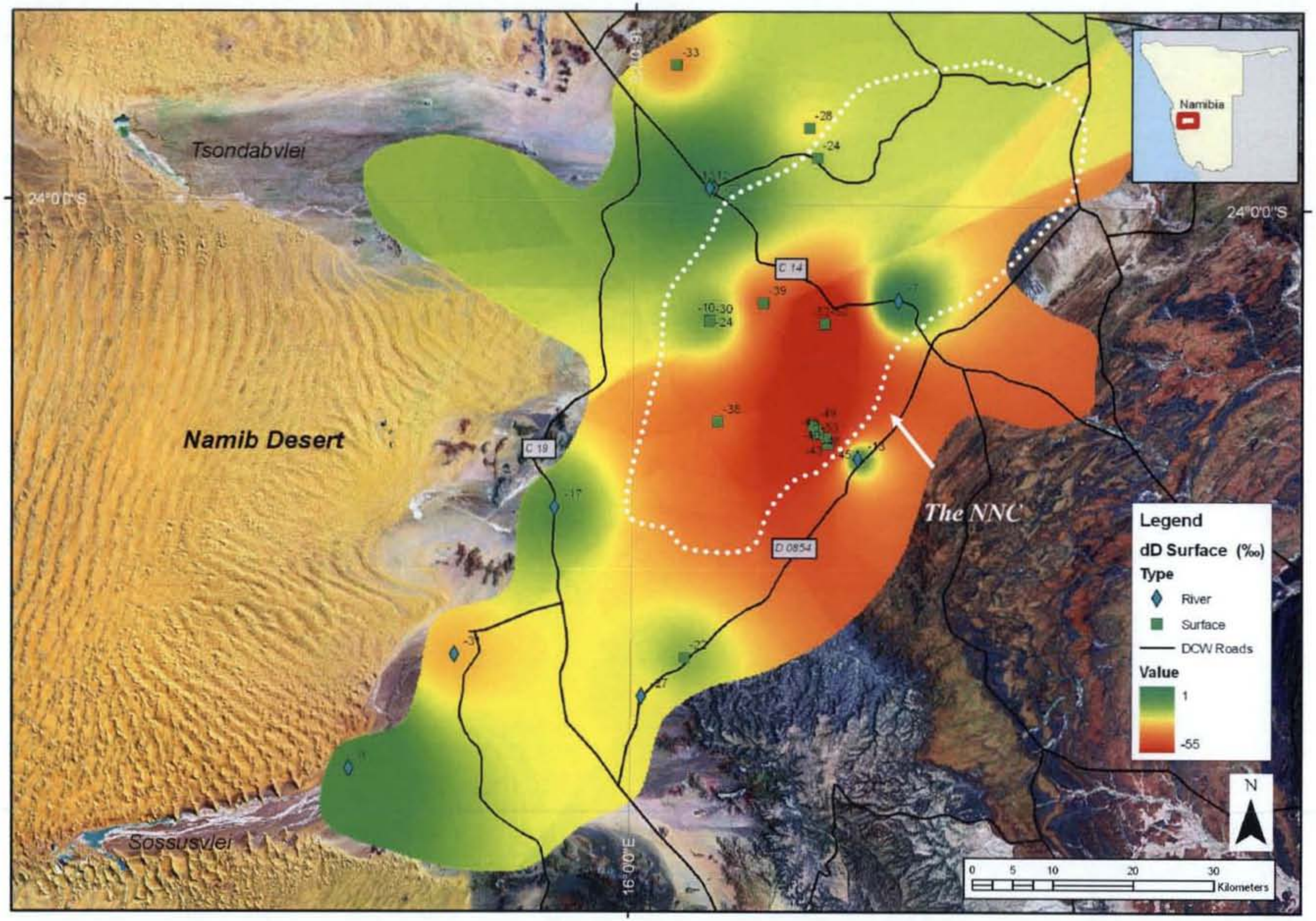


Figure 52: Position of sample sites with contouring of δD values of surface water in Naukluft (Inversed Distance Weighting interpolation from mean values of all four seasons) [Map]. 1:500000. Roads: DCW (Digital Chart of World), NASA Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab. University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: ESRI, Inc.

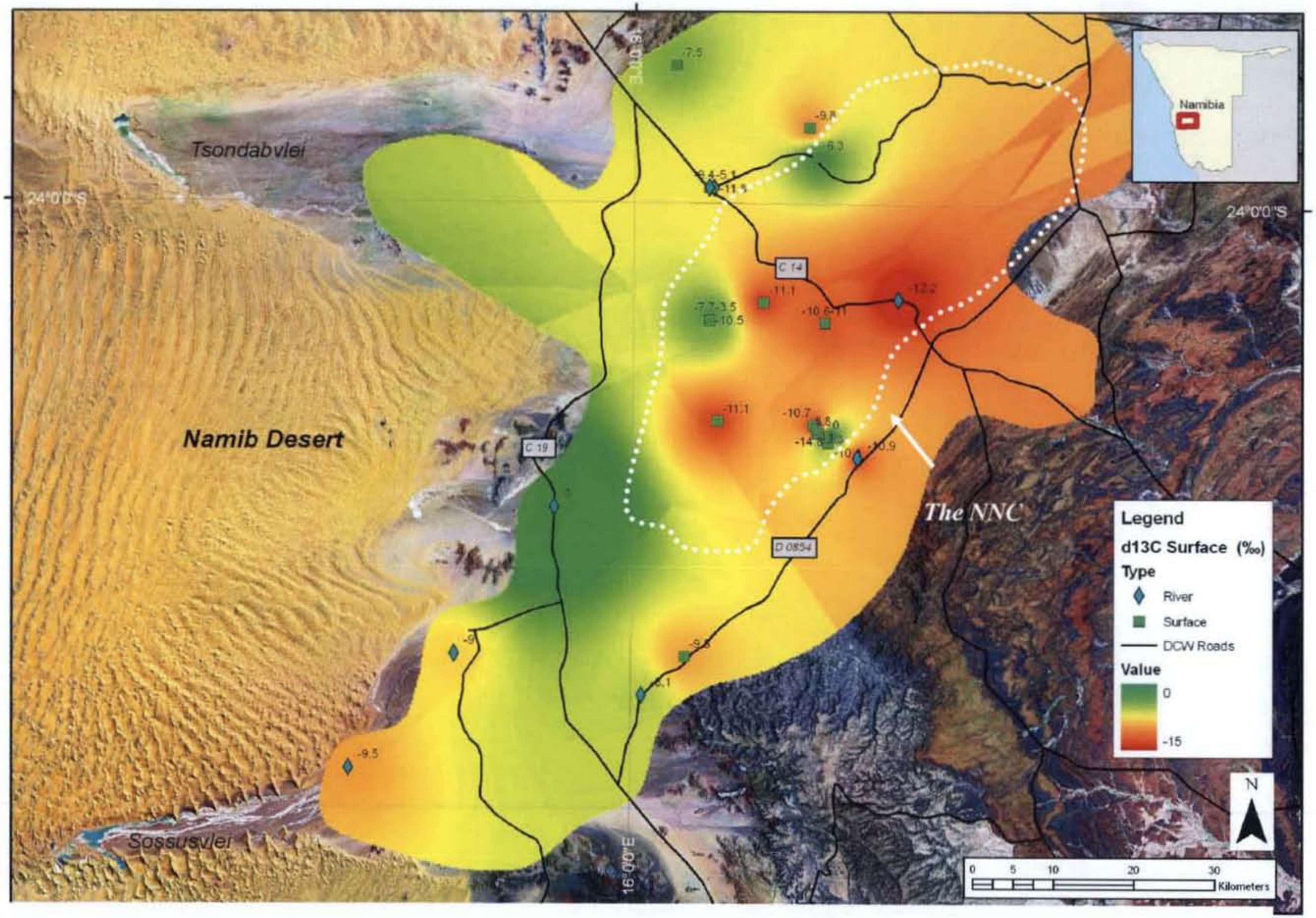


Figure 53: Position of sample sites with contouring of $\delta^{13}C$ values of surface water in Naukluft (Inversed Distance Weighting interpolation from mean values of all four seasons) [Map]. 1:500000. Roads: DCW (Digital Chart of World), NASA Satellite Image (ETM), ESRI data and maps [computer files]. GIS lab. University of Cape Town 2010. Using: ArcGIS [GIS software]. Version 9.3.1 Redlands, CA: ESRI, Inc.

5.2.4 Amount

Dansgaard (1964) described the amount effect as the relationship between δD and $\delta^{18}O$ values and the amount of monthly precipitation in tropical regions. The greater the proportion of rain removed from a given air mass, the lower the δ values of subsequent precipitation will be. Rapidly ascending air masses result in significant cooling, causing massive rainout, low values of F (fraction of remaining water in the cloud) and very negative δ values of precipitation (Dansgaard, 1964; Sharp, 2007). Although the Naukluft is not located in a tropical region, it does seem to have a significant amount effect.

During the wet field seasons (March 2008 and February 2009), precipitation samples were collected without an accurate measurement of the amount of rain that had fallen prior to sampling. Although observed weather patterns in the Naukluft were qualitatively noted, it is difficult to quantify the amount effect. Future hydrological research in the area should involve setting up permanent rain gauges in the region allowing for sampling to take place with the simultaneous knowledge of the exact amount of rain fallen in any one rain event. From this study, $\delta^{18}O$ and δD data do seem to indicate that the amount effect plays an important role in determining the stable isotope composition of the precipitation and in turn that of the groundwater, although this could only be confirmed with consideration of 'age' of the water.

Rainfall data, written as monthly average values from Büllsport (E, Sauber, pers. comm., 2008), was plotted against $\delta^{18}O$ and δD did indicate that in months where the average amount of rainfall is greater the average $\delta^{18}O$ and δD values of the rainfall are more negative. However, using an average monthly value is not conclusive enough to propose that there is an amount affect.

The anomalously negative $\delta^{18}O$ and δD values of the one precipitation sample (P130) could be because of the increase in altitude in the north of the area where the sample was collected, or due to the amount effect as a result of the heavy downpour for a period prior to sample collection. In this case, it is much more likely that this anomalous low value was due to the amount effect, as the difference in altitude is small (< 600 m).

5.3 Comparison with other arid and karstic regions

5.3.1 $\delta^{18}O$ and δD: Naukluft vs. other karstic and arid regions

Although in-depth stable isotope work has not been done on many water bodies in Africa or at the same latitude as the Naukluft region it is important to have a look at other arid and karstic regions, despite them being situated in more humid or temperate climates. These comparisons are important as karstic regions have very distinctive recharge patterns, based on the fact that water flows in low resistance, open conduits, bypassing the effects of granular or fracture permeability of the aquifer (White, 2002). A comparison of $\delta^{18}O$ and δD values has been drawn between regions with Mediterranean climates, tropical and arid climates and of both karstic and crystalline aquifers (**Figure 54**). The average $\delta^{18}O$ and δD values of all the sample sites from the Naukluft from all fours seasons was used in this comparison.

Spring, borehole and surface water collected from the Southern Spain karst systems, located in a Mediterranean climate zone, (Kohfahl *et al*, 2008 (n = 40); Vandenschrick *et al*, 2002 (n = 39)) has more negative $\delta^{18}O$ and δD values than the Naukluft water, plotting on the negative end of GMWL in the $\delta^{18}O$ and δD plot in **Figure 54**. In a more tropical karst system from Belize in Central America (Marfia *et al*, 2004), the ground- and surface- water samples (n = 27) plot in a less negative $\delta^{18}O$ and δD region than the Naukluft on the $\delta^{18}O$ and δD plot and indicate a slightly evaporated source, positioned to the left of the GMWL.

In very arid regions such as Libya and the Sinai Desert (Gat and Issar, 1974 (n = 46); Gonfiantini and Zuppi, 2003(n= 50)) the groundwater data from Sinai and the ground- and surface- water from Libya plot slightly above the Naukluft on the GMWL, although, the Naukluft has by far the greatest overall variation along the GMWL. This may indicate a large discrepancy between two end-members, in this case, the local precipitation and the groundwater. It may however, also may be partly due to the size of the much larger Naukluft data set. (n = 145). Rainfall from Syria (Kattan, 1997) plots on a LMWL to the right and parallel to the GMWL and this is often the case in arid regions. The Naukluft rainfall data however, only plots above the GMWL in March 2008. The comparison indicates that the lower the latitude or the more arid the climate, the higher the $\delta^{18}O$ and δD values will be, because of increasing evaporation of the source. Evaporation causes a depletion in the lighter isotopes resulting in an increase in the heavier isotopes hence the less negative $\delta^{18}O$ and δD values.

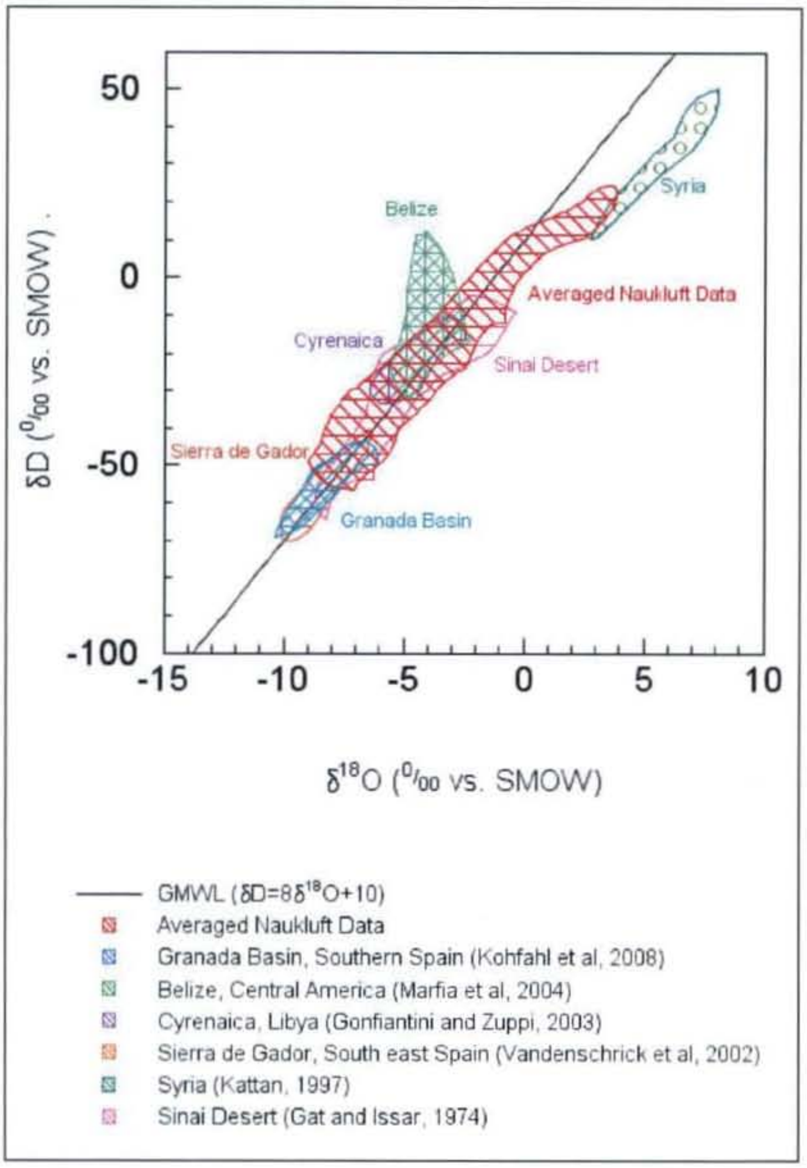


Figure 54: $\delta^{18}O$ vs. δD plot showing comparison of Naukluft to other arid and karstic environments (Kohfahl *et al*, 2008; Marfia *et al*, 2004; Gonfiantini and Zuppi, 2003; Vandenschrick *et al*, 2002; Kattan, 1997 and Gat and Issar, 1974)

The comparative data above are all representative of sources from the Northern Hemisphere. The data from Southern Spain was recharged by precipitation with its source region in both the Atlantic Ocean and the Mediterranean Sea. A LMWL for Granada was established from precipitation data to be $\delta D = 6.9\delta^{18}O + 2$ (Kohfal *et al*, 2008). Precipitation sourcing water from the Mediterranean typically has a high deuterium excess (average d=19‰), characterized by the lower humidity conditions (Kattan, 1997). The precipitation samples from Syria were typical of Mediterranean precipitation (Kattan, 1997). These samples clearly show a clear temperature effect. However, the amount effect was hard to recognize due to monthly composite sampling. The precipitation data for Belize, was taken to be the same as that of Vera Cruz in Mexico, with $\delta^{18}O$ = -3.6‰ and δD = -22.9‰ (Gat *et al*, 1994; Marfia *et al*, 2004). The Belize groundwater ($\delta^{18}O$ = -4.2 ‰ and δD = -14‰) and precipitation ($\delta^{18}O$ = -3.6 ‰ and δD = -23‰) $\delta^{18}O$ and δD values, are more similar to each other than the Naukluft groundwater ($\delta^{18}O$ = -6.7 ‰ and δD = -44‰) and Naukluft precipitation ($\delta^{18}O$ = -2.2 ‰ and δD = -9‰) are to each other. The precipitation values from Belize are slightly more negative than those of the Naukluft. Rainfall from Eliat on the Mediterranean seacoast of Northern Sinai has average annual values of $\delta^{18}O$ = -0.08‰ and δD = 7.8, respectively (Gat and Issar, 1974). It was established that the isotope composition of the water sources was not conclusive criterion for distinguishing between direct rain infiltration and recharge through surface flow (Gat and Issar, 1974). The rainfall values reflected the altitude at which precipitation occurred. It was noted by Gat and Issar (1974) that the spread of the Sinai $\delta^{18}O$ and δD data was much greater than that of groundwater from more temperate climates.

5.3.2 ***$\delta^{13}C$: Naukluft vs. other karstic and arid regions***

Obtaining $\delta^{13}C$ values of DIC in karst waters from around the globe was problematic, as they are not frequently measured for aquifer assessment. The Naukluft has been compared to two areas; the tropical karst area of Belize (Marfia *et al*, 2004) and the arid region of Libya (Gonfiantini and Zuppi, 2003) (**Figures 55 and 56**). Marfia *et al* (2004) used stable isotopes (δD, $\delta^{18}O$ and $\delta^{13}C$) and major ions to show the rapid recharge rate and influence of groundwater geochemistry on surface water in Belize in Central. In Libya, the aquifers were mostly confined and showed no modern recharge (Gonfiantini and Zuppi, 2003).

The Naukluft $\delta^{13}C$ values plot between those of the arid and tropical climates. The data from Belize has values closer to -20‰ (Marfia *et al*, 2004), as expected in tropical climates where soil covering will have a greater effect on $\delta^{13}C$ values whereas Libya had slightly less negative values at around -5‰ (Gonfiantini and Zuppi, 2003) with very little influence from soil sources. Libya and Belize also show a greater variation in $\delta^{13}C$ values (Gonfiantini and Zuppi, 2003; Marfia *et al*, 2004), whereas the Naukluft waters seem to be more homogenous. This comparison seems to indicate that climate indirectly affects the $\delta^{13}C$ values and drier climates have values closer to 0‰.

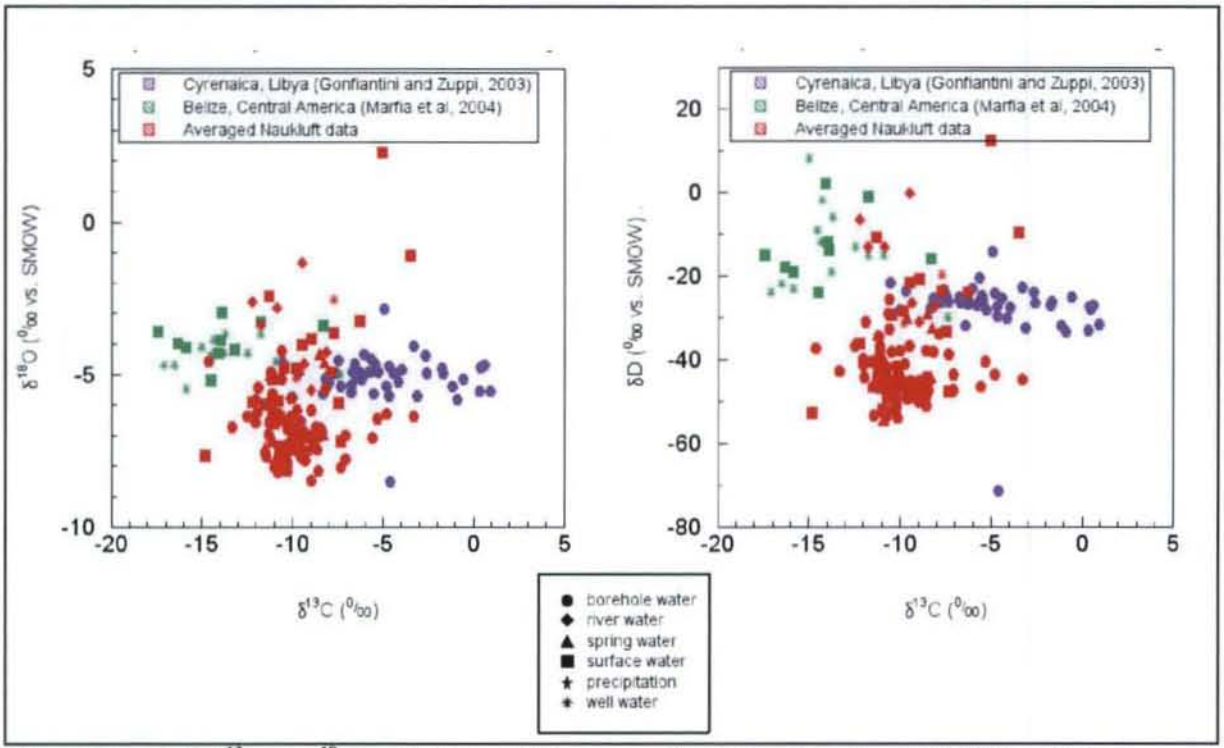


Figure 55 and 56: δ^{13}C vs. δ^{18}O and δD Naukluft compared to Belize (Marfia *et al*, 2004) and Libya (Gonfiantini and Zuppi, 2003). (Colour of sample represents region and shape represents type of sample collected)

5.4 Recharge Processes in the Naukluft Region

Usually, groundwater systems do a remarkably good job of integrating the local precipitation and any associated amount effect that operates in the recharge zone (Criss, 1999). In the Naukluft, it is evident that this is not entirely the case. The groundwater and surface water have more negative δD and δ^{18}O compared to the precipitation in the Naukluft. The amount-weighted δ^{18}O average of precipitation being -0.1‰ (n = 15), groundwater-4.9‰ (n = 235) and rivers and streams -1.1‰ (n = 73). The weighted δD average of precipitation being -0.4‰ (n = 15), groundwater-32‰ (n = 235) and rivers and streams -7.2‰ (n = 73). While the weighted δ^{13}C average of precipitation were, -0.6‰ (n = 10), groundwater-7‰ (n = 221) and rivers and streams -1.8‰ (n = 62).

There are a number of possibilities as to why the groundwater in the Naukluft is more negative than the local precipitation. In semi-arid regions, only large storm events recharge groundwater systems and δD and δ^{18}O values of those rain events will differ from the overall average (Sklash and Farvolden, 1978; Fredrickson and Criss, 1999; Criss, 1999). Another explanation is that the groundwater has migrated kilometres from higher elevation and higher latitude and accordingly can have lower δD and δ^{18}O values than the local precipitation (Dansgaard, 1964; Criss, 1999). In the Naukluft, this would mean that the groundwater would have to travel hundreds even thousands of kilometres from a place of higher elevation and latitude and from an area that receives significant amounts of rainfall, which in Namibia is very unlikely. Lastly, this discrepancy may be explained by the groundwater being recharged during ancient pluvial periods when meteoric precipitation had different values and a lower deuterium excess than today (Criss, 1999).

One of the principal effects of rainfall is to displace the groundwater into stream channels. Numerous studies have shown that 50% of flowing surface water represents "pre-event" water even during major storm events (Sklash and Farvolden, 1978; Fredrickson and Criss, 1999; Criss, 1999). In the Naukluft, the surface water contains a significant groundwater signature indicative of 'pre-event' water as described above. The average $\delta^{18}O$ and δD values of surface water in the Naukluft are -5.3‰ and -35‰ respectively. These values are significantly closer to the groundwater δ values ($\delta^{18}O$ = -6.7‰ and δD = -44‰) than that of the precipitation ($\delta^{18}O$ = -2.2‰ and δD = -9‰). However, the Tsondab River (R12 and ABABIS-R06) ($\delta^{18}O$ = -3.0‰ and δD = -10‰) with no spring supplementing it, has more negative $\delta^{18}O$ and δD values than rain water but less negative values than the other surface waters. This clearly indicates a mix between pre-event and event water.

The large difference between precipitation and groundwater isotope values is probably due to only large rain events recharging the groundwater. This was evident on a small scale during the storms of February 2009. It was in this month that rainfall had increasingly more negative $\delta^{18}O$ and δD values, because of the amount effect, and it is these waters that are most probably recharging the groundwater aquifers. For example, samples P124 (δD = -31‰ and $\delta^{18}O$ = -5.6‰), P125 (δD = -39‰ and $\delta^{18}O$ = -6.4‰) and P130 (δD = -95‰ and $\delta^{18}O$ = -14.4‰) were sampled on different days but all in heavy storms, i.e. a large rain event. Sample P130 was sampled at the end of a particularly heavy rainstorm (no measurement of amount taken) causing flash flooding throughout the region.

The precipitation data from March 2008 plot on an evaporation trend with a shallower slope compared to the GMWL and this could imply evaporation during precipitation. However, this trend is not seen in February 2009, possibly due to the extreme weather conditions experienced. February 2009 had anomalously high rainfall and therefore the fractionation effect due to evaporation as the rain was falling was possibly smaller. In June/July 2008 and July 2009, evaporative fractionation is also seen in a few surface water samples with a similar shallower slope as compared to the GMWL. It is clear that the effects of evaporation in surface water are likely to be greatest in hot arid, windy areas (eg. Criss, 1999). In this case, the arid Naukluft climate resulted in only a limited number of evaporated surface water samples and only in the dry seasons, months after the last rainfall.

5.4.1 Groundwater residence time

In order to determine the mean residence time of the groundwater in the Naukluft, ^{14}C was analysed (Bernhard, 2009) and from this data the 'age' of the water in the region was estimated. Thirteen groundwater sources (collected in June 2008) throughout the region were analysed at UNIL. The ^{14}C data of the groundwater in the region can be divided into three distinct groups of 'ages'. Using a complex mixing model ($\delta^{13}C$ mixing model for mixed C3-C4 plants, with $\delta^{13}C_{rech}$ at pH 7 (25°)) it was established (Bernhard, 2009) that one area (Kulala at the edge of the Namib Desert in the southwest) tapped relatively old water, around 13000 yrs. The majority of the samples have younger 'ages' of approximately 1000yrs and in two areas (Panorama on the west of the NNC and Nauzerus in the northwest of the NNC) the groundwater had ^{14}C activity comparable to modern rain water.

Table 8: $^{14}C_{age}$ (years) (Bernhard, 2009) and δ values from 13 sites throughout the Naukluft

	Sample Name	Type	$\delta^{18}O$ (UCT)	δD (UCT)	$^{14}C_{age}$ (UNIL)	$d^{13}C$ DIC (UNIL)	DIC mg L (UNIL)	Location
1	Bulls08-2B01	borehole	-6.5	-53	1095	-10.7	669.0	Büllsport
2	NNL08-2B09	borehole	-6.3	-42	1387	-12.7	429.4	Namib Naukluft Lodge
3	2S15	spring	-8.1	-59	1217	-11.3	472.1	Blässkranz
4	2B23	borehole	-7.1	-55	1265	-11.2	605.3	Tsams West
5	2B33	borehole	-6.2	-46	13050	-4.6	528.8	Kulala Desert Lodge
6	2B37	borehole	-5.9	-42	27	-13.2	424.7	Panorama
7	2B61	borehole	-6.4	-42	212	-11.0	409.0	Solitaire Guest Farm
8	2B65	borehole	-8.3	-41	2277	-10.6	547.1	Escourt: Tsondab River
9	2B79	borehole	-7.3	-49	340	-11.1	535.3	Hauchabfontein
10	2B82	borehole	-6.0	-44	1344	-13.1	507.0	Neu Onis
11	2S84	spring	-7.1	-45	1202	-11.5	444.0	Neuras Estate
12	2W97	well	-5.3	-32	-2207	-10.2	651.9	Nauzérus
13	2B112	borehole	-7.8	-46	574	-10.8	513.8	Smalstreep

The negative age (-2207 years) in **Table 6** is sample 2W97. Its age can be explained by the Bomb Peak Effect with an input of $^{14}C_{atmospheric}$ in excess of that calculated for the standard in the 1950s, which would give it an age younger than 50 years, i.e. after 1963 (Bernhard, 2009). It is unusual that this effect was only observed in the ^{14}C value of one sample and it suggested that future research in the area focus on this particular area to establish whether recharge path-ways are indeed unique in that area. The difficulty with this specific sample is that it was taken from a well-point that was not entirely sealed off from the atmosphere and with its very shallow water-table; the water may be more representative of the recent rains than of the groundwater itself, despite having bailed to a steady-state EC. This might explain its recent age. Sample B37, however, also has an extremely recent age (27 years) and this was taken from a deep borehole that had been pumping all day prior to collection, it is unlikely that this represents anything other than the groundwater. It is possible that this sample site has been contaminated by recent recharge perhaps during flooding. It is remarkable that the "oldest" water (2B33) is located at the western end of the Tsauchab River, near the end of its course, where one might intuitively think that recent waters would reside, or at least waters that have distinctive surface water values. It is suggested that this deep borehole (<100m) tapping this old water, is a confined aquifer entirely separate from other aquifers in the NNC.

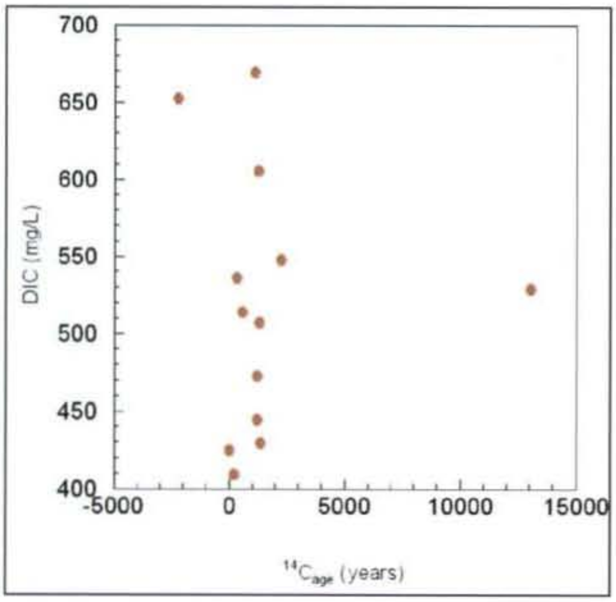
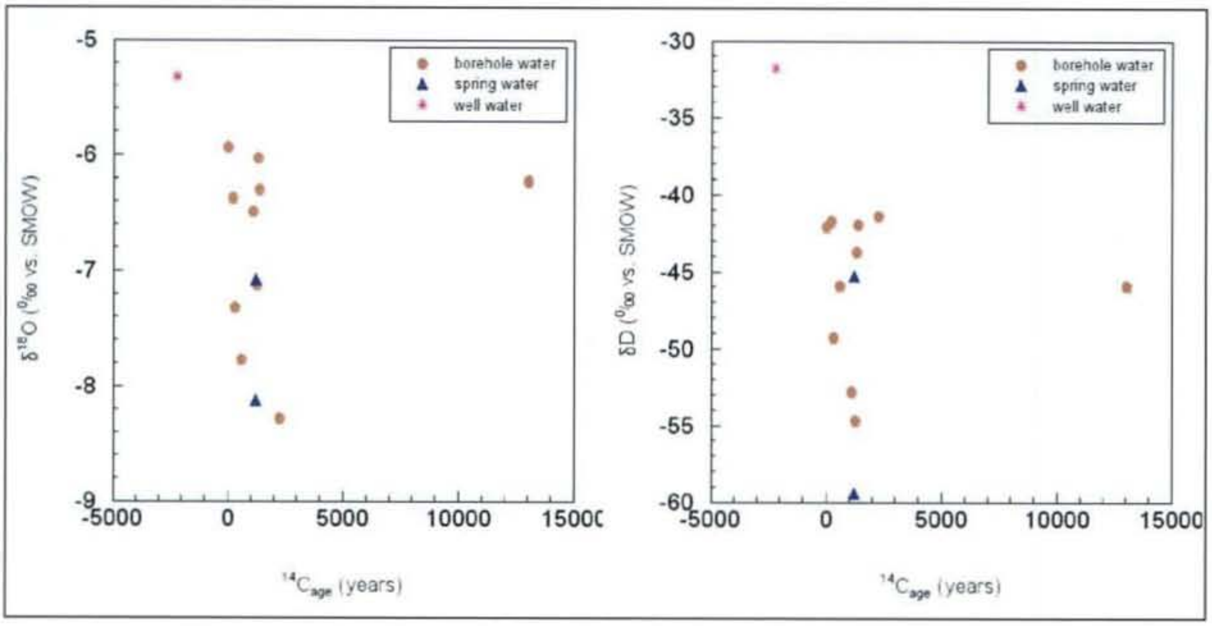


Figure 57: $^{14}C_{age}$ (years) vs. DIC (mg/L) (Bernhard, 2009) sampled from 13 sites throughout the Naukluft

In **Figure** 57, the $^{14}C_{age}$ vs. DIC (mg/L) plot, shows very little correlation between 'age' and amount of carbon (A Pearson r value of -0.03 with the outlier, indicating a very weak correlation and a Pearson r value of -0.2 without the outlier indicating a still very weak correlation). Considering that small amounts of CO_2 do not consistently yield the younger 'ages', it is suggested that these 'ages' are indicative of the residence time. A smaller amount of dissolved CO_2 would have been more readily altered by a very small proportion of modern precipitation and thus likely to yield young ages, however this does not seem to be the case in the Naukluft.

5.5 Characterising the Naukluft aquifer/s

In order to characterize the Naukluft aquifer/s it is important to look at ^{14}C data along with $\delta^{18}O$, δD and $\delta^{13}C$ data. The $^{14}C_{age}$ diagrams vs. $\delta^{18}O$ and δD (**Figures 58 and 59**) indicate a significant variation in $\delta^{18}O$ and δD values for samples having a similar 'age'. Hence it is difficult to make conclusions as to the number of distinct sources based solely on the age data. Future work in the Naukluft should include a more comprehensive ^{14}C study to clarify the distribution of 'ages' in groundwaters from the Naukluft Region.



Figures 58 and 59: $^{14}C_{age}$ (years) (Bernhard, 2009) vs. $\delta^{18}O$ and δD values from 13 sites throughout the Naukluft. Shows three distinct groupings

The ^{14}C 'ages' of the groundwater suggest that recharge is relatively rapid in the area. Taking into account the stable isotope data, the differences in the stable isotope compositions of rainwater (assuming the precipitation is representative of the region) and groundwater suggests a number of recharge processes:

- Recharge is occurring in another region;

- The aquifer is only recharged by major storm events when the precipitation has been affected by the amount effect and hence has more negative δ values;
- The aquifer is a large, well-mixed body and any infiltrating precipitation of less negative δ values is not noticeable.

The present results do not indicate significant variation between groundwater collected in different seasons. This lack of seasonality suggests that the amount affect may not be a reasonable explanation for the huge difference between the δ values of the groundwater and the precipitation on its own, unless of course it was in conjunction with an aquifer that was large and very well mixed. A smaller aquifer would show a marked difference when the precipitation infiltrated in the rainy season and when rain ceased in the dry season. The relatively homogenous $\delta^{13}C$ values from the Naukluft data compared with other karstic and arid regions may support this theory of a large rapidly mixed aquifer.

The Naukluft Mountains are the most likely area for recharge to occur. The possibility of orogenic rainfall occurring in the NNC suggests that it is unlikely that recharge occurs elsewhere in the relatively flat landscape surrounding the NNC. Due to the aridity of the climate resulting in some evaporation of the precipitation prior to infiltration, it is suggested that only high rainfall events recharge the aquifer/s. As supported by the comparison with other areas around the globe (**Figures 55 and 56**), it is suggested that drier climates seem to have $\delta^{13}C$ values that are less negative and closer to 0‰. It is therefore likely that the reason for the soil CO_2 having little impact on the δ values in the rainy season is not due to recharge elsewhere, but rather is indicative of the climate in the region. The greater variation of EC values of the groundwater in summer, seems to show that precipitation is infiltrating the groundwater. However, the plots also indicate an increase in EC values correlating with more negative $\delta^{18}O$ and δD values of the groundwater in summer. It is possible that the more negative δ values of the groundwater have homogenized the less negative precipitation.

The isopleth diagrams of the groundwater seem to indicate that the NNC is divided in two separate halves along its long axis, running northeast-southwest, which could indicate two distinct aquifers, the one recharging the Tsondab River in the North and the other the Tsauchab River in the South. The area surrounding the NNC shows another distinct source at the edge of the Namib Desert. This suggestion of a separate aquifer on the eastern edge of the Namib would be supported by the groundwater 'ages' supplied above.

To characterize the Naukluft aquifer/s fully would require much more detailed precipitation sampling (including records of daily temperature and amount), a clearer understanding of the geology of the nappe complex, conclusive understanding of the recharge capabilities of the aquifers through pump testing and further detailed age determination of many water sources throughout the Naukluft. The isotopes alone however, give an indication of an aquifer that is large and well mixed and is probably only recharged through large rainout events, with an entirely distinct aquifer at depth supplying areas at the edge of the desert.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The rivers, streams and groundwater in the Naukluft have average $\delta^{18}O$ and δD values of between -7.0‰ and -5.0‰ and between -45‰ and -30‰ respectively, with all values plotting close to the Global Meteoric Water Line. The majority of the borehole data for both seasons plots at the negative end of GMWL ($\delta^{18}O$ between -8.0‰ and -6.0‰ and δD between -40‰ and -50‰), whereas surface waters and rivers in March 2008 and February 2009 had higher δD and $\delta^{18}O$ values. The precipitation data collected in March 2008 shows a greater change in $\delta^{18}O$ than δD compared to the GMWL. This is evidence of evaporative fractionation, which is common in such arid climates. This however, is not seen in the precipitation samples from February 2009, which is possibly as a result of the extreme rainfall events in February, with little evaporation occurring as the rain was falling. Evaporative fractionation also affected a sub-set of surface waters from June 2008 and June 2009, due to the relatively warm and very dry winters experienced in the region whereas the majority of river and stream water samples plotted on the GMWL.

Compared to other arid and karstic regions, the Naukluft waters show a greater variability in $\delta^{18}O$ and δD values as there is a large difference between end-member sources, namely precipitation and groundwater. The effects of the region's climate may also play a role in the large range of $\delta^{18}O$ and δD values, as the Naukluft Region, although arid, receives greater annual rainfall, as a result of its elevation, than the surrounding semi-arid and desert landscape. Inversely, the $\delta^{13}C$ values of the Naukluft Region waters show very little variation, as a result of the arid climate, which prevents the formation of deep soil profiles.

The precipitation, surface- and ground- water interactions in the Naukluft are representative of the complexities of recharge in arid and karstic regions. In areas where evaporation rates are high, as is the case in the Naukluft, large amounts of precipitation are needed to infiltrate the aquifer/s for groundwater recharge to occur. The stable isotope ratios of oxygen and hydrogen of the precipitation in the Naukluft Region is then altered by the amount effect. The surface water samples represent a mixture of both 'pre-event' and 'event' water and their stable isotope ratios are then further altered by the altitude effect. The groundwater, although having similar $\delta^{18}O$ and δD values throughout the Naukluft, has residence times representing three different 'ages' of water (Bernhard, 2009).

It is likely, due to the large variability between groundwater and precipitation stable isotope values, that only large rain events infiltrate the aquifer/s in the Naukluft. It is proposed that the aquifer/s are fairly homogenous, characteristic of a large, well-mixed source. According to the spatial distribution of the stable isotope values throughout the Naukluft, it is likely that boreholes in the NNC tap water from at least two distinct aquifers. Supported by age determination (Bernhard, 2009) an entirely separate, confined source is present at the edge of the Namib Desert.

The ^{14}C 'age' determination of the majority of the groundwater samples in the Naukluft may show recent recharge but the rate of extraction of the groundwater still needs to be monitored, particularly as rainfall in Southern Africa is unpredictable. Even if accurate rainfall predictions were made and sufficient precipitation occurred, hundreds to thousands of years between recharge of Naukluft aquifers would be too long a period of time to sustain human activities, if this resource was over-exploited due to poor management.

It is hoped that this study will provide a clearer understanding of the hydrological processes in the Naukluft Region, resulting in a sustainable source of water for all Namibians into the future. It is clear that a more stringent management scheme needs to be put in place. Despite the at-a-glance fertility of this Naukluft oasis, alongside the vast Namib Desert, it would be unwise to assume that it will always remain as such.

6.2 Recommendations

The Namibian government is committed to increasing the access of rural households to reliable sources of safe drinking water from 50% at Independence (1990) to 80% by 2010 (National Planning Commission, 1996). Namibia is an extremely arid country and is subject to frequent and recurring droughts. With no perennial rivers, the country relies substantially on groundwater to provide the population with potable water. These groundwater sources are not recharged frequently and the population taps fossil water, of an inferior quality and limited supply. In the Naukluft, the entire local community relies on groundwater for their personal and agricultural needs. ^{14}C data analysis indicated that the majority of the groundwater in the region had relatively recently been recharged. Although these are by no means fossil waters, a span of a thousand years for recharge is still significantly long enough to have a lasting effect on the population in the region should the supply be poorly managed.

The population in the Naukluft is growing significantly along with an increase of tourists in the region putting added pressure on the water supply. Some recommendations for water management in the area include:

- The abstraction of groundwater needs to be monitored, in order to assess groundwater usage in the area:
    - A region-wide census on the number of boreholes and location, their yield (if in use), the depth of the borehole and the depth-to-water needs to be established.
    - Any further borehole drilling in the region should be strictly controlled and regulated.
- Strategic placement of monitored boreholes in the Naukluft-Namib Park is imperative in order to assess groundwater levels and water quality on a regular basis:
    - A few monitored boreholes should be situated on the eastern edge of the Namibian Desert, where the oldest water is located. Further monitored boreholes should be placed in the east and the west of NNC, where two distinct aquifers are likely to be situated. Lastly, monitored boreholes should be placed in the north of the NNC, where the youngest 'age' water can be found.
    - The monitored boreholes should be fitted with water level measurement devices, EC meters, flow metres and ph/redox metres for water quality. For real-time remote monitoring, these meters should be connected to a telemetry system to transmit readings to the internet at regular intervals. Mobile signals can then be sent to alert the appropriate people of any significant changes in the quality and level of the water.

- Frequent water sampling and analyses needs to occur in order to monitor water quality, to assess flow regimes in the aquifers and to test the reliability of remote monitoring systems:
    - Water quality testing should occur frequently as an indicator of a dwindling/contaminated source.
    - Stable isotope analysis should continue for a long-term indicator of recharge processes.
- Environmental monitoring of fragile ecosystems needs to occur regularly to preserve the biodiversity and vegetation biomes of the Naukluft Region:
    - Increased usage of water from ephemeral rivers such as the Tsondab and the Tsauchab Rivers flowing westward into the Namib Desert leaves the environment around these rivers particularly at risk. In the past, these rivers were utilized by opportunistic nomadic pastoralists whose environmental impact was limited (De Bruine and Rukira, 1997). Increased demand for water in the region will increase usage of river water for personal and commercial use, and therefore it is essential that the current degree of utilization be managed properly.
- A water tax may need to be established for users using over a certain threshold of water to encourage users to be water-wise and to subsidize the provision of water to rural communities:
    - Despite the very polarized anthropological uses of water in the Naukluft, from supplying large hotels to watering of livestock for personal and/or commercial use, this limited water supply should be considered common property and treated as such.
- Government needs to subsidize installation and maintenance of boreholes in rural villages in order to provide potable water to the people:
    - Through this project, it was established that many rural villages tap water that is significantly inferior according to the Namibian water quality guidelines. Through educated borehole placement and deeper drilling, the water quality can be much improved in many areas.
- Education on sustainable water usage needs to be addressed in the Naukluft in order to ensure the success of any water management schemes:
    - The education and cooperation of the local community will be essential to the success of a water management scheme in the area.
    - International visitors should also be made aware of the scarcity of water in the region with appropriate information brochures and advertising.

The local Namibian community should be included in all decisions made with regard to a water management scheme, as they are ultimately responsible for water abstraction in the region and will thus be most affected if the source should dwindle. It is essential that further water research, expanding on this study, continues in the area until the aquifer/s can be accurately defined, and the recharge processes fully understood. With this knowledge, accurate, strategic water management plans should be put in place to ensure the sustainability of this renewable resource.

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Appendix 1: Isotope Data

Note: "mean" and "std dev". refers to the average and deviation from the average of all values from all the seasons the sample was collected. "no." refers to the number of samples used to calculate the mean and standard deviation.

Table 1A: Isotope Data

Sample	Type	Lat.	Long.	Alt. (m)	Mar08 $\delta^{18}O$ (‰)	Mar08 δD (‰)	Mar08 $\delta^{13}C$ (‰)	Jun08 $\delta^{18}O$ (‰)	Jun08 δD (‰)	Jun08 $\delta^{13}C$ (‰)	Feb09 $\delta^{18}O$ (‰)	Feb09 δD (‰)	Feb09 $\delta^{13}C$ (‰)	Jul09 $\delta^{18}O$ (‰)	Jul09 δD (‰)	Jul09 $\delta^{13}C$ (‰)	$\delta^{18}O$ mean (‰)	$\delta^{18}O$ stdev (‰)	δD mean (‰)	δD stdev (‰)	$\delta^{13}C$ mean (‰)	$\delta^{13}C$ stdev (‰)	no.
A01	Surface	-24.266	16.240		-6.5	-43		-3.9	-48	-11.9	-6.1	-38	-11.7	-6.9	-45	-8.8	-5.9	1.3	-43	4	-10.8	1.8	4
A02	Surface	-24.273	16.242	1426	-6.8	-42		-6.2	-48	-9.7	-6.8	-43	-11.5	-7.1	-46	-9.2	-6.7	0.4	-45	3	-10.1	1.2	4
B03	Borehole	-24.262	16.243	1453	-8.0	-56	-8.9	-5.9	-56	-11.5	-8.3	-55	-10.3	-7.2	-50	-9.8	-7.4	1.1	-54	3	-10.1	1.1	4
P04	Precipitation	-24.266	16.240		-2.6	-7											-2.6		-7				1
A05	Surface	-24.266	16.240		-6.1	-40											-6.1		-40				1
A06	Surface	-24.261	16.228	1528	-6.9	-44		-7.4	-54	-2.8	-7.2	-45	-10.5	-7.3	-48	-8.8	-7.2	0.2	-48	5	-7.3	4.0	4
A07	Surface	-24.261	16.229	1530	-7.2	-47	-7.7	-7.4	-53	-8.8	-7.1	-45	-10.4	-7.3	-49	-8.5	-7.2	0.1	-49	4	-8.8	1.1	4
R12	River	-24.109	16.326	1333	-2.4	-3					-2.9	-10	-12.2				-2.6	0.3	-7	5	-12.2		2
B13	Borehole	-24.137	16.346	1442	-7.8	-53		-9.3	-44	-11.9	-7.1	-48	-11.7	-6.2	-41	-10.8	-7.6	1.3	-47	5	-11.5	0.6	4
S15	Spring	-24.124	16.289	1474	-7.7	-49	-10.8	-8.1	-59	-10.9	-7.9	-51	-11.3	-7.7	-51	-10.3	-7.9	0.2	-53	5	-10.8	0.4	4
S16	Spring	-24.119	16.291	1428	-8.4	-51	-10.7	-8.1	-62	-11.1	-8.4	-55	-11.3	-7.4	-50	-10.6	-8.0	0.5	-55	5	-11.0	0.3	4
P18	Precipitation	-24.027	16.154	1159	4.3	23											4.3		23				1
P19	Precipitation	-24.178	15.981	1097	3.9	25											3.9		25				1
S20	Spring	-24.134	16.094	1321	-2.1	-7	-11.3				-2.8	-15					-2.5	0.5	-11	6	-11.3		2
A21	Surface	-24.133	16.094	1325	-2.4	-16					-7.1	-41	-11.0	-1.5	-14	-4.4	-3.7	3.0	-24	15	-7.7	4.7	3
A22	Surface	-24.133	16.094	1325	-2.2	-9		6.6	29	0.3	-6.9	-41	-7.6	-1.9	-17	-3.1	-1.1	5.6	-10	29	-3.5	4.0	4
B23	Borehole	-24.287	15.993	1198	-6.9	-37		-7.1	-55	-12.1	-7.3	-49	-10.6	-6.6	-43	-11.1	-7.0	0.3	-46	7	-11.3	0.8	4
A24	Surface	-24.249	16.105	1355	-5.4	-32	-11.5	-3.8	-46	-10.9	-5.8	-35	-11.9	-5.6	-39	-10.2	-5.2	0.9	-38	6	-11.1	0.8	4
B26	Borehole	-24.252	16.082	1344	-4.5	-29	-5.5	-4.6	-38	-8.3	-4.9	-29	-8.2	-5.7	-41	-9.4	-4.9	0.5	-34	6	-7.9	1.7	4
B27	Borehole	-24.266	16.040	1275	-7.2	-41	-9.3	-7.0	-52								-7.1	0.2	-46	7	-9.3		2
P28	Precipitation	-24.236	15.953	1102	0.3	9											0.3		9				1
R29	River	-24.347	15.905	991	-4.0	-17											-4.0		-17				1
R31	River	-24.645	15.652	676	-1.4	0	-9.5										-1.4		0		-9.5		1
B32	Borehole	-24.648	15.786	737	-7.2	-43	-12.8	-6.8	-49	-6.7	-7.2	-48	-6.8	-6.5	-42	-7.2	-6.9	0.3	-45	3	-8.4	2.9	4
B33	Borehole	-24.628	15.749	715	-6.6	-47		-6.2	-46	-4.9	-6.5	-44	-4.9	-5.9	-39	-4.7	-6.3	0.3	-44	3	-4.8	0.1	4
B34	Borehole	-24.686	15.773	724	-6.4	-41	-2.1	-6.5	-51	-4.2	-6.7	-45	-3.1	-6.1	-43	-3.9	-6.4	0.2	-45	4	-3.3	0.9	4
B35	Borehole	-24.684	15.820	758	-7.2	-45	-6.0	-7.1	-52	-8.1	-7.3	-48	-7.3	-6.5	-45	-7.1	-7.0	0.3	-48	3	-7.1	0.8	4
R36	River	-23.982	16.099	1090	-3.1	-17					-6.3	-36	-9.4				-4.7	2.3	-27	14	-9.4		2
B37	Borehole	-24,413	16.056	1253	-5.0	-30	-9.3	-5.9	-42	-12.8	-6.1	-39	-11.6	-5.5	-36	-10.6	-5.7	0.5	-37	5	-11.1	1.5	4
R38	River	-24.560	16.014	968	-3.2	-16	-9.0	-4.3	-29	-7.0	-5.5	-35	-10.4	-4.1	-29	-6.0	-4.3	0.9	-27	8	-8.1	2.0	4
B39	Borehole	-24.547	15.921	881	-7.4	-46	-9.3	-7.3	-55	-5.8	-7.7	-50	-10.8				-7.5	0.2	-50	4	-8.6	2.5	3
B40	Borehole	-24.640	15.962	887	-7.2	-50	-8.8	-7.1	-54	-10.3	-7.2	-48	-9.5	-6.6	-44	-9.2	-7.0	0.3	-49	4	-9.5	0.7	4
B41	Borehole	-24.661	15.983	906	-7.6	-45	-9.1	-7.5	-54	-10.4	-7.6	-50	-9.5	-6.9	-49	-9.3	-7.4	0.3	-50	4	-9.6	0.6	4

Table 1B: Isotope Data

Sample	Type	Lat.	Long.	Alt. (m)	Mar08 δ^{18}O (‰)	Mar08 δD (‰)	Mar08 δ^{13}C (‰)	Jun08 δ^{18}O (‰)	Jun08 δD (‰)	Jun08 δ^{13}C (‰)	Feb09 δ^{18}O (‰)	Feb09 δD (‰)	Feb09 δ^{13}C (‰)	Jul09 δ^{18}O (‰)	Jul09 δD (‰)	Jul09 δ^{13}C (‰)	δ^{18}O mean (‰)	δ^{18}O stdev (‰)	δD mean (‰)	δD stdev (‰)	δ^{13}C mean (‰)	δ^{13}C stdev (‰)	no.
B42	Borehole	-24.621	15.967	890	-7.5	-48	-9.6	-7.4	-55	-10.7	-7.4	-50	-10.3	-6.9	-48	-10.3	-7.3	0.3	-50	3	-10.2	0.5	4
A43	Surface	-24.517	16.067	1037	-3.6	-19	-7.6	-6.1	-40	-9.2	-1.1	7	-12.6	-5.4	-36	-8.6	-4.0	2.2	-22	21	-9.5	2.2	4
P44	Precipitation	0.000	0.000		1.8	12											1.8		12				1
B45	Borehole	-24.444	16.172		-6.5	-39		-6.2	-47	-11.1	-6.1	-39	-11.4	-5.2	-36	-12.3	-6.0	0.6	-40	5	-11.6	0.6	4
B46	Borehole	-24.346	16.246	1287	-6.4	-38	-9.3	-6.2	-44	-11.7	-6.3	-43	-11.2				-6.3	0.1	-42	3	-10.7	1.3	3
B47	Borehole	-24.288	16.279	1324	-5.9	-42	-11.2										-5.9		-42		-11.2		1
S48	Spring	-24.275	16.265	1396	-3.5	-15	-10.2	-6.2	-41	-7.4	-3.8	-21	-11.1	-6.1	-43	-9.8	-4.9	1.5	-30	14	-9.6	1.6	4
B51	Borehole	-24.263	16.246	1452				-8.2	-53	-11.1	-8.3	-55	-10.5				-8.2	0.1	-54	1	-10.8	0.4	2
A53	Surface	-24.256	16.226	1621				-7.9	-59	(-18.5)	-7.4	-47	-11.2				-7.7	0.4	-53	8	-11.2	5.2	2
A54	Surface	-24.252	16.223	1617				-7.8	-52	-9.9	-7.4	-47	-11.6				-7.6	0.3	-49	3	-10.7	1.2	2
B55	Borehole	-24.142	16.084	1362				-5.2	-26	-10.6							-5.2		-26		-10.6		1
A56	Surface	-24.134	16.094	1322				-4.3	-23	-10.5	-6.2	-37	-11.8	-3.8	-29	-9.1	-4.8	1.2	-30	7	-10.5	1.4	3
A57	Spring	-24.129	16.098	1615				0.1	5	-6.3	-7.8	-47	-11.5				-3.8	5.6	-21	36	-8.9	3.7	2
B58	Borehole	-24.178	15.981	1097				-7.5	-41	-9.9	-7.5	-51	-10.1				-7.5	0.0	-46	7	-10.0	0.1	2
B59	Borehole	-24.121	15.906	978				-7.1	-42	-8.8	-7.3	-49	-9.2	-6.7	-47	-9.3	-7.0	0.3	-46	3	-9.1	0.3	3
B60	Borehole	-24.074	15.888	949				-7.0	-37	-8.4	-7.1	-48	-8.8	-6.7	-48	-8.6	-7.0	0.2	-44	6	-8.6	0.2	3
B61	Borehole	-23.866	16.054	1160				-6.4	-42	-10.1							-6.4		-42		-10.1		1
B62	Borehole	-23.866	16.061	1165				-3.0	-37	-16.6	-6.2	-38	-12.6				-4.6	2.3	-37	0	-14.6	2.9	2
B64	Borehole	-24.049	15.801	871				-6.4	-38	-5.0	-6.5	-43	-5.7				-6.5	0.1	-40	3	-5.4	0.5	2
B65	Borehole	-23.995	15.710	812				-8.3	-41	-10.3	-8.4	-55	-10.6	-7.9	-54	-10.0	-8.2	0.3	-50	8	-10.3	0.3	3
B66	Borehole	-24.006	15.820	873				-7.9	-45	-10.3							-7.9		-45		-10.3		1
B67	Borehole	-24.144	15.962	1045				-7.2	-45	-9.7	-7.3	-49	-9.9				-7.2	0.1	-47	3	-9.8	0.1	2
B69	Borehole	-24.481	15.802	781				-7.2	-40	-10.6	-7.2	-49	-9.6	-6.8	-47	-9.7	-7.1	0.2	-45	5	-10.0	0.6	3
B70	Borehole	-24.506	15.832	799				-7.3	-43	-10.1	-7.3	-50	-9.7	-6.8	-50	-9.3	-7.1	0.3	-48	4	-9.7	0.4	3
B71	Borehole	-24.486	15.798	781				-7.1	-42	-9.8	-7.2	-49	-9.7				-7.2	0.1	-46	5	-9.7	0.1	2
B72	Borehole	-24.514	15.782	767				-7.4	-44	-9.9	-7.5	-50	-9.6				-7.5	0.1	-47	5	-9.7	0.2	2
B73	Borehole	-24.632	15.978	902				-7.3	-42	-11.2	-7.4	-50	-10.3				-7.4	0.1	-46	6	-10.7	0.7	2
B74	Borehole	-24.618	15.991	924				-6.9	-44	-8.8	-6.8	-46	-10.1				-6.9	0.1	-45	1	-9.5	0.9	2
B75	Borehole	-24.602	15.986	955				-6.8	-40	-9.8	-6.9	-47	-10.4				-6.8	0.1	-43	5	-10.1	0.4	2
B76	Borehole	-24.614	15.992	934				-7.0	-39	-10.6	-6.7	-45	-10.0				-6.8	0.2	-42	4	-10.3	0.4	2
B77	Borehole	-24.675	15.807	736				-8.4	-39	-6.3	-7.2	-48	-7.9				-7.8	0.8	-44	6	-7.1	1.1	2
B78	Borehole	-24.724	15.824	744				-6.9	-42								-6.9		-42				1
B79	Borehole	-24.517	16.076	1051				-7.3	-49	0.1	-6.8	-44	-11.2				-7.1	0.3	-47	4	-5.6	8.0	2

Table 1C: Isotope Data

Sample	Type	Lat.	Long.	Alt. (m)	Mar08 $\delta^{18}O$ (‰)	Mar08 δD (‰)	Mar08 $\delta^{13}C$ (‰)	Jun08 $\delta^{18}O$ (‰)	Jun08 δD (‰)	Jun08 $\delta^{13}C$ (‰)	Feb09 $\delta^{18}O$ (‰)	Feb09 δD (‰)	Feb09 $\delta^{13}C$ (‰)	Jul09 $\delta^{18}O$ (‰)	Jul09 δD (‰)	Jul09 $\delta^{13}C$ (‰)	$\delta^{18}O$ mean (‰)	$\delta^{18}O$ stdev (‰)	δD mean (‰)	δD stdev (‰)	$\delta^{13}C$ mean (‰)	$\delta^{13}C$ stdev (‰)	no.
B80	Borehole	-24.519	16.074	1039				-6.3	-44	-12.0							-6.3		-44		-12.0		1
S81	Spring	-24.503	16.115	1096				-6.7	-41	-11.2	-5.9	-37	-11.1	-6.1	-42	-10.5	-6.2	0.4	-40	3	-11.0	0.4	3
B82	Borehole	-24.286	16.281	1296				-6.0	-44	-13.1	-5.9	-40	-11.8	-5.6	-40	-11.2	-5.8	0.2	-41	2	-12.1	1.0	3
S83	Spring	-24.462	16.238	1181				-7.2	-47	-9.9	-7.2	-46	-10.5				-7.2	0.0	-47	1	-10.2	0.4	2
S84	Spring	-24.463	16.238	1185				-7.1	-45	-5.3	-6.9	-43	-11.2				-7.0	0.1	-44	2	-8.3	4.2	2
B85	Borehole	-24.028	16.155	1163				-6.3	-43	-11.7	-6.9	-45	-10.8				-6.6	0.4	-44	2	-11.3	0.6	2
B86	Borehole	-24.116	16.224	1324				-7.5	-53	-10.3	-7.4	-50	-10.0				-7.5	0.0	-51	2	-10.2	0.2	2
A87	Surface	-24.136	16.236	1491				-7.9	-53	-10.5	-8.1	-51	-10.9	-7.5	-53	-10.3	-7.8	0.3	-52	1	-10.6	0.3	3
A88	Surface	-24.136	16.236	1482				-8.2	-51	-11.3	-8.1	-52	-11.0	-7.6	-53	-10.5	-8.0	0.3	-52	1	-11.0	0.4	3
A89	Surface	-24.113	16.160	1519				-7.3	-48	-11.0	-5.4	-31	-11.3				-6.3	1.4	-39	12	-11.1	0.2	2
S90	Spring	-24.110	16.178	1459				-7.7	-48	-11.6	-7.1	-45	-11.4				-7.4	0.5	-46	1	-11.5	0.2	2
B91	Borehole	0.000	0.000					-7.7	-53	-11.5							-7.7		-53		-11.5		1
A92	Surface	-23.982	16.093	1073				2.3	12	-5.1							2.3		12		-5.1		1
B93	Borehole	-23.970	16.146	1140				-6.6	-39	-12.5	-6.6	-41	-11.6				-6.6	0.0	-40	2	-12.0	0.7	2
A94	Surface	-23.914	16.215	1225				-4.5	-29	-9.3	-5.1	-28	-10.4				-4.8	0.4	-28	1	-9.8	0.8	2
A95	Surface	-23.948	16.225	1273				-4.2	-30	-4.5	-3.6	-20	-9.5	-2.1	-21	-4.8	-3.3	1.1	-24	6	-6.3	2.8	3
S96	Spring	-23.945	16.226	1268				-4.5	-31	-6.4	-4.1	-27	-10.7				-4.3	0.3	-29	2	-8.5	3.1	2
W97	Well	-23.821	16.343	1645				-5.3	-32	-9.2	-5.3	-32	-10.4	-4.8	-31	-10.0	-5.1	0.3	-31	0	-9.8	0.6	3
S98	Spring	-23.829	16.341	1615				-3.2	-27	-5.9	-5.4	-34	-9.4	-5.3	-36	-9.4	-4.6	1.2	-33	5	-8.3	2.0	3
B99	Borehole	-23.850	16.505	1619				-7.2	-48	-9.5	-7.3	-50	-9.7				-7.3	0.1	-49	1	-9.6	0.1	2
B100	Borehole	-23.845	16.531	1596				-7.6	-46	-9.7							-7.6		-46		-9.7		1
B101	Borehole	-23.905	16.481	1602				-6.6	-41	-11.1	-5.7	-38	-11.7	-6.1	-40	-10.7	-6.1	0.4	-40	2	-11.2	0.5	3
B102	Borehole	-23.952	16.441	1640				-8.2	-51	-8.6							-8.2		-51		-8.6		1
B103	Borehole	-24.007	16.426	1658				-8.0	-52	-10.3							-8.0		-52		-10.3		1
B104	Borehole	-24.020	16.431	1651				-8.1	-39	-7.3							-8.1		-39		-7.3		1
B105	Borehole	-24.013	16.446	1674				-8.2	-40	-9.8	-6.0	-49	-7.9	-7.0	-55	-7.9	-7.1	1.1	-48	7	-8.5	1.1	3
B106	Borehole	-23.986	16.454	1643				-9.0	-40	-8.2	-8.6	-58	-9.5	-7.9	-53	-9.1	-8.5	0.5	-50	9	-8.9	0.7	3
B107	Borehole	-24.135	16.402	1403				-7.8	-37	-9.5							-7.8		-37		-9.5		1
B108	Borehole	-24.119	16.433	1410				-6.5	-29	-10.7							-6.5		-29		-10.7		1
B109	Borehole	-23.969	16.559	1502				-5.3	-31	-11.6	-5.7	-32	-12.3				-5.5	0.3	-31	1	-11.9	0.5	2
B110	Borehole	-23.955	16.485	1581				-5.2	-47	-11.1	-7.4	-46	-10.9	-6.9	-43	-9.7	-6.5	1.1	-45	2	-10.6	0.8	3
B111	Borehole	-23.955	16.487	1583				-8.0	-50	-9.4				-7.7	-47	-9.1	-7.8	0.2	-48	2	-9.3	0.2	2
B112	Borehole	-23.962	16.488	1579				-7.8	-46	-10.5	-7.2	-46	-11.1	-7.0	-46	-9.3	-7.3	0.4	-46	0	-10.3	0.9	3

Table 1D: Isotope Data

Sample	Type	Lat.	Long.	Alt. (m)	Mar08 $\delta^{18}O$ (‰)	Mar08 δD (‰)	Mar08 $\delta^{13}C$ (‰)	Jun08 $\delta^{18}O$ (‰)	Jun08 δD (‰)	Jun08 $\delta^{13}C$ (‰)	Feb09 $\delta^{18}O$ (‰)	Feb09 δD (‰)	Feb09 $\delta^{13}C$ (‰)	Jul09 $\delta^{18}O$ (‰)	Jul09 δD (‰)	Jul09 $\delta^{13}C$ (‰)	$\delta^{18}O$ mean (‰)	$\delta^{18}O$ stdev (‰)	δD mean (‰)	δD stdev (‰)	$\delta^{13}C$ mean (‰)	$\delta^{13}C$ stdev (‰)	no.
B113	Borehole	-23.918	16.537	1564				-7.5	-47	-11.2	-7.6	-51	-9.3				-7.5	0.1	-49	3	-10.3	1.3	2
B114	Borehole	-23.948	16.496	1570				-6.7	-38	-10.0							-6.7		-38		-10.0		1
S115	Spring	-23.952	16.494	1560				-7.5	-46	-8.2	-7.8	-50	-10.5	-7.3	-43	-8.9	-7.5	0.2	-47	4	-9.2	1.2	3
B116	Borehole	-23.892	16.551	1561				-8.2	-52	-10.3							-8.2		-52		-10.3		1
P117	Precipitation	-24.266	16.240								-1.2	3	-11.9				-1.2		3				1
P118	Precipitation	-24.266	16.240								-1.4	2	-15.6				-1.4		2				1
P119	Precipitation	-24.266	16.240								-2.1	-2	-8.4				-2.1		-2				1
R120	river	-24.288	16.278								-2.8	-13	-10.9				-2.8		-13		-10.9		1
P121	Precipitation	-24.266	16.240								-2.0	-7	-14.0				-2.0		-7				1
B122	Borehole	0.000	0.000								-5.0	-35	-11.2				-5.0		-35		-11.2		1
B123	Borehole	-24.211	16.514								-4.8	-38	-10.5				-4.8		-38		-10.5		1
P124	Precipitation	-24.137	16.346								-5.6	-31	-36.3				-5.6		-31				1
P125	Precipitation	-24.079	16.056								-6.3	-39	-29.0				-6.3		-39				1
A126	Surface	-23.843	16.050								-5.9	-33	-7.5				-5.9		-33		-7.5		1
B127	Borehole	-23.843	16.050								-6.8	-47	-11.6	-6.4	-43	-10.9	-6.6	0.3	-45	2	-11.3	0.5	2
S128	Spring	-24.283	16.086								-6.9	-45	-11.5	-6.4	-41	-10.4	-6.6	0.3	-43	3	-11.0	0.8	2
S129	Spring	-24.279	16.091								-7.1	-46	-11.1				-7.1		-46		-11.1		1
P130	Precipitation	-23.819	16.344								-14.4	-95	-43.8				-14.4		-95				1
S131	Spring	0.000	0.000								-5.1	-34	-11.2				-5.1		-34		-11.2		1
A132	Surface	0.000	0.000								-5.9	-36	-12.2				-5.9		-36		-12.2		1
B133	Borehole	-24.472	15.852								-6.4	-44	-9.7	-6.0	-38	-9.7	-6.2	0.3	-41	5	-9.7	0.0	2
P134	Precipitation	-24.486	15.798								-4.8	-22	-8.4				-4.8		-22				1
P135	Precipitation	-24.517	16.076								0.0	12	-15.1				0.0		12				1
R136	River	-24.514	15.782								-5.5	-31	-9.0				-5.5		-31		-9.0		1
S139	Spring	-24.461	16.240								-7.2	-47	-11.1				-7.2		-47		-11.1		1
B140	Borehole	-23.916	16.307								-7.8	-53	-10.7				-7.8		-53		-10.7		1
B141	Borehole	-23.916	16.307								-7.8	-53	-10.8				-7.8		-53		-10.8		1
B142	Borehole	-23.861	16.374								-7.0	-46	-9.7				-7.0		-46		-9.7		1
B143	Borehole	-23.819	16.344								-6.5	-46	-9.6				-6.5		-46		-9.6		1
P144	Precipitation	-23.819	16.344								-2.6	-17	-13.2				-2.6		-17				1
B146	Borehole	-24.121	16.432								-6.2	-47	-8.3	-7.3	-48	-8.6	-6.8	0.8	-48	1	-8.5	0.2	2
W147	Well	-23.897	16.477								-2.8	-21	-8.4	-2.3	-18	-7.1	-2.6	0.4	-20	2	-7.7	0.9	2
Bulls-B01	Borehole	-24.186	16.395	1403	-6.5	-44	-10.1	-6.5	-53	-11.3							-6.5	0.0	-48	7	-10.7	0.8	2

Table 1E: Isotope Data

Sample	Type	Lat.	Long.	Alt. (m)	Mar08 δ^{18}O (‰)	Mar08 δD (‰)	Mar08 δ^{13}C (‰)	Jun08 δ^{18}O (‰)	Jun08 δD (‰)	Jun08 δ^{13}C (‰)	Feb09 δ^{18}O (‰)	Feb09 δD (‰)	Feb09 δ^{13}C (‰)	Jul09 δ^{18}O (‰)	Jul09 δD (‰)	Jul09 δ^{13}C (‰)	δ^{18}O mean (‰)	δ^{18}O stdev (‰)	δD mean (‰)	δD stdev (‰)	δ^{13}C mean (‰)	δ^{13}C stdev (‰)	no.
Bulls-B02	Borehole	-24.119	16.345	1382	-7.0	-40											-7.0		-40				1
Klip-B03	Borehole	-24.218	16.512	1421	-4.3	-25		-4.3	-42	-11.0	-4.3	-34	-10.8	-4.1	-32	-10.0	-4.2	0.1	-33	7	-10.6	0.5	4
Zais-B04	Borehole	-24.027	16.153	1161	-7.3	-38		-6.6	-46	-11.3	-6.6	-42	-11.2	-6.1	-36	-10.8	-6.6	0.5	-41	4	-11.1	0.2	4
Ababis-B05	Borehole	-23.982	16.093	1080	-3.0	-23		-6.3	-50	-3.2	-6.0	-39	-10.8	-6.7	-41	-10.5	-5.5	1.7	-38	11	-8.2	4.3	4
Ababis-R06	River	-23.982	16.093	1080	-2.0	1					-4.7	-27	-11.8				-3.4	1.9	-13	20	-11.8		2
Sol-B07	Borehole	-23.898	16.014	1079	-6.8	-38	-8.1	-6.7	-55	-9.3							-6.7	0.1	-47	12	-8.7	0.8	2
NNL-B08	Borehole	-23.973	15.843	898				-6.1	-60	-10.9	-8.1	-54	-10.4	-7.8	-45	-10.6	-7.4	1.1	-53	8	-10.6	0.3	3
NNL-B09	Borehole	-23.980	15.852	913	-8.2	-42		-6.3	-42	-12.7	-5.5	-31	-12.6	-5.5	-33	-12.2	-6.4	1.3	-37	6	-12.5	0.3	4
NDL-B10	Borehole	-24.126	15.957	1040	-7.1	-39		-7.5	-56	-9.5	-7.1	-46	-9.9	-6.8	-44	-9.8	-7.1	0.3	-46	7	-9.7	0.2	4
Sol-B11	Borehole	-23.894	16.005	1070				-7.0	-50		-6.7	-23	-8.6	-6.6	-41		-6.8	0.2	-38	14	-8.6		3
Sol-B12	Borehole	-23.894	16.005	1070				-6.7	-43	-13.3							-6.7		-43		-13.3		1
NNL-B13	Borehole	-24.049	15.960	1072				-5.8	-50	-9.4	-5.9	-43	-10.8				-5.8	0.1	-47	6	-10.1	1.0	2
NNL-B14	Borehole	-24.034	15.894	953				-6.0	-47	-10.0	-6.3	-44	-8.0				-6.2	0.2	-45	2	-9.0	1.4	2
				Mean	**-4.9**	**-29**	**-9.1**	**-6.4**	**-43**	**-9.4**	**-6.3**	**-40**	**-11.1**	**-6.1**	**-41**	**-9.1**							
				Stdev	**3.0**	**21**	**2.2**	**2.1**	**13**	**2.7**	**1.9**	**15**	**4.6**	**1.5**	**9**	**2.0**							
				Max.	**4.3**	**25**	**-2.1**	**6.6**	**29**	**0.3**	**0.0**	**12**	**-3.1**	**-1.5**	**-14**	**-3.1**							
				Min.	**-8.4**	**-56**	**-12.8**	**-9.3**	**-62**	**-16.6**	**-14.4**	**-95**	**-43.8**	**-7.9**	**-55**	**-12.3**							

Appendix 2: *In situ* Geochemistry Data

Table 2A: *In situ* Geochemistry Data

	March 2008					June 2008					February 2009					July 2009				
Sample	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**
A01	7.80	874	23.7	613	426	8.21	897	13.9	623	443	8.07	697	22.4	483	345	7.66	457	15.6	457	328
A02	7.45	931	24.6	648	466	7.74	956	21.2	662	472	7.61	506	25.3	488	346	7.22	699	17.9	499	354
B03	7.22	1028	29.6	684	478	7.29	1013	18.5	705	501	7.21	762	27.7	550	389	6.94	1077	14.2	772	552
P04	7.42	513	18.4	395	279															
A05	7.86	816	22.1	576	412															
A06	8.52	715	23.5	500	354	8.52	821	11.2	574	569	7.99	714	21	499	356	7.78	662	10.8	464	334
A07	8.44	687	27.2	478	339	8.68	824	12	604	568	8.44	649	23.3	450	320	7.78	673	9.8	471	332
R12	8.38	201	23.7	141	100						8.74	178.6	31.9	128.8	91.5					
B13	7.26	997	27.4	704	504	7.54	1064	22.2	753	737	7.10	981	25.8	680	488	6.01	868	24.1	610	435
S15	7.14	945	26.8	651	469	7.48	1013	24.9	725	519	7.00	926	23.9	646	454	6.82	858	22	602	425
S16	7.30	948	28.3	658	458	7.28	1104	25.7	774	552	7.20	966	27	676	491	6.04	833	21.5	583	417
P18																				
P19	7.72	73.4	N/A	42.7	30.5															
S20	8.68	1271	26.6	851	614															
A21	9.23	503	22.4	357	253						8.46	308	21	214	153	8.85	764	11.9	557	394
A22	9.75	425	20.7	296	210	9.55	757	12.6	519	318	8.77	373	21.5	259	184	9.14	710	11.5	488	353
B23	7.57	1055	31.3	730	526	7.24	1175	28.8	823	586	7.44	863	32.4	609	435	7.02	1110	30	780	554
A24	7.97	980	25.7	685	477	8.14	933	18.7	651	464	8.13	133.2	24.2	106	74.3	8.12	812	21.2	563	414
B26	8.16	1087	26.9	751	548	8.16	1199	25.7	833	590	8.10	287	26.8	200	141	7.76	1243	27.2	854	613
B27	7.59	1002	26.3	699	495	7.88	1108	28	777	553										
P28	5.47	131.1	22.7	91.6	64.8															
R29	8.20	131.2	18.5	91.9	63.7															
R31	8.36	652	29	658	465															
B32	8.33	1751	31.2	1230	871	7.96	1843	32.5	1285	918	7.50	1608	33	1128	786	7.76	1702	31.2	1183	843
B33	8.22	2240	34.6	1570	1130	8.24	2390	33.3	1680	1200	7.66	2150	32	1480	1070	7.85	2240	32.7	1580	1090
B34	7.86	1642	32.6	1145	807	7.96	1742	30.5	1218	867	7.53	1559	31	1096	778	7.64	1588	28.8	1113	785
B35	7.54	1509	32	1061	744	7.62	1642	29.5	1148	809	7.07	1403	32.5	982	730	7.43	1392	26.7	970	692
R36	8.23	114.4	23.8	78.8	60.8						8.54	218	22.7	151	106					
B37	7.50	852	27.4	588	427	6.96	944	26.1	698	470	6.46	856	29.6	601	427	6.45	730	27.2	515	367
R38	8.45	474	29.3	331	235	9.38	788	20.1	557	396	8.33	545	31.7	375	270	9.11	765	26.5	522	362
B39	7.28	1981	32.8	1383	987	7.37	1599	31.6	1117	787	7.08	916	32.2	640	457					
B40	7.02	2.21	30.2	1530	1080	7.32	2310	30	1610	1140	7.04	1420	29.6	0	0	7.03	2700	29.5	1880	1340
B41	6.96	1516	29.9	1050	746	7.14	1658	27.1	1155	820	6.96	899	30	625	445	7.01	1577	29.1	1102	786

Table 2B: *In situ* Geochemistry Data

	March 2008					June 2008					February 2009					July 2009				
Sample	pH	EC (µS)	T (ºC)	TDS (mg/L)	Sal (ppm)	pH	EC (µS)	T (ºC)	TDS (mg/L)	Sal (ppm)	pH	EC (µS)	T (ºC)	TDS (mg/L)	Sal (ppm)	pH	EC (µS)	T (ºC)	TDS (mg/L)	Sal (ppm)
B42	7.03	1513	29.3	1074	757	7.16	1674	29.8	1178	838	6.98	816	30.4	571	414	7.11	1549	29.3	1080	764
A43	8.75	760	30.2	540	389	8.64	936	12.2	658	464	8.27	144.4	25.9	102.3	72.5	8.42	883	19.2	613	456
P44	7.21	66.6	23.1	45.2	27.5															
B45						7.78	1665	17	1165	826	7.37	1578	26.8	1108	791	7.28	1336	24.9	925	655
B46	7.40	990	23.5	684	497	7.37	1204	26.4	838	603	7.28	1029	27.6	716	521					
B47	6.85	886	26	632	452															
S48	7.53	612	26.5	424	309	7.44	1104	21.8	775	555	7.55	655	28.5	429	329	7.26	986	24.2	691	492
B51						7.21	1075	25.8	747	534	7.06	839	28.9	587	416					
A53						7.52	921	19.8	651	658	7.56	662	22.6	464	327					
A54						7.49	946	17.6	656	641	7.77	691	23.2	493	353					
B55						7.98	1184	21.5	828	589										
A56						8.27	1022	16.4	721	512	7.76	498	24.4	339	239	8.13	854	15.4	598	428
A57						8.27	470	10.7	333	234	8.10	191.2	21.3	133.9	95.6					
B58						7.50	432	29.2	626	307	7.26	776	28.8	544	388					
B59						7.70	682	29.2	861	428	7.96	666	33	465	333	7.63	735	28.8	506	354
B60						7.91	660	26.4	943	472	7.89	756	32	526	376	7.77	799	30.2	540	403
B61						7.42	1222	21	848	603										
B62						6.96	1739	28.2	1218	866	7.11	1524	27.2	1068	762					
B64						7.87	1114	27.6	788	560	7.96	977	30.8	682	492					
B65						7.46	1222	29.5	861	613	7.59	1115	34	775	551	7.17	1125	31	825	590
B66						7.52	1339	26.9	935	667										
B67						7.71	891	29.6	627	445	7.08	699	27	488	348					
B69						7.41	1620	25.7	1119	1134	7.06	743	29.8	518	366	7.17	1351	26.5	935	667
B70						7.46	1095	29	767	550	7.12	376	30.3	268	188	7.53	1000	20.9	695	496
B71						7.55	1324	30	934	660	7.21	604	29.8	425	303					
B72						7.89	772	25.9	539	383	7.55	86.1	33.1	58.6	41.6					
B73						7.18	1688	28.7	1190	840	6.88	927	33	642	458					
B74						7.22	1970	22.8	1379	990	7.01	1073	33.8	749	528					
B75						7.22	1893	25.8	1323	948	6.98	1139	30.1	803	572					
B76						7.20	2010	25.8	1400	1000	7.02	929	30.8	681	485					
B77						7.79	1628	29.9	1160	829	6.99	1532	30.6	1071	758					
B78						7.88	1653	28.9	1163	824										
B79						7.53	1246	21.1	868	622	6.89	1097	25.9	783	558					

Table 2C: *In situ* Geochemistry Data

	March 2008					June 2008					February 2009					July 2009				
Sample	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**
B80						7.31	1550	23.2	1091	779										
S81						7.56	857	26.4	605	431	7.26	768	27.6	540	383	6.99	816	29.8	566	402
B82						7.04	858	28.3	549	402	6.83	986	29.4	688	489	7.00	776	238	543	385
S83						8.01	924	20.5	646	465	7.73	885	26.3	885	442					
S84						7.66	1100	21.8	770	534	7.49	1453	26.5	1015	725					
B85						7.31	1549	21.8	1083	772	7.19	1198	29.7	838	591					
B86						7.35	1236	23.33	856	618	7.27	748	30	752	533					
A87						7.62	988	23	690	490	7.03	790	27.2	573	406	7.26	885	22.7	619	443
A88						7.48	970	22.9	669	486	8.12	824	28.1	574	410	7.23	877	23	613	438
A89						8.19	936	21.1	650	477	8.71	721	26.1	501	363					
S90						7.48	1010	22.1	704	501	7.63	839	27	585	420					
B91						7.30	975	24.3	681	487										
A92						7.36	954	25.1	679	480										
B93						7.36	954	25.1	679	480	7.25	809	26	569	405					
A94						8.26	3.86	21.2	2.68	1940	8.64	335	28.2	232	164					
A95						8.94	1083	11.6	767	544	8.87	780	28.7	518	385	9.28	1046	26.4	723	505
S96						8.24	1236	20.6	865	618	7.67	1165	28.8	814	578					
W97						7.91	1333	19.8	931	655	7.50	1195	22	833	591	7.34	1088	22.1	757	539
S98						8.54	1686	17.3	1236	858	8.07	1234	22.3	856	603	8.17	1325	18	965	683
B99						7.02	1017	22.4	711	509	7.37	902	26.9	623	446					
B100						7.11	939	22.2	656	465										
B101						7.22	1664	20.5	1164	832	7.35	1262	30.1	876	619	7.24	1314	20.8	943	670
B102						7.52	1198	20.7	849	603										
B103						7.16	1330	22.6	938	665										
B104						7.54	1230	23.2	861	612										
B105						7.69	917	19.1	641	458	7.52	1365	28.2	954	690	7.40	1163	16	813	580
B106						7.42	990	20.3	695	498	7.18	898	24.3	623	440	7.03	1070	20.8	748	534
B107						7.32	1805	23	1255	894										
B108						7.52	1831	22.5	1259	897										
B109						7.42	937	22	658	470	7.30	744	27	525	374					
B110						7.56	1186	22	807	573	7.06	1059	29.3	753	537	7.16	1015	15.8	707	506
B111						7.41	1094	19.4	766	546						7.31	1090	16	760	541
B112						7.33	849	22.7	595	424	7.06	827	25.5	569	417	7.40	780	20.3	550	385

Table 2D: *In situ* Geochemistry Data

	March 2008					June 2008					February 2009					July 2009				
Sample	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**
B113						7.12	862	22.9	602	432	7.10	969	26.6	674	482					
B114						7.62	920	29.9	651	462										
S115						8.20	852	18.6	595	428	7.63	711	23.9	499	355	8.15	803	10.5	560	400
B116						7.41	1026	21.8	719	518										
P117											7.30	27	n/a	21.2	140					
P118											5.67	11	n/a	10.7	5.9					
P119											7.33	20.6	n/a	14.2	9.6					
R120											8.48	281	31.5	196	132					
P121											7.37	29.1	n/a	19.3	13.4					
B122											6.99	1430	24.8	1013	717					
B123											7.08	1483	26.4	1026	732					
P124											7.08	9.7	23.7	9.1	6					
P125											6.63	12.7	24.6	8.8	6.1					
A126											7.96	201	25.7	149	103					
B127											7.57	1006	29	692	500	7.42	966	26.9	688	488
S128											7.27	800	25.8	559	398	8.05	900	20	629	449
S129											7.93	299	23.4	208	146					
P130											7.13	0	30.2	0	0					
S131											7.50	38.6	26.5	23.3	17.7					
A132											7.91	244	27.5	1170	118					
B133											7.04	1420	30.3	994	710	7.15	3790	25.4	2640	1870
P134											8.18	0		0	0					
P135											7.64	30.1	24.1	20.8	14.5					
R136											7.06	209		145	104					
S139											7.21	852	27.5	590	433					
B140											7.27	960	26.3	672	478					
B141											7.07	1043	26	728	524					
B142											7.20	1255	25.7	905	643					
B143											7.28	1023	20.6	715	504					
P144											7.74	28.6	22.4	19.8	14					
B146											6.91	5210	25.5	3640	2620	7.20	1535	21.1	1054	718
W147											7.91	1048	24.6	730	513	8.31	1065	21.2	727	541
Bulls-B01	7.24	1249	26	877	622	7.45	1583	23.4	1107	794										

Table 2E: *In situ* Geochemistry Data

	March 2008					June 2008					February 2009					July 2009				
Sample	**pH**	**EC (µS**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm**	**pH**	**EC (µS)**	**T (°C)**	**TDS (mg/L)**	**Sal (ppm)**
Bulls-B02	7.17	1983	26	1379	989															
Klip-B03	6.89	1374	25.2	1386	986	7.04	1984	25.8	1383	986	6.87	1844	24.6	1283	915	6.84	1800	18.9	1243	882
Zais-B04	7.05	13.61	27.2	954	682	7.37	1984	25.2	1390	983	7.39	1350	28.7	957	680	6.88	1252	24.7	875	624
Ababis-B05	7.69	731	27.8	519	365	7.65	1363	25.7	945	742	7.77	1072	25.1	744	528	7.40	1302	26.2	892	644
Ababis-R06	8.55	133.5	27.7	93.2	66.5						8.99	233	26.1	162	115					
Sol-B07	7.10	1344	[34.4]	945	684	7.33	1472	26.7	1033	741										
NNL-B08	7.08	1413	30.1	697	978	7.25	1459	31	1015	703	7.36	1264	29.3	877	622	6.74	1339	28	947	673
NNL-B09	7.22	804	29.8	401	562	7.36	761	29.9	529	385	7.25	736	26.8	516	367	6.94	768	28.9	560	406
NDL-B10	7.49	881	30.5	630	446	7.44	843	28	590	422	7.65	661	32	462	331	5.68	701	34.4	485	344
Sol-B11						8.35	2380	30.1	1660	1160	7.37	1282	25.2	895	637	6.64	2040	23	1373	973
Sol-B12						7.47	2130	30.1	1510	1060										
NNL-B13						7.14	1980	31.6	1374	963	7.29	1823	29.6	1268	904					
NNL-B14						7.98	2500	30.2	1770	1240	7.60	2510	28.7	1750	1250					

Appendix 3: Sample site descriptions

Note: "n/a" and "N/A" refer to data that is not available, measurements that were not taken and/or photograph that was not available

N/A

Sample Name:	**A01**
Sample Type:	Surface
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Naukluft Camp Ground
Location Description:	Stream at camp site
Latitude:	24°15'57"
Longitude:	16°14'22.3"
Altitude:	n/a
Sampling Notes:	River at camping site. Running stream. Clear water

Sample Name:	**A02**
Sample Type:	Surface
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Naukluft Camp Ground
Location Description:	20m from Sole dolomite type locality
Latitude:	24°16'21.5"
Longitude:	16°14'30.1"
Altitude:	1426m
Sampling Notes:	Surface water seepage on Sole dolomites.

Sample Name:	**B03**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Naukluft Camp Ground
Location Description:	Borehole in metal shelter. Sinkplaat huisie.
Latitude:	24°15'44.2"
Longitude:	16°14'36.1"
Altitude:	1453m
Sampling Notes:	Borehole water taken from tap 1m away.
Depth of borehole:	26m
Depth to water:	8.7m/ 8.55m/13.6m
Yield of borehole:	5.5m3/h

N/A

Sample Name:	**P04**
Sample Type:	Precipitation
Sample Season:	March 08
Location:	Naukluft camp Ground
Location Description:	Rained throughout the night - heavy thunder storm.
Latitude:	24°15'57"
Longitude:	16°14'22.3"
Altitude:	n/a
Sampling Notes:	Rainwater collected in large bucket overnight.

N/A

Sample Name: **A05**
Sample Type: Surface
Sample Season: March 08
Location: Naukluft Camp Ground
Location Description: Same stream as A01
Latitude: 24°15'57"
Longitude: 16°14'22.3"
Altitude: n/a
Sampling Notes: Same stream at camp site after lots of rain.

Sample Name: **A06**
Sample Type: Surface
Sample Season: March 08, June 08, Feb 09, July 09
Location: Waterkloof Trail
Location Description: Large pool situated in tufa beds. Clear water and pool not very disturbed.
Latitude: 24°15'40.5"
Longitude: 16°13'41.82
Altitude: 1528m
Sampling Notes: Sample collected from deepest part of pool

Sample Name: **A07**
Sample Type: Surface
Sample Season: March 08, June 08, Feb 09, July 09
Location: Waterkloof Trail
Location Description: Downstream from A06 in next pool. Clear water ±3m depth. Tufa outcrop over hangs the pool.
Latitude: 24°15'41.16"
Longitude: 16°13'43.44"
Altitude: 1530m
Sampling Notes: Sampled from deepest part of pool

Sample Name: **R12**
Sample Type: River
Sample Season: March 08, Feb 09
Location: Tsondab river
Location Description: North of büllsport on solitaire road
Latitude: 24°06'31.5"
Longitude: 16°19'34.9"
Altitude: 1333m
Sampling Notes: Tsondab. Very merky river water. Samples taken whilst raining in March.

Sample Name:	**B13**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Büllsport Campsite
Location Description:	North of Büllsport
Latitude:	24°08'12.3"
Longitude:	16°20'44.6"
Altitude:	1442m
Sampling Notes:	Borehole was covered by two rocks. No pump nearby-borehole not in use. In June 08 was in use.
Depth of borehole:	n/a
Depth to water:	19.07m/18.9m/19.4m/19.3m
Yield of borehole:	unknown, bailed

Sample Name:	**S15**
Sample Type:	Spring
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Blasskranz farm
Location Description:	Clear spring about 4x3m in tufa which contains large clasts of dolomite (±1m).
Latitude:	24°07'24.9"
Longitude:	16°17'20.6"
Altitude:	1474m
Sampling Notes:	Dived in to get water in bottom of pool.

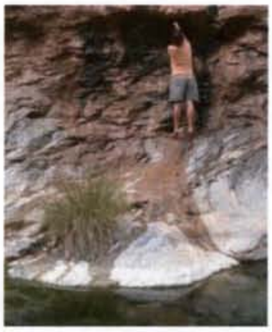
Sample Name:	**S16**
Sample Type:	Spring
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Blasskranz farm
Location Description:	In valley east of previous spring sample.
Latitude:	24°07'07.4"
Longitude:	16°17'28.2"
Altitude:	1428m
Sampling Notes:	Water seeping out of rock, underneath reeds/grass. In July 09, almost all dried up due to over-extraction.

N/A

Sample Name:	**P18**
Sample Type:	Precipitation
Sample Season:	March 08
Location:	Zais
Location Description:	Outside Zais farm on road.
Latitude:	24°01'36.9"
Longitude:	16°09'15"
Altitude:	1159m
Sampling Notes:	Rainwater collected in green bucket

N/A

Sample Name:	**P19**
Sample Type:	Precipitation
Sample Season:	March 08
Location:	Weltevrede
Location Description:	Stood in Jodie's tent, so temp discarded.
Latitude:	24°10'39"
Longitude:	15°58'51.7"
Altitude:	1097m
Sampling Notes:	Rainwater collected in bucket over night during storm.



Sample Name:	**S20**
Sample Type:	Spring
Sample Season:	March 08, Feb 09
Date:	03/08/07
Location:	Die Valle
Location Description:	Water dripping out of rocks in valley
Latitude:	24°08'02.7"
Longitude:	16°05'38.7"
Altitude:	1321m
Sampling Notes:	Kate had to rock-climb to get to the source where water seeped out.

Sample Name:	**A21**
Sample Type:	Surface
Sample Season:	March 08, Feb 09, July 09
Location:	Die Valle
Location Description:	Tufa rocks surround waterfall and pool.
Latitude:	24°07'58.3"
Longitude:	16°05'40"
Altitude:	1325m
Sampling Notes:	Water from waterfall accumulates in pool.

Sample Name:	**A22**
Sample Type:	Surface
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Die Valle
Location Description:	Tufa rocks surround waterfall and pool.
Latitude:	24°07'58.3"
Longitude:	16°05'40"
Altitude:	1325m
Sampling Notes:	Water running over tufa rocks in the form of a waterfall.

Sample Name:	**B23**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Tsams- Wes
Location Description:	Water sampled 42m from borehole from black plastic pipe.
Latitude:	24°17'13.2"
Longitude:	15°59'33.7"
Altitude:	1198m
Sampling Notes:	Tsams Wes. Pump had to be switched on manually (Generator)
Depth of borehole:	n/a
Depth to water:	59m
Yield of borehole:	n/a

Sample Name:	**A24**
Sample Type:	Surface
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Tsams-Ost
Location Description:	Lots of frogs/tadpoles. Not very deep into valley. Close to old campsite.
Latitude:	24°14'55"
Longitude:	16°06'17"
Altitude:	1355m
Sampling Notes:	Water running through reeds in bend of river.

Sample Name:	**B26**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Tsams-Ost
Location Description:	On road in Tsams Ost at "wasser" sign.
Latitude:	24°15'08"
Longitude:	16°04'55"
Altitude:	1344m
Sampling Notes:	Yellow Manual pump for borehole
Depth of borehole:	n/a
Depth to water:	12.3m/ 11.3m/none/6.15m
Yield of borehole:	n/a

N/A

Sample Name:	**B27**
Sample Type:	Borehole
Sample Season:	March 08, June 08
Location:	Tsams-Ost
Location Description:	Road to Tsams-Wes
Latitude:	24°15'56.8"
Longitude:	16°02'23.5"
Altitude:	1275m
Sampling Notes:	Windmill transports water through a plastic pipe +/-40m and through a tank.
Depth of borehole:	n/a
Depth to water:	n/a

N/A

Sample Name:	**P28**
Sample Type:	Precipitation
Sample Season:	March 08
Location:	Tsams-Wes
Location Description:	On way back to main road
Latitude:	24°14'10.2"
Longitude:	15°57'10.86"
Altitude:	1102m
Sampling Notes:	Collected during heavy downpour in bucket

Sample Name:	**R29**
Sample Type:	River
Sample Season:	March 08
Location:	South of Sukses on main road South.
Location Description:	Full running river after lots of rain.
Latitude:	24°20'48.3"
Longitude:	15°54'18.2"
Altitude:	991m
Sampling Notes:	South of Sukses. Water less merky than usual for rivers.

Sample Name:	**R31**
Sample Type:	River
Sample Season:	March 08
Location:	Soussusvlei Park
Location Description:	Tsauchab River. Extremely merky water
Latitude:	24°38'41.8"
Longitude:	15°39'08.4"
Altitude:	676m
Sampling Notes:	Didn't filter water before using probe: it created disturbed readings because of the silty water.

Sample Name:	**B32**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Little Kulala
Location Description:	Arid environment-no vegetation.
Latitude:	24°38'51.5"
Longitude:	15°47'08"
Altitude:	737m
Sampling Notes:	Submerged pump. Re-did probe readings
Depth of borehole:	±160m
Depth to water:	65.1m
Yield of borehole:	n/a

Sample Name:	**B33**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Little Kulala
Location Description:	Water meter broke. Kragpomp.
Latitude:	24°37'39.8"
Longitude:	15°44'57.2"
Altitude:	715m
Sampling Notes:	Been pumping since 8am. Re-did probe readings.
Depth of borehole:	n/a
Depth to water:	>100m
Yield of borehole:	n/a

Sample Name:	**B34**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Geluk Farm
Location Description:	Eric's Farm
Latitude:	24°41'07.8"
Longitude:	15°46'22.2"
Altitude:	724m
Sampling Notes:	Water tasted nice.
Depth of borehole:	n/a
Depth to water:	45m
Yield of borehole:	5m^3/h

Sample Name:	**B35**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	La Mirage
Location Description:	Over road from La Mirage hotel
Latitude:	24°41'00.8"
Longitude:	15°49'13.3"
Altitude:	758m
Sampling Notes:	Traveled in plastic pipe app 20m
Depth of borehole:	n/a
Depth to water:	60-65m
Yield of borehole:	25m^3/h

Sample Name:	**R36**
Sample Type:	River
Sample Season:	March 08, Feb 09
Location:	Noab River
Location Description:	Near Ababis
Latitude:	23°58'56.8"
Longitude:	16°05'54.8"
Altitude:	1090m
Sampling Notes:	Running very strong after rain. Clearer water (not so merky)

Sample Name:	**B37**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Panorama
Location Description:	End of the road at Panorama.
Latitude:	24°04'45.5"
Longitude:	16°03'21.9"
Altitude:	1248m
Sampling Notes:	Solar powered pump. Pump always running, reservoir often full
Depth of borehole:	n/a
Depth to water:	n/a/38.7m/37.6m/30.4m
Yield of borehole:	n/a

Sample Name:	**R38**
Sample Type:	River
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Tsauchab river
Location Description:	Just East of Betesde retreat, the river crosses the road (D0854).
Latitude:	24°33'36.5"
Longitude:	16°00'49.5"
Altitude:	968m
Sampling Notes:	Deeper and clearer river water. Often has a distinct smell and lots of algae growing.

Sample Name:	**B39**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09
Location:	Hebron Farm
Location Description:	Just South of Sesreim on C19
Latitude:	24°32'49.5"
Longitude:	15°55'15.1"
Altitude:	881m
Sampling Notes:	Took sample from pipe +/-4m from borehole. Water was very good tasting water.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B40**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Desert Homestead
Location Description:	On C19 opposite little sossus lodge.
Latitude:	24°38'24.9"
Longitude:	15°57'43.4"
Altitude:	887m
Sampling Notes:	Took directly from borehole under straw house. Water didn't taste exceptionally good.(brackish)
Depth of borehole:	app 90m
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B41**
Sample Type:	Borehole
Sample Season:	Mar-08
Location:	Little Sossus Lodge
Location Description:	Junction between C19 and D0854
Latitude:	24°31'40.9"
Longitude:	15°58'59.5"
Altitude:	906m
Sampling Notes:	Pressure tanks present to pump water up the hill
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B42**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Sossusvlei Campsite
Location Description:	Pump situated under a shelter
Latitude:	24°37'16.4"
Longitude:	15°57'59.9"
Altitude:	890m
Sampling Notes:	Started pump. Samples taken at source.
Depth of borehole:	n/a
Depth to water:	8.9m
Yield of borehole:	n/a

Sample Name:	**A43**
Sample Type:	Surface
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Hauchabfontein
Location Description:	Tsauchab river
Latitude:	24°31'1.8"
Longitude:	16°04'36.54"
Altitude:	1037m
Sampling Notes:	Water close to spring source. Very clear water with plenty bubbles. Water all year round according to owner

N/A

Sample Name:	**P44**
Sample Type:	Precipitation
Sample Season:	March 08
Location:	n/a
Location Description:	Near Tsuachab River Camp on D0850 east.
Latitude:	n/a
Longitude:	n/a
Altitude:	n/a
Sampling Notes:	Rainwater collected in green bucket

Sample Name:	**B45**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Tsauchab River Camp
Location Description:	Just next to Tsauchab river.
Latitude:	24°26'37.98"
Longitude:	16°10'17.88"
Altitude:	1152m
Sampling Notes:	Borehole pumped by windmill.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B46**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09
Location:	Onis
Location Description:	On D 0854 south of Naukluft park
Latitude:	24°20'45"
Longitude:	16°14'44"
Altitude:	1287m
Sampling Notes:	Borehole next to farm house pumping into reservoir. Pump has been on for 20min.
Depth of borehole:	50m
Depth to water:	9.6m
Yield of borehole:	n/a

N/A

Sample Name:	**B47**
Sample Type:	Borehole
Sample Season:	March 08
Location:	Neu Onis
Location Description:	Further north east of Onis
Latitude:	24°17'15.1"
Longitude:	16°16'45.5"
Altitude:	1324m
Sampling Notes:	Borehole pumping into reservoir 40m away through plastic pipe.
Depth of borehole:	40m
Depth to water:	n/a
Yield of borehole:	20m^3/h

Sample Name:	**S48**
Sample Type:	Spring
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Neu Onis
Location Description:	On edge of naukluft Mountains. Limestone has calcite veins throughout
Latitude:	24°16'30.1"
Longitude:	16°15'53"
Altitude:	1396m
Sampling Notes:	Water taken where seeping out of limestone on ground surface

Sample Name:	**B51**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Namib-Naukluft park, near reception
Location Description:	Opposite previously sampled borehole at reception
Latitude:	24°15'46.6"
Longitude:	16°14'43.8"
Altitude:	1452m
Sampling Notes:	Was not working March 2008
Depth of borehole:	±12m?
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**A53**
Sample Type:	Surface
Sample Season:	June 08, Feb 09
Location:	Waterkloof trail
Location Description:	Water pool further along Waterkloof trail, thought it was the last water but it wasn't
Latitude:	24°15'23.2"
Longitude:	16°13'34.6"
Altitude:	1621m
Sampling Notes:	None

Sample Name:	**A54**
Sample Type:	Surface
Sample Season:	June 08, Feb 09
Location:	Waterkloof trail
Location Description:	Last water on Waterkloof Trail
Latitude:	24°15'06.6"
Longitude:	16°13'22.5"
Altitude:	1617m
Sampling Notes:	Small still pond at end of intermittent pools connected by thin steam

Sample Name:	**B55**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Weltevrede, Die Valle
Location Description:	Solar powered borehole leading to a tank 10m away, going through pipes to a shower
Latitude:	24°08'32.4"
Longitude:	16°05'02.4"
Altitude:	1362m
Sampling Notes:	Waited a while to ensure we weren't getting water sitting in the pipes
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**A56**
Sample Type:	Surface
Sample Season:	June 08, Feb 09, July 09
Location:	Die valle
Location Description:	Collected from pool below seepage collected March 09 at die valle.
Latitude:	24°08'02.9"
Longitude:	16°05'39.4"
Altitude:	1322m
Sampling Notes:	None

Sample Name:	**A57**
Sample Type:	Spring
Sample Season:	June 08, Feb 09
Location:	Tufa cave, Die Valle
Location Description:	Cascade tufa blocking river valley, technically a spring.
Latitude:	24°07'45.6"
Longitude:	16°05'51.2"
Altitude:	1615m
Sampling Notes:	Sampled from large murky pool 10m in diameter. Sampled nearest to where we thought the water emanated.

N/A

Sample Name:	**B58**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Weltevrede campsite
Location Description:	On C19
Latitude:	24°10'39"
Longitude:	15°58'51.7"
Altitude:	1097m
Sampling Notes:	Taken from a hosepipe, closest to borehole
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B59**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Namib Desert Lodge
Location Description:	On the C19, sample taken next to Lodge
Latitude:	24°07'14.8"
Longitude:	15°54'21.6"
Altitude:	978m
Sampling Notes:	Pumped through pipe into water storage tank, thick black plastic pipe
Depth of borehole:	85m
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B60**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Namib Desert Lodge
Location Description:	5km from desert lodge. Shareholders cottage.
Latitude:	24°04'28.1"
Longitude:	15°53'17.3"
Altitude:	949m
Sampling Notes:	Sample taken from tap 10m from borehole.
Depth of borehole:	n/a
Depth to water:	72.6m
Yield of borehole:	n/a

Sample Name:	**B61**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Solitaire Guest Farm
Location Description:	North of Solitaire on C14
Latitude:	23° 51' 59.3"
Longitude:	16° 03' 14.8"
Altitude:	1160m
Sampling Notes:	Solar powered pump, through 50m black plastic piping. Pump runs all day.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B62**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Solitaire Guest Farm
Location Description:	North of Solitaire on C14
Latitude:	23° 51' 56.1"
Longitude:	16° 03' 39.9"
Altitude:	1165m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B64**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Escourt
Location Description:	At wardens houses in Escourt
Latitude:	24° 02' 57.7"
Longitude:	15° 48' 02.2"
Altitude:	871m
Sampling Notes:	Water taken from metal pipe from the borehole.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B65**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Escourt
Location Description:	Solar powered pump in middle of vegetated dune field, west of houses. Southern side of Tsauchab river.
Latitude:	23° 59' 41.7"
Longitude:	15° 42' 35.7"
Altitude:	812m
Sampling Notes:	Water taken as water pumps into tank from metal pipe.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B66**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Escourt
Location Description:	Windmill in valley North of houses
Latitude:	24° 00' 23.0"
Longitude:	15° 49' 10.3"
Altitude:	873m
Sampling Notes:	Very rusted windmill, possibly high Fe content. Apparently lots of water here.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B67**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Camp Agama
Location Description:	At the campsite
Latitude:	24° 08' 38.7"
Longitude:	15° 57' 42.1"
Altitude:	1045m
Sampling Notes:	Black pvc pipe straight from borehole.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B69**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Sossusvlei lodge
Location Description:	At the lodges.
Latitude:	24° 28' 53.1"
Longitude:	15° 48' 08.4"
Altitude:	781m
Sampling Notes:	Taken from pvc pipe 200m away from borehole.
Depth of borehole:	30m
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B70**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Sossusvlei Lodge/Sossusvlei Desert Camp
Location Description:	Borehole southeast of Sossusvlei lodge.
Latitude:	24° 30' 22.6"
Longitude:	015° 49' 55.1"
Altitude:	799m
Sampling Notes:	Pumps a few meters through a black pvc pipe.
Depth of borehole:	80m
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**B71**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Sesriem Campsite
Location Description:	At the Campsite.
Latitude:	24° 29' 08.4"
Longitude:	015° 47' 52.2"
Altitude:	781m
Sampling Notes:	Taken from pipe a few meters from borehole.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B72**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Sossus Dune Lodge
Location Description:	Round some hills from Sesriem, close to Sesreim canyon
Latitude:	24° 30' 52.1"
Longitude:	015° 46' 56.5"
Altitude:	767m
Sampling Notes:	Taken from pipe a few hundred metres from borehole
Depth of borehole:	20m
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B73**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	A Little Sossus Lodge
Location Description:	At old sossusvlei campsite, east of B42
Latitude:	24° 37' 55.3"
Longitude:	015° 58' 42.1"
Altitude:	902m
Sampling Notes:	Straight from borehole through black pvc pipe
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B74**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Betesda Christian Retreat
Location Description:	On D 0854, at the campsite.
Latitude:	24° 37' 04.7"
Longitude:	015° 59' 27.1"
Altitude:	924m
Sampling Notes:	Windmill pumps water from an apparently shallow aquifer.
Depth of borehole:	n/a
Depth to water:	6m/6.2m
Yield of borehole:	n/a

Sample Name:	**B75**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Betesda Christian Retreat
Location Description:	North of Campsite
Latitude:	24° 36' 08.2"
Longitude:	015° 59' 07.9"
Altitude:	955m
Sampling Notes:	Solar powered pump, water taken right at borehole.
Depth of borehole:	50m
Depth to water:	32m
Yield of borehole:	n/a

Sample Name:	**B76**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Betesda Christian Retreat
Location Description:	Nearer to campsite at the fence.
Latitude:	24° 36' 51.2"
Longitude:	015° 59' 30.8"
Altitude:	934m
Sampling Notes:	Solar powered pump.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**B77**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Namib Sky Balloon Safari's
Location Description:	Just next to Namib Sky adventures, at workers houses.
Latitude:	24° 40' 31.2"
Longitude:	015° 48' 25.1"
Altitude:	736m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B78**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Namib Sky Balloon Safari's
Location Description:	South of Namib sky adventures, in hills.
Latitude:	24° 43' 25.1"
Longitude:	015° 49' 25.0"
Altitude:	744m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B79**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Hauchabfontein
Location Description:	Borehole south of house on banks of Tsauchab.
Latitude:	24° 31' 01.3"
Longitude:	016° 04' 34.5"
Altitude:	1051m
Sampling Notes:	March 08 a generator was here, no a huge windmill.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B80**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Hauchabfontein
Location Description:	West of house.
Latitude:	24° 31' 09.6"
Longitude:	016° 04' 26.2"
Altitude:	1039m
Sampling Notes:	Generator needed to start pump.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**S81**
Sample Type:	Spring
Sample Season:	June 08, Feb 09, July 09
Location:	Tsauchab River Camp
Location Description:	Oewald Camp spring
Latitude:	24° 30' 11.0"
Longitude:	016° 06' 53.5"
Altitude:	1096m
Sampling Notes:	Water collected from seep out of the rocks into the Tsauchab river.

Sample Name:	**B82**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Neu Onis
Location Description:	Directly East +-500m of last borehole B47
Latitude:	24° 17' 10.2"
Longitude:	016° 16' 50.0"
Altitude:	1296m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**S83**
Sample Type:	Spring
Sample Season:	June 08, Feb 09
Location:	Neuras
Location Description:	On D0850 South
Latitude:	24° 27' 44.7"
Longitude:	016° 14' 15.7"
Altitude:	1181m
Sampling Notes:	Artesian well, told that water not sourced from Naukluft but from Mariental

Sample Name:	**S84**
Sample Type:	Spring
Sample Season:	June 08, Feb 09
Location:	Neuras
Location Description:	On D0850 South
Latitude:	24° 27' 47.8"
Longitude:	016° 14' 15.7"
Altitude:	1185m
Sampling Notes:	2nd artesian well. Sampled at source of water. Told that all wells lie along fault.

Sample Name:	**B85**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Zais
Location Description:	Opposite Zais on C14
Latitude:	24° 01' 39.3"
Longitude:	016° 09' 19.3"
Altitude:	1163m
Sampling Notes:	Generator pumps water into feeding trough.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B86**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Frans' house (Arbeid Adelt)
Location Description:	On Arbeid Adelt road
Latitude:	24° 06' 58.7"
Longitude:	016° 13' 26.5"
Altitude:	1324m
Sampling Notes:	Solar powered pump, pumps water into dam, a few tens of metres away.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**A87**
Sample Type:	Surface
Sample Season:	June 08, Feb 09, July 09
Location:	
Location Description:	Spring just above large tufa, last water seen in river valley.
Latitude:	24° 08' 10.8"
Longitude:	016° 14' 08.1"
Altitude:	1491m
Sampling Notes:	None

Sample Name:	**A88**
Sample Type:	Surface
Sample Season:	June 08, Feb 09, July 09
Location:	Above Blasskopf tufa, through Arbeid Adelt entrance
Location Description:	Spring just further above tufa, 20m downstream from A87.
Latitude:	24° 08' 09.2"
Longitude:	016° 14' 08.6"
Altitude:	1482m
Sampling Notes:	None

Sample Name:	**A89**
Sample Type:	Surface
Sample Season:	June 08, Feb 09
Location:	Arbeid Adelt
Location Description:	A long hiking trail west from Tufa shelter.
Latitude:	24° 06' 48.0"
Longitude:	016° 09' 36.9"
Altitude:	1519m
Sampling Notes:	None

Sample Name:	**S90**
Sample Type:	Spring
Sample Season:	June 08, Feb 09
Location:	"Tufa Cave Rest Camp" Arbeid Adelt
Location Description:	Just next to Tufa shelter
Latitude:	24° 06' 37.2"
Longitude:	016° 10' 39.5"
Altitude:	1459m
Sampling Notes:	Water continuously emerging from natural spring, Archimedes screw used to extract water from source.

N/A

Sample Name:	**B91**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Arbeid Adelt homestead
Location Description:	Just next to house.
Latitude:	n/a
Longitude:	n/a
Altitude:	n/a
Sampling Notes:	Sample taken from inflow pipe at the Arbeid Adelt homestead.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**A92**
Sample Type:	Surface
Sample Season:	June 08
Location:	Ababis (Tsondab River)
Location Description:	Just next to borehole in almost dry Tsondab river bed.
Latitude:	23° 58' 56.3"
Longitude:	016° 05' 34.2"
Altitude:	1073m
Sampling Notes:	Sampled from remaining water in otherwise dry river bed.

Sample Name:	**B93**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Ababis
Location Description:	Along D1261 on right of road
Latitude:	23° 58' 11.7"
Longitude:	016° 08' 45.0"
Altitude:	1140m
Sampling Notes:	Sampled from overflow from tank.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**A94**
Sample Type:	Surface
Sample Season:	June 08, Feb 09
Location:	Ababis
Location Description:	Along D1261 on left of the road, take a long road towards a house.
Latitude:	23° 54' 49.4"
Longitude:	016° 12' 53.3"
Altitude:	1225m
Sampling Notes:	Water sampled from tributary of the Tsondab. Apparently water very brack and not drinkable.

Sample Name:	**A95**
Sample Type:	Surface
Sample Season:	June 08, Feb 09, July 09
Location:	Reimhoogte Pass
Location Description:	Appears to be very close to a source on the way to Noab. (At a fence)
Latitude:	23° 56' 51.1"
Longitude:	016° 13' 28.5"
Altitude:	1273m
Sampling Notes:	None

Sample Name:	**S96**
Sample Type:	Spring
Sample Season:	June 08, Feb 09
Location:	Reimhoogte Pass
Location Description:	On the way to Noab, further downstream from A95.
Latitude:	23° 56' 43.3"
Longitude:	016° 13' 33.1"
Altitude:	1268m
Sampling Notes:	Sampled as water seeped from the rocks.

Sample Name:	**W97**
Sample Type:	Well
Sample Season:	June 08, Feb 09, July 09
Location:	Nauzuras
Location Description:	At the entrance to the farm.
Latitude:	23° 49' 15.2"
Longitude:	016° 20' 33.3"
Altitude:	1645m
Sampling Notes:	Windmill pumps water from hand dug well into dam, took water just before going into dam.
Depth of borehole:	n/a
Depth to water:	9.7m
Yield of borehole:	n/a

Sample Name:	**S98**
Sample Type:	Spring
Sample Season:	June 08, Feb 09, July 09
Location:	Nauzuras
Location Description:	2nd spring past the koppie
Latitude:	23° 49' 43.6"
Longitude:	016° 20' 27.8"
Altitude:	1615m
Sampling Notes:	Sampled from seep from the rocks.

Sample Name:	**B99**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Lepel
Location Description:	Garies Rest Camp, the windmill at Efram's house.
Latitude:	23° 51' 01.3"
Longitude:	016° 30' 17.2"
Altitude:	1619
Sampling Notes:	Windmill pumps water into dam, sample taken just before entering the dam.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B100**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Diamant
Location Description:	East of Lepel
Latitude:	23° 50' 42.0"
Longitude:	016° 31' 51.0"
Altitude:	1596m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B101**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Blaubeker
Location Description:	One road South from Lepel.
Latitude:	23° 54' 18.2"
Longitude:	016° 28' 50.7"
Altitude:	1602m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B102**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Arbeidsloon
Location Description:	South of Blaubeker
Latitude:	23° 57' 07.6"
Longitude:	016° 26' 27.0"
Altitude:	1640m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B103**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Tsabisis
Location Description:	South of Arbeidsloon
Latitude:	24° 00' 26.8"
Longitude:	016° 25' 35.3"
Altitude:	1658
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	±18m
Yield of borehole:	n/a

Sample Name:	**B104**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Tsabisis
Location Description:	East of B103
Latitude:	24° 01' 12.3"
Longitude:	016° 25' 53.2"
Altitude:	1651m
Sampling Notes:	Windmill pumped water discontinuously
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B105**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Kranzkop
Location Description:	East of Tsabisis
Latitude:	24° 00' 46.4"
Longitude:	016° 26' 44.0"
Altitude:	1674m
Sampling Notes:	Not a strong borehole can't use pump.
Depth of borehole:	±66m
Depth to water:	±24m
Yield of borehole:	n/a

Sample Name:	**B106**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	North of Kranzkop
Location Description:	On the way to Rietoog
Latitude:	23° 59' 09.9"
Longitude:	016° 27' 14.4"
Altitude:	1643m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B107**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Geenvlakte
Location Description:	Just East of Büllsport
Latitude:	24° 08' 04.9"
Longitude:	016° 24' 06.8"
Altitude:	1403m
Sampling Notes:	None
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B108**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Laybank
Location Description:	East of Geenvlakte
Latitude:	24° 07' 09.1"
Longitude:	016° 25' 59.3"
Altitude:	1410m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B109**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Rietoog
Location Description:	Christiaan Mouers' house
Latitude:	23° 58' 10.0"
Longitude:	016° 33' 31.7"
Altitude:	1502m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B110**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Smalstreep
Location Description:	AC Hagen's house
Latitude:	23° 57' 18.6"
Longitude:	016° 29' 07.0"
Altitude:	1581m
Sampling Notes:	none
Depth of borehole:	±55m
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**B111**
Sample Type:	Borehole
Sample Season:	June 08, July 09
Location:	Smalstreep
Location Description:	AC Hagen's gate
Latitude:	23° 57' 18.6"
Longitude:	016° 29' 14.5"
Altitude:	1583m
Sampling Notes:	Windmill pumps water
Depth of borehole:	±70m
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B112**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Smalstreep
Location Description:	West of House
Latitude:	23° 57' 41.5"
Longitude:	016° 29' 16.0"
Altitude:	1579m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**B113**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Garies Oos
Location Description:	Borehole at the house
Latitude:	23° 55' 04.0"
Longitude:	016° 32' 14.8"
Altitude:	1564m
Sampling Notes:	none
Depth of borehole:	80m
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**B114**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Garies Wes
Location Description:	South down road from B113
Latitude:	23° 56' 53.6"
Longitude:	016° 29' 44.3"
Altitude:	1570m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**S115**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Garies Wes
Location Description:	Spring in river bed
Latitude:	23° 57' 06.1"
Longitude:	016° 29' 37.9"
Altitude:	1560m
Sampling Notes:	none

Sample Name:	**B116**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Slangpoort
Location Description:	Windmill on the bend of the C24 before Rietoog
Latitude:	23° 53' 32.7"
Longitude:	016° 33' 02.0"
Altitude:	1561m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**P117**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Naukluft Camp Ground
Location Description:	At the Campsite
Latitude:	24°15'57"
Longitude:	16°14'22.3"
Altitude:	n/a
Sampling Notes:	Rainwater collected from the night of the 15th

N/A

Sample Name:	**3P118**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Naukluft Camp Ground
Location Description:	At the Campsite
Latitude:	24°15'57"
Longitude:	16°14'22.3"
Altitude:	n/a
Sampling Notes:	Rainwater collected during the day

N/A

Sample Name:	**P119**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Naukluft Camp Ground
Location Description:	At the Campsite
Latitude:	24°15'57"
Longitude:	16°14'22.3"
Altitude:	n/a
Sampling Notes:	Rainwater collected from the night of the 16th

N/A	**Sample Name:**	**R120**
	Sample Type:	river
	Sample Season:	Feb 09
	Location:	Neu onis
	Location Description:	Tsauchab river running through farm
	Latitude:	24°17'18.42"
	Longitude:	16°16'41.196"
	Altitude:	n/a
	Sampling Notes:	none

N/A	**Sample Name:**	**P121**
	Sample Type:	Precipitation
	Sample Season:	Feb 09
	Location:	Naukluft Camp Ground
	Location Description:	At the Campsite
	Latitude:	24°15'57"
	Longitude:	16°14'22.3"
	Altitude:	n/a
	Sampling Notes:	Rainwater collected from night of 17th

N/A	**Sample Name:**	**B122**
	Sample Type:	Borehole
	Sample Season:	Feb 09
	Location:	Klipheuwel
	Location Description:	The School
	Latitude:	n/a
	Longitude:	n/a
	Altitude:	n/a
	Sampling Notes:	Sample taken from in the middle of the school quad
	Depth of borehole:	n/a
	Depth to water:	n/a
	Yield of borehole:	n/a

N/A	**Sample Name:**	**B123**
	Sample Type:	Borehole
	Sample Season:	Feb 09
	Location:	Klipheuwel
	Location Description:	Klipheuwel Winkel
	Latitude:	24°12'40.68"
	Longitude:	16°30'50.54"
	Altitude:	n/a
	Sampling Notes:	Hand pump
	Depth of borehole:	n/a
	Depth to water:	n/a
	Yield of borehole:	n/a

N/A

Sample Name:	**P124**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Büllsport Campsite
Location Description:	North of Büllsport
Latitude:	24°08'12.3"
Longitude:	16°20'44.6"
Altitude:	1442m
Sampling Notes:	none

N/A

Sample Name:	**P125**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Panorama (Mountain)
Location Description:	On road to borehole
Latitude:	24°04'45.5"
Longitude:	16°03'21.9"
Altitude:	1248m
Sampling Notes:	Rainwater collected from the afternoon on panorama road

N/A

Sample Name:	**A126**
Sample Type:	Surface
Sample Season:	Feb 09
Location:	Solitaire Guest Farm
Location Description:	River around borehole
Latitude:	23° 51' 56.1"
Longitude:	16° 03' 39.9"
Altitude:	1165m
Sampling Notes:	none

N/A

Sample Name:	**B127**
Sample Type:	Borehole
Sample Season:	Feb 09, July 09
Location:	Solitaire Guest Farm
Location Description:	New borehole north of lodge (cows)
Latitude:	23° 51' 45.79"
Longitude:	16° 03' 2"
Altitude:	n/a
Sampling Notes:	none
Depth of borehole:	drilled 135m
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**S128**
Sample Type:	Spring
Sample Season:	Feb 09, July 09
Location:	Tsams Ost
Location Description:	Small fontein
Latitude:	24° 16' 58.22"
Longitude:	16° 5' 10.36"
Altitude:	n/a
Sampling Notes:	Have to swim for sample

Sample Name:	**S129**
Sample Type:	Spring
Sample Season:	Feb 09
Location:	Tsams Ost
Location Description:	Grootfontein
Latitude:	24° 16' 46.06"
Longitude:	16° 5' 28.46"
Altitude:	n/a
Sampling Notes:	Swam for sample

N/A

Sample Name:	**P130**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Nauzerus
Location Description:	none
Latitude:	23° 49' 8.90"
Longitude:	016° 20' 38.22"
Altitude:	n/a
Sampling Notes:	none

N/A

Sample Name:	**S131**
Sample Type:	Spring
Sample Season:	Feb 09
Location:	Tsams Ost
Location Description:	Just upstream from A24
Latitude:	n/a
Longitude:	n/a
Altitude:	n/a
Sampling Notes:	Water seeping out of rock on right-hand-side of river.

N/A

Sample Name:	**A132**
Sample Type:	Surface
Sample Season:	Feb 09
Location:	Tsams Ost
Location Description:	Further upstream from seepage nearer to the spring
Latitude:	n/a
Longitude:	n/a
Altitude:	n/a
Sampling Notes:	none

Sample Name:	**B133**
Sample Type:	Borehole
Sample Season:	Feb 09, July 09
Location:	Sossusvlei lodge
Location Description:	On road into sesriem.
Latitude:	24° 28' 19.52"
Longitude:	16° 51' 8.06"
Altitude:	n/a
Sampling Notes:	Solar powered. Water taken as water enters dam out of black pipe. Andries says it tastes funny.
Depth of borehole:	60m
Depth to water:	40m

N/A	**Sample Name:**	**P134**
	Sample Type:	Precipitation
	Sample Season:	Feb 09
	Location:	Sesriem Campsite
	Location Description:	At the campsite
	Latitude:	24° 29' 08.4"
	Longitude:	015° 47' 52.2"
	Altitude:	781m
	Sampling Notes:	Rainwater collected on night of 22nd

N/A	**Sample Name:**	**P135**
	Sample Type:	Precipitation
	Sample Season:	Feb 09
	Location:	Hauchabfontein
	Location Description:	Collected at Hauchabfontein farm
	Latitude:	24° 31' 01.3"
	Longitude:	016° 04' 34.5"
	Altitude:	1051m
	Sampling Notes:	Rainwater collected afternoon Hauchabfontein

N/A	**Sample Name:**	**R136**
	Sample Type:	Surface
	Sample Season:	Feb 09
	Location:	Tsauchab river
	Location Description:	Opposite entrance to Sossus Dune Lodge
	Latitude:	24° 30' 52.1"
	Longitude:	015° 46' 56.5"
	Altitude:	767m
	Sampling Notes:	none

N/A	**Sample Name:**	**S139**
	Sample Type:	Spring
	Sample Season:	Feb 09
	Location:	Neuras
	Location Description:	Fountain number 3
	Latitude:	24° 27' 40.10"
	Longitude:	016° 14' 22.24"
	Altitude:	n/a
	Sampling Notes:	none

N/A	**Sample Name:**	**B140**
	Sample Type:	Borehole
	Sample Season:	Feb 09
	Location:	Noab
	Location Description:	Windmill next to veg garden
	Latitude:	23° 54' 58.64"
	Longitude:	016° 18' 24.67"
	Altitude:	n/a
	Sampling Notes:	Taken from pipe pumping into dam from windmill
	Depth of borehole:	60
	Depth to water:	14m

Sample Name:	**B141**
Sample Type:	Borehole
Sample Season:	Feb 09
Location:	Noab
Location Description:	Windmill at the river
Latitude:	23° 54' 58.64"
Longitude:	016° 18' 24.37"
Altitude:	n/a
Sampling Notes:	Pumps with diesel pump.
Depth of borehole:	50m
Depth to water:	9m
Yield of borehole:	n/a

N/A

Sample Name:	**B142**
Sample Type:	Borehole
Sample Season:	Feb 09
Location:	Nauzuras
Location Description:	On boundary between nauzerus and Noab.
Latitude:	23° 51' 38.52"
Longitude:	016° 22' 26.00"
Altitude:	n/a
Sampling Notes:	Apparently Water undrinkable.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**B143**
Sample Type:	Borehole
Sample Season:	Feb 09
Location:	Nauzuras
Location Description:	Windmill north of the house at Nauzerus
Latitude:	23° 49' 8.90"
Longitude:	016° 20' 38.22"
Altitude:	n/a
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**P144**
Sample Type:	Precipitation
Sample Season:	Feb 09
Location:	Nauzuras
Location Description:	At farm house
Latitude:	23° 49' 8.90"
Longitude:	016° 20' 38.22"
Altitude:	n/a
Sampling Notes:	rainwater in collected in afternoon

N/A

Sample Name:	**B146**
Sample Type:	Borehole
Sample Season:	Feb 09, July 09
Location:	Lay-Bank
Location Description:	East Of Büllsport
Latitude:	24°07'15.1"
Longitude:	16°25'55.1"
Altitude:	n/a
Sampling Notes:	Got from borehole west of 3B108
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**W147**
Sample Type:	Well
Sample Season:	Feb 09, July 09
Location:	On blaubeker road from Lepel
Location Description:	none
Latitude:	23°53'48.1"
Longitude:	16°28'37.7"
Altitude:	n/a
Sampling Notes:	Bailed water from well
Depth of borehole:	n/a
Depth to water:	7.3m
Yield of borehole:	n/a

Sample Name:	**Büllsport-B01**
Sample Type:	Borehole
Sample Season:	March 08, June 08
Location:	Büllsport
Location Description:	A few km south of Büllsport
Latitude:	24°11'08.1"
Longitude:	16°23'43.2"
Altitude:	1403m
Sampling Notes:	Windmill pumps water into tank.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

N/A

Sample Name:	**Büllsport-B02**
Sample Type:	Borehole
Sample Season:	March 08
Location:	Büllsport
Location Description:	To the east of mountains
Latitude:	24° 07' 08.6"
Longitude:	016° 20' 43.6"
Altitude:	1382m
Sampling Notes:	Used bailer to sample water
Depth of borehole:	n/a
Depth to water:	16.35m
Yield of borehole:	n/a

N/A	**Sample Name:**	**Klipheuwel-B03**
	Sample Type:	Borehole
	Sample Season:	March 08, June 08, Feb 09, July 09
	Location:	Klipheuwel
	Location Description:	South of Bûllsport , Nabaseb
	Latitude:	24° 13' 04.5"
	Longitude:	016° 30' 42.6"
	Altitude:	1421m
	Sampling Notes:	Borehole situated in the middle of a kraal. Apparently cleanest water in village.
	Depth of borehole:	n/a
	Depth to water:	10.95m/none/6.1m/none
	Yield of borehole:	n/a

	**Sample Name:**	**Zais-B04**
	Sample Type:	Borehole
	Sample Season:	March 08, June 08, Feb 09, July 09
	Location:	Zais
	Location Description:	Well at the house
	Latitude:	24° 01' 36.9"
	Longitude:	016° 09' 09.8"
	Altitude:	1161m
	Sampling Notes:	Bailed the water out
	Depth of borehole:	n/a
	Depth to water:	14.15m/none/9.2m/12.5m
	Yield of borehole:	n/a

	**Sample Name:**	**Ababis-B05**
	Sample Type:	Borehole
	Sample Season:	March 08, June 08, Feb 09, July 09
	Location:	Ababis
	Location Description:	Next to the Tsondab river at the lodge.
	Latitude:	23° 58' 55.7"
	Longitude:	016° 05' 34.7"
	Altitude:	1080m
	Sampling Notes:	Bailed the water out, but was continuously pumping elsewhere.
	Depth of borehole:	n/a
	Depth to water:	7.48m/8.3m/7.2m/6.2m
	Yield of borehole:	n/a

N/A	**Sample Name:**	**Ababis-R06**
	Sample Type:	River
	Sample Season:	March 08, Feb 09
	Location:	Ababis
	Location Description:	Next to Ababis-B05, the Tsondab river.
	Latitude:	23° 58' 56.4"
	Longitude:	16° 05' 34.8"
	Altitude:	1080m
	Sampling Notes:	Water taken directly from stream.

N/A

Sample Name:	**Solitaire-B07**
Sample Type:	Borehole
Sample Season:	March 08, June 08
Location:	Solitaire Country Lodge
Location Description:	Borehole at the house
Latitude:	23° 53' 54.4
Longitude:	16° 00' 50.8
Altitude:	1079m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**NNL-B08**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Namib Naukluft Lodge
Location Description:	North of NNL-B09, generator
Latitude:	23° 58' 24.2"
Longitude:	15° 50' 35.2"
Altitude:	898m
Sampling Notes:	none
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**NNL-B09**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Namib Naukluft Lodge
Location Description:	Other side of Marble Mountain
Latitude:	23° 58' 46.5'
Longitude:	15° 51' 06.3'
Altitude:	911m
Sampling Notes:	Generator pumps water daily to the lodge
Depth of borehole:	±85m
Depth to water:	n/a
Yield of borehole:	15m^3/hr

Sample Name:	**NDL-B10**
Sample Type:	Borehole
Sample Season:	March 08, June 08, Feb 09, July 09
Location:	Namib Desert Lodge
Location Description:	On C19, next to abandoned petrol station
Latitude:	24° 07' 34.2"
Longitude:	15° 57' 25.4"
Altitude:	1046m
Sampling Notes:	Electrically driven pump.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**Solitaire-B11**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09, July 09
Location:	Solitaire Country Lodge
Location Description:	Solitaire, east of shop
Latitude:	23° 53' 36.8"
Longitude:	16° 00' 17.3"
Altitude:	1070m
Sampling Notes:	Water pumped through pvc pipe tens of meters. Pumped daily
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**Solitaire-B12**
Sample Type:	Borehole
Sample Season:	June 08
Location:	Solitaire Country Lodge
Location Description:	Solitaire, west of shop
Latitude:	23° 53' 37.4"
Longitude:	16° 00' 16.3"
Altitude:	1070m
Sampling Notes:	Water pumped through pvc pipe tens of meters. Pumped daily
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

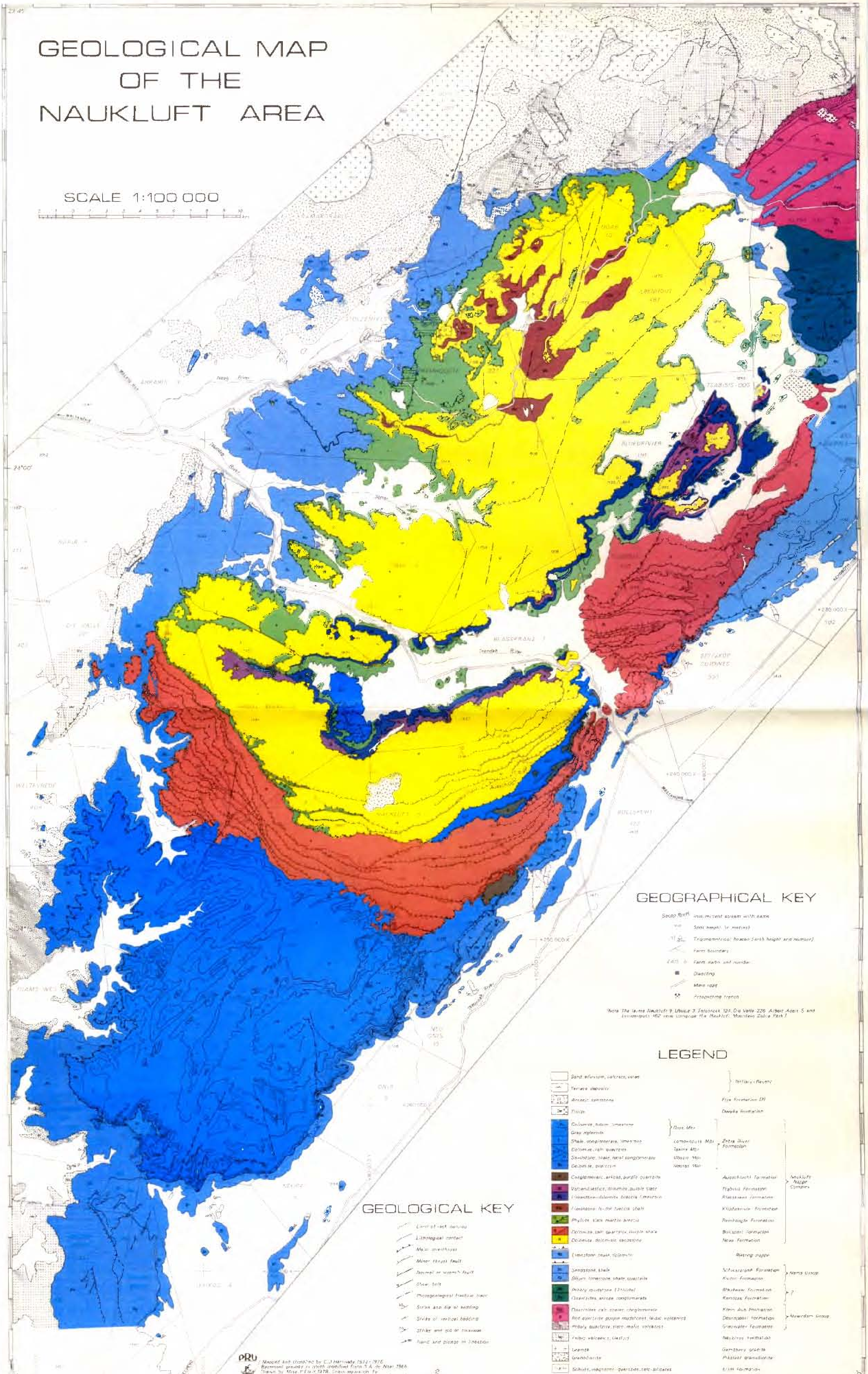
Sample Name:	**NNL-B13**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Namib Naukluft Lodge
Location Description:	South of Lodge, Escourt road
Latitude:	24° 02' 55.3"
Longitude:	15° 57' 37.2"
Altitude:	1072m
Sampling Notes:	Water sampled as water was entering tank from pipe.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Sample Name:	**NNL-B14**
Sample Type:	Borehole
Sample Season:	June 08, Feb 09
Location:	Namib Naukluft Lodge
Location Description:	South of Lodge Escourt Road
Latitude:	24° 02' 03.9"
Longitude:	015° 53' 37.2"
Altitude:	953m
Sampling Notes:	Water sampled as water was entering tank from pipe.
Depth of borehole:	n/a
Depth to water:	n/a
Yield of borehole:	n/a

Appendix 4: Geological Maps

GEOLOGICAL MAP OF THE NAUKLUFT AREA

SCALE 1:100 000



GEOGRAPHICAL KEY

Sesso River	Intermittent stream with name
	Spot height (in metres)
	Trigonometrical beacon (with height and number)
	Farm boundary
	Farm name and number
■	Dwelling
	Main road
	Prospecting trench

(Note: The farms Naukluft 9, Ubusis 3, Felsenrock 124, Die Valle 226, Arbeit Adelt 5 and Lemoenputs 162 now comprise the Naukluft Mountain Zebra Park.)

LEGEND

Sand, alluvium, calcrete, scree			Tertiary - Recent	
Terrace deposits				
Arkosic sandstone			[illegible] Formation (?)	
Tillite			Dwyka Formation	
Dolomite, tufaceous limestone	Onis Mbr	Zebra River Formation		Naukluft Nappe Complex
Grey dolomite				
Shale, conglomerate, limestone	Lemoenputs Mbr			
Dolomite, calc quartzite	Tsams Mbr			
Sandstone, shale, basal conglomerate	Ubusis Mbr			
Dolomite, quartzite	Neuras Mbr			
Conglomerate, arkose, purple quartzite		Aubschlucht Formation		
Volcaniclastics, dolomite, purple slate		Tsabisis Formation		
Limestone-dolomite breccia, limestone		Blasskrans Formation		
Limestone, ls-dol breccia, shale		Kliphoekrivier Formation		
Phyllite, slate, marble breccia		Remhoogte Formation		
Dolomite, calc quartzite, purple shale		Bullsport Formation		
Dolomite, dolomitic sandstone		Noab Formation		
Limestone, shale, dolomite		Dassie nappe		
Sandstone, shale		Schwarzrand Formation		Nama Group
Dolomite, limestone, shale, quartzite		Kuibis Formation		
Pebbly mudstone (?tillite)		Blaubeker Formation		?
Quartzites, arkose, conglomerate		Kamtsas Formation		
Quartzites, calc-shales, conglomerate		Klein Aub Formation		Rehoboth Group
Red quartzite, purple mudstones, felsic volcanics		Doornpoort Formation		
Pebbly quartzite, slate, mafic volcanics		Grauwater Formation		
Felsic volcanics, clastics		Nückopf Formation		
Granite		Gamsberg granite		
Granodiorite		Piksteel granodiorite		
Schists, magnetite-quartzite, calc-silicates		Elim Formation		

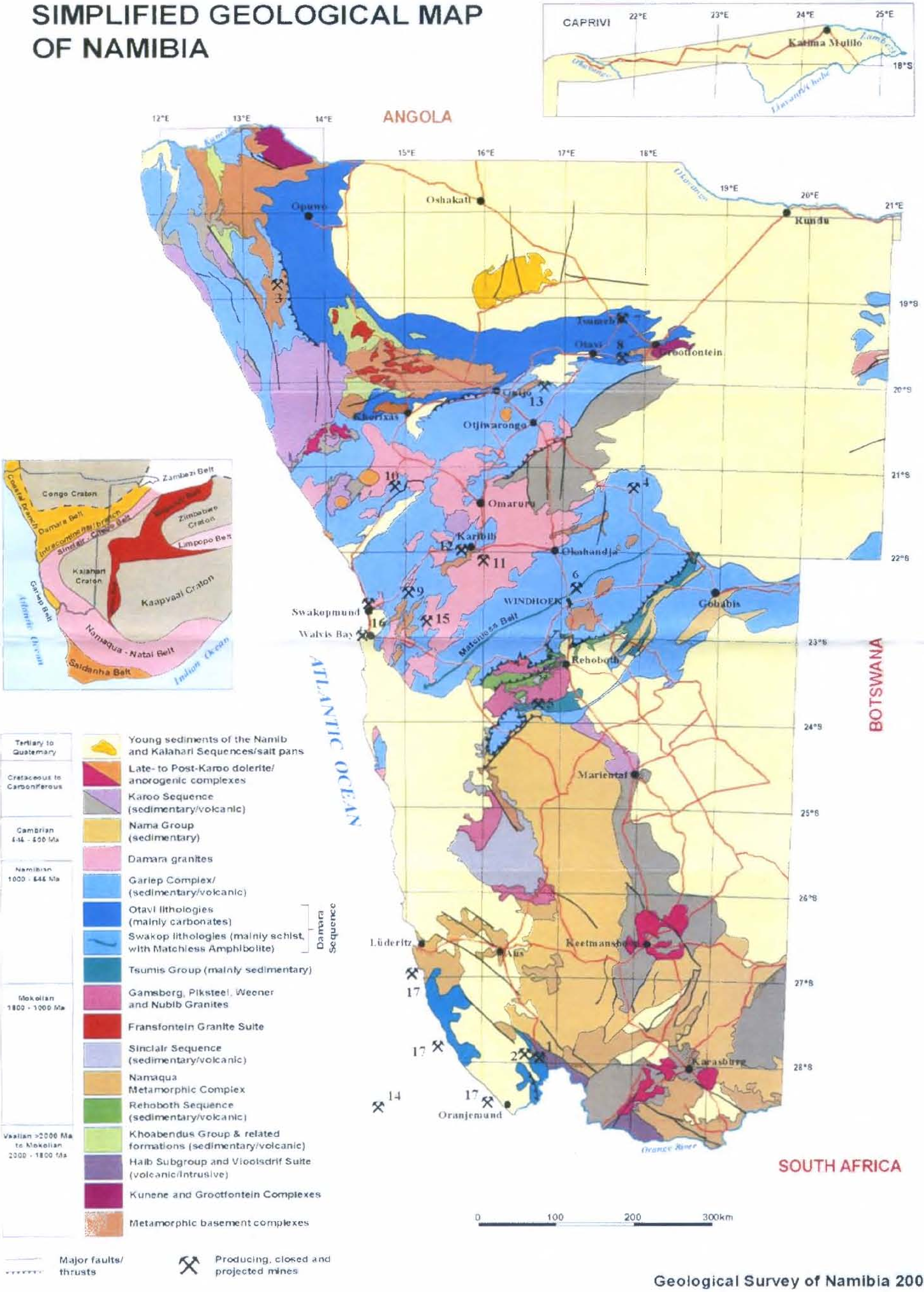
GEOLOGICAL KEY

	Limit of rock outcrop
	Lithological contact
	Major overthrust
	Minor thrust fault
	Normal or wrench fault
	Shear belt
	Photogeological fracture trace
	Strike and dip of bedding
	Strike of vertical bedding
	Strike and dip of cleavage
	Trend and plunge of lineation

PRU

Mapped and compiled by C.J. Hartnady 1972 - 1978.
Basement geology in north modified from S.A. de Waal 1966.
Drawn by Miss P. Clark 1978. Colour separation by
Miss R. Abrahams and Mrs D. Rouxs, 1980. Precambrian Research
Unit, Department of Geology, University of Cape Town.

SIMPLIFIED GEOLOGICAL MAP OF NAMIBIA



Geological Survey of Namibia 2005