REGIONAL TECTONOSTRATIGRAPHIC ARCHITECTURE OF THE OWAMBO BASIN AND REASSESSMENT OF ITS HYDROCARBON POTENTIAL

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Mtundeni Ndafyaalako

Student number: 200636979

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Supervisor: Dr. Ansgar Wanke (University of Namibia)

Co-supervisor: Raydel Toirac Proenza (Pioneer Oil & Gas cc)

ABSTRACT

The Owambo Basin is one of Namibia's two main onshore basins and is a significant target area for hydrocarbon exploration. Although exploration activities in the Owambo Basin commenced in the 1950s spanning more than 58 years, no commercial discovery of hydrocarbons has been made in this basin to date. Numerous hydrocarbon occurrences have been reported throughout the basin, and available geophysical data suggests the presence of both structural and stratigraphic signatures that may be associated with petroleum traps. However, the lack of critical understanding of the tectonic and stratigraphic framework in the context of the petroleum system has made it difficult to apply a systematic approach during previous hydrocarbon exploration activities in basin.

Analysis and interpretation of recently reprocessed vintage 2D seismic lines makes it possible to characterize the tectonostratigraphic domain of the Owambo basin, therefore allowing proper understanding of the petroleum system's evolution through time and hence the application of a systematic approach in hydrocarbon exploration.

Hydrocarbon trap formation is influenced by three main phases of deformations during the evolution of the Owambo Basin: (1) Rifting phase – rifting of the Rodinia continent that resulted in north-northwest-trending normal faulting in the metamorphic Precambrian basement; (2) Collision phase – Convergence and collision of the Kalahari Congo, and South America cratons that resulted in the Damara Orogeny; (3) Rift Phase - extensional faulting that resulted in the opening of the South Atlantic.

The tectonic events that were accompanied by the deformation in the Owambo basin led to the present tectonostratigraphic architecture of the basin. Three prominent sequences were deposited and are recognized on the seismic data: the Damara (Nosib

and Otavi and Mulden groups), Karoo and Kalahari sequences. Potential hydrocarbon significance has been recognized within these sequences such as source rocks (Otavi group – post-glacial deposition carbonates within the Abenab Subgroup and post glacial deposits and restricted intra-platform carbonates of the Tsumeb subgroup; Mulden group – black shales; Karoo supergroup – shales). Reservoirs are associated to the Otavi group carbonates, the Mulden group sandstones as well as the syn-rift sands in the deeper sections within the Nosib group.

Migration pathways and trapping structures related to the tectonic events as well as stratigraphic mechanisms have been recognized on the seismic data. Several leads have been mapped from magnetics and gravity data which may be potential trapping structures for hydrocarbon accumulations.

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LIST OF ABBREVIATIONS

MME:	Ministry of Mines and Energy
NAMCOR:	National Petroleum Corporation of Namibia
OML:	Otavi Mountainland
SRD:	seismic reference datum
TD:	total depth
TOC:	total organic carbon

UNITS

km:	kilometer
km^2:	square kilometer
m:	meter
Ma:	million years ago
ms:	millisecond

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DECLARATIONS

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CHAPTER 1

INTRODUCTION

The Owambo Basin is located in the northernmost portion of Namibia, extends northwards into the southern part of Angola and could possibly extend northeastwards into Zambia. This basin is geographically located between 14°-18°E and 19°S in Namibian territory and it is the largest basin in Namibia with an approximate area of up to 350,000 km^2. Some authors refer to the Owambo Basin as the Etosha Basin, perhaps associating the greater basin to the deepest depression within the Owambo Basin, the Etosha Pan. This name is somehow misleading because the Etosha Pan is only a small portion within the Owambo Basin.

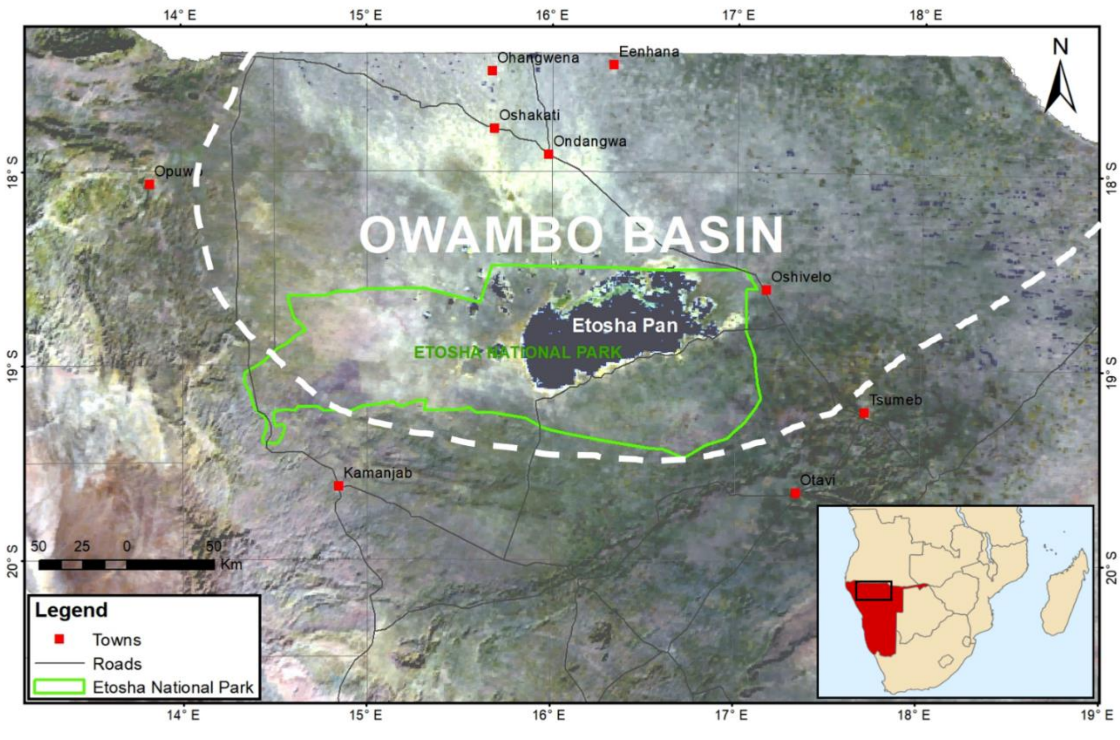


Figure 1: Location of the Owambo Basin in northern Namibia and southern Angola

The Owambo Basin is an intra-cratonic basin, resting on lower- to mid-Proterozoic metamorphic basement and containing as much as 8000m of late Proterozoic to recent sediments which include the Damara, Karoo and Kalahari Sequences (Miller, 1997).

Relief within the basin itself is less than 100m and thus relatively flat. According to Miller (1997), the lowest point of the Owambo Basin is within the Etosha Pan having an average elevation of just above 1000m, progressively rising towards the base of the rim - about 1150m in the southwest, 1250m in the west and 1200m in the south. The basin rims are characterized by a mountainous nature, reaching elevations of 1500-1700m within Angola and 1400-2100m in the western and southern rims within Namibia.

Although hydrocarbon exploration activities in the Owambo Basin commenced in the 1950s, this basin is still considered a modern frontier hydrocarbon basin with only one test of potential reservoir horizons. Past exploration efforts span more than 58 years, resulting in acquisition of about 2500km of 2D seismic, drilling of 5 exploration wells, 5 acquisition campaigns of aero gravity-magnetic data and at least two soil-gas sampling campaigns. However, no commercial discovery of hydrocarbons has been made in this basin to date.

The hydrocarbon potential of the Owambo Basin is deemed high although some risk is associated with the possible over-maturity of the source rocks and degradation of hydrocarbon accumulations (Martinez & Muundjua, 2012). Numerous hydrocarbon occurrences have been reported throughout the basin, and available geophysical data suggests the presence of both structural and stratigraphic anomalies that can be associated to petroleum traps. However, the lack of critical understanding of the tectonic and stratigraphic framework in the context of the petroleum system has made it difficult to apply a systematic approach during previous hydrocarbon exploration activities in basin. Analysis and interpretation of the recently reprocessed vintage 2D seismic lines makes it possible to characterize the tectonostratigraphic domain of the Owambo Basin, therefore allowing proper understanding of the petroleum system's evolution through time and hence the application of a systematic approach in hydrocarbon exploration.

1.1 Statement of the Problem

Previous hydrocarbon exploration campaigns have not met the required targets, largely due to limited incentives that are in turn related to limited information. Through the analysis of past exploration reports, it is evident that the main information shortage is the tectonostratigraphic framework. Enhancing this information and performing lead identification has the potential to revive the interest in the basin.

1.2 Objectives of the study

This research project aims to provide a basin-wide stratigraphic and structural characterization of the Owambo Basin from the point of view of hydrocarbon prospectivity within the basin. Emphasis has been on the recognition of foreland basin architecture relating to the Damara Orogeny and subsequent deformation phases, and the identifications of leads for associated hydrocarbon traps and migration pathways.

Specific objectives include the following:

(A) a seismic tectonostratigraphic characterization

(B) a structural characterization

(C) reassessment of the hydrocarbon potential

(D) creation of a leads inventory

1.3 Significance of the Study

Increased understanding of the Owambo Basin in terms of stratigraphic and structural architecture as well as performing leads identification will possibly revive exploration interest in the basin, potentially leading to new data acquisition and future drilling campaigns.

CHAPTER 2

LITERATURE REVIEW

2.1 Geological and Structural Setting

The Owambo Basin is an intra-cratonic basin resting on lower- to mid-Proterozoic metamorphic basement overlain by Proterozoic to Recent sediments which include the Damara, Karoo and Kalahari Sequences (Hedberg, 1979; Miller, 1997; Gray et al., 2008,; Hoak et al., 2014). The basement is formed by continental-scale oval-shaped cratonic nuclei, now preserved either as large inliers, namely the Kunene and Kamanjab inliers of the Congo Craton in northern Namibia and basement of the Kalahari Craton in the Southern Margin Zone of the Damara Belt (Gray et al., 2008).

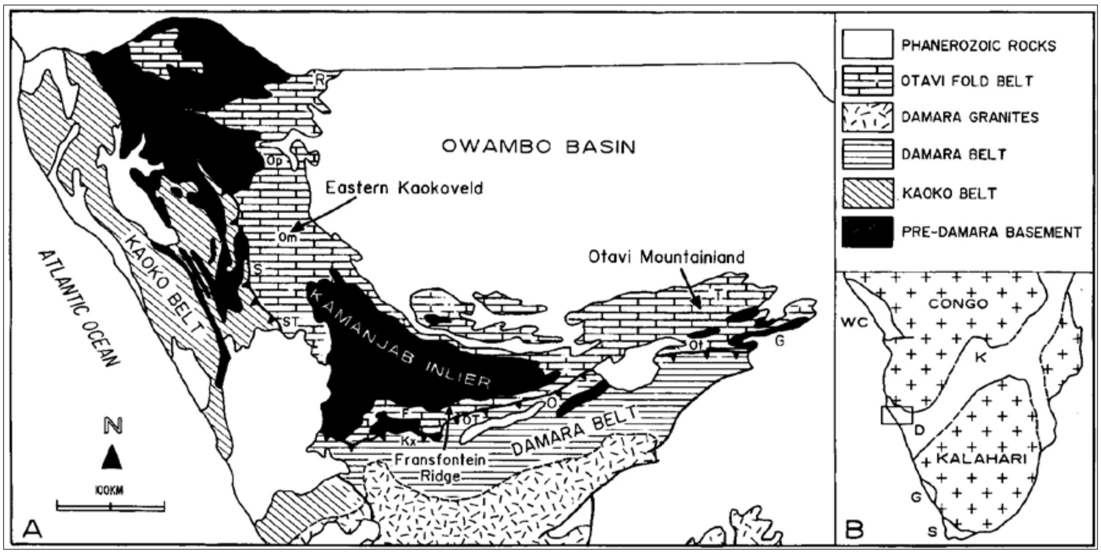


Figure 2: Present day location of the Owambo Basin in relation to the Damara and Kaoko Belts (Hoffman & Prave, 1996)

At the location of the present day Owambo Basin in northern Namibia, continental rifting occurred in the Late Neoproterozoic at about 780–740 Ma (Hoffman & Prave, 1996; Martinez & Muundjua, 2012) being associated with distinct volcanism, and the opening of the Khomas Sea forming the two conjugated margins of the Congo and Kalahari cratons. Overlying the rift sequence on both cratons, Otavi Group carbonates were deposited mainly represented by turbiditic greywacke (Gray et al., 2008).

According to Hoak et al. (2014), three main phases of deformations occurred during the evolution of the Owambo Basin that influence hydrocarbon trap formation: (1) Rifting phase – rifting of the Rodinia continent that resulted in north-northwest-trending normal faulting in the metamorphic Precambrian basement; (2) Collision phase – Convergence, closure of the Adamastor Ocean and collision of the Kalahari, South American and Congo cratons that resulted in the Damara Orogeny and the Kaoko Belt (Figure 3); (3) Rift Phase - extensional faulting that resulted in the opening of the South Atlantic. However, Martinez & Muundjua (2012) using the model in DeCelles & Giles (1996) suggested a fourth stage during (4) a stable back-bulge basin that accompanied the Karoo foreland basin system of the Cape Orogeny.

At present day, the basin is bound by fold-belts (Figure 2): to the west is the sinistral transpressional Kaoko belt (Gray et al., 2008; Martinez & Muundjua, 2012; Hoak et al., 2014), whereas to the south is the Damara Belt which is an assymetric doubly vergent orogen that formed during high-angle convergence between the Congo and Kalahari cratons (Gray et al., 2008). Dominant structural grain features have been mapped from Landsat images and surface geology supported by potential field data. (Gray, et al., 2008; Martinez & Muudjua, 2012; Hoak et al., 2014).

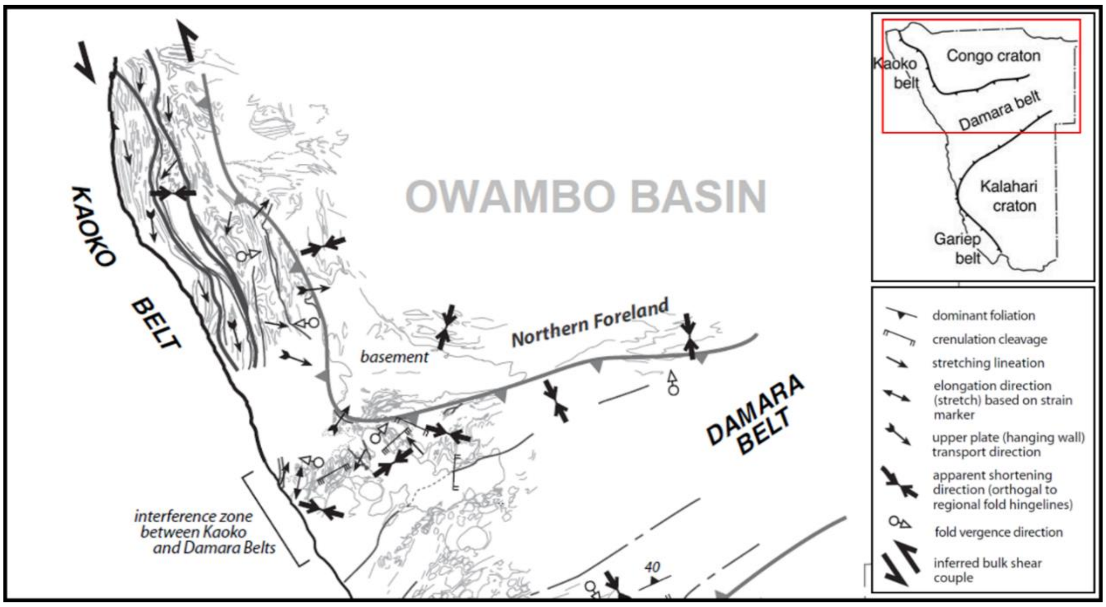


Figure 3: Map of the deformation kinetics of the Damara and Kaoko Belts in relation to the Owambo Basin (modified from Hoffman & Prave, 1996)

2.2 Geology and Stratigraphic Framework of the Owambo Basin

2.2.1 Damara Sequence

The Owambo Basin deposition was initiated by intracontinental rifting approximately 900 Ma ago with the deposition of the fluviatile Nosib Group consisting of sandstones, mixtites and conglomerates reaching a maximum known thickness of some 1383m (Hedberg, 1979; Miller, 1997; Gray et al., 2008; Hoak et al., 2014). Deposition of the entire Damara Sequence is thought to have spanned the Neoproterozoic between at least 770 and 600 Ma (Gray et al., 2008).

Rifting was followed by spreading to the south and west of the present day Owambo Basin. The Owambo Basin area became a stable platform on which the Otavi Group carbonates were deposited between 730 and 700 Ma (Hedberg, 1979; Miller, 1997; Martinez & Muundjua, 2012). The Abenab (Berg Aukas, Gauss and Auros Formations) and Tsumeb (Maieberg, Elandshoek, Schwarzrand and Hüttenberg

Formations) Subgroups represent two cycles of platform carbonate deposition separated by the widespread glacial episode represented by the tillites and iron formation of the Chuos Formation (part of the Tsumeb Subgroup). The position of the Chuos glaciogenic unit is disputed: Hedberg (1979), Miller (1997), Miller (2008) and Hoak, et al. (2014) place it between the Abenab and Tsumeb Subgroups while both Bechstädt, et al. (2009) and Martinez & Muundjua (2012) place it within the lower Nosib. On the other hand, Bechstädt, et al. (2009) and Martinez & Muundjua (2012) describe a second glacial unit aged about 635 Ma, the Ghaub diamictites, and place it at the beginning of the Tsumeb Subgroup, while the other authors did not describe this unit. The Abenab and Tsumeb Subgroups achieve maximum known thicknesses of 1915m and 5700m respectively (Miller, 1997). The carbonates of the Damara Supergroup pose as potential reservoir and source rocks while parts of the glacial intervals are potential source rocks.

The closure of the oceans south and west of the Owambo Basin and the subsequent continental collision of the Damara Orogen led to uplift and erosion south and west of the Owambo Basin (Gray et al., 2008) and as a result the Mulden Group molasse was deposited unconformably on the Otavi Group carbonates between 650 and 600 Ma (Gray et al., 2008; Martinez & Muundjua, 2012). The Mulden Group (Tschudi, Kombat and Owambo Formations) is dominated by shales and siltstones and contains minor black shales (Kombat Formation) and carbonates (Owambo Formation) (Hedberg, 1979; Miller, 1997; Miller, 2008). The Mulden Group and the underlying stratigraphy were subsequently folded to produce the uplifted southern and western basin edges as they are observed today. According to Miller (1997), the Mulden Group reaches a maximum known thickness of 5223m. The presence of potential sandstones reservoirs, source rocks (black shales) and shale seals within the Mulden Group indicate its hydrocarbon potential (see Figure 6).

2.2.1.1 The Nosib Group

As described by Miller (1997), the Nosib Group sediments were deposited as a molasse during intracontinental rifting, which commenced the development of the northeast-trending branch of the Damara Orogen. Hedberg (1979) has observed outcrop relationships along the southern and western basin margins, and interpreted that the Nosib Group was deposited into syntectonic grabens during early rifting. Deposition of the Nosib Group is suggested to have commenced at about 900 Ma and was completed by about 730 Ma (Miller, 1983). During this period, deepening may have gradually occurred, as according to Miller (1983), the Kaoko Belt which is the north-trending mobile belt to the west, is believed to have been a deep-water basin (Adamastor Ocean) by the end of Nosib deposition.

The Nosib Group is composed of interbedded marine and continental clastics with minor carbonates (Hoak et al., 2014). Two formations are distinguished within the Nosib Group: the Nabis Formation which is laterally extensive and the top laterally-limited Varianto Formation. However, this inclusion of the Varianto Formation within the Nosib Group is disputed.

2.2.1.2 The Nabis Formation.

The Nabis Formation is siliciclastic, mainly made up of an upward-fining succession of conglomerate and feldspathic sandstone with local lenses of phyllite (Bechstädt, et al., 2009; Miller 1997). The Nabis Formation is laterally extensive and is made of massive, largely clast-supported, basal conglomerate reaching 280m in thickness, although it reaches an approximate thickness of 400m in the Otavi Mountain Land area (Miller 1997; Miller, 2008), while pinching out to the east. This unit contains subangular-subrounded pebbles and cobbles of quartzite, granite and gneiss set in a grey-maroon feldspathic, gritty to coarse-grained sandy matrix (Miller 1997; Miller, 2008).

In the northwest, the Nabis Formation contains clasts whose size decreases towards the upper section. In most places, the grade of the basal conglomerate increases upwards, going through an interbedded transition zone into medium to coarse-grained, moderately to poorly sorted buff to light reddish brown sandstone for example at Otjovazandu, reaching a thickness of up to 1000m (Miller, 1997; 2008). Up to 20% of the sandstone section is made up of local grit and conglomerate lenses. Miller (1997) suggested that these lenses decrease in both thickness and quantity upwards; while the pebbles in these conglomerates (mainly quartzite) also decrease in size upwards.

The sandstones can be distinguished as lithic arenite and feldspathic greywacke to arkose, feldspathic sandstone and quartzite. The sandstones present a thin to massive and lenticular bedding, cross-bedding and floating pebbles (mainly quartzite, minor granite and schist) that make up around 1% of the rock, decreasing in quantity upwards. As far as bedding is concerned, planes and foresets are defined by heavy mineral laminae (Miller, 1997; 2008).

Upward the unit, the sandstone becomes medium to very fine grained and sorting improves, while both, bedding and grain size decrease (Miller, 1997; 2008). Quartz grains are subangular to subrounded whereas feldspar, mainly K-feldspar, is observed to be subrounded in thin section. Minor constituent of fine grained white mica, magnetite and hematite make up between 1 to 10% of the rock (Miller, 1997; 2008).

Depositional environment of the Nosib Group: Conglomerates have been derived from the basement that underlies the Nosib Group (Miller, 1997; 2008). Miller (1997) is of the opinion that the upward fining corresponds to erosion of initial basement highs, a time-transgressive basal contact, a gradual moderation of relief, and infilling of depressions. The poor sorting, cross-bedding, heavy mineral laminae, the high labile content and the general absence of shales/phyllite and carbonates suggest continental conditions (Hedberg, 1979). Diamictites with lenticular intervals of laminated iron formation indicate a fluviatile environment (Hoffmann & Prave, 1996).

2.2.2 The Otavi Group in the Otavi Mountainland (OML)

As described by Martinez & Muundjua (2012), the Otavi carbonates were deposited in a shallow carbonate ramp platform as part of the southern passive continental margin of the Congo Craton, during a predominantly extensional tectonic regime. Miller (1997) suggests that the contemporaneous sea-floor spreading (where today's central part of the basin is located) could have lasted from about 730 Ma to 700 Ma. Both Miller (1997), Bechstädt et al. (2009) and Hoffmann & Prave (1996) coincide with Martinez & Muundjua (2012), describing that the Otavi Group was deposited on the stable northern platform of the Khomas Sea simultaneously as the south evolved from intracontinental rifting through a phase of spreading into a narrow deep-water ocean with a mid-oceanic ridge. Overlying the rift sequence on both Congo and Kalahari cratons, Otavi Group carbonates were deposited mainly as turbiditic greywacke on the slope and deeper areas; and as autochtonous platform carbonates (Gray et al., 2008). According to Miller (1997), the thickness of the Otavi Group carbonates reach up more than 5000m and represent a deposition time span of about 200 Ma (Hoffmann & Prave, 1996).

The group is subdivided into the underlying Abenab Subgroup (which contains the Berg Aukas, Gauss and Auros Formations) and the overlying Tsumeb Subgroup (which contains the Maieberg, Elandshoek and Hüttenberg Formations). The subgroups are separated by the Ghaub Formation which is a well-known carbonate clast-rich diamictite, commonly referred to as the Otavi tillite. It is worth noting that this Ghaub formation replaces the old SACS (1980) nomenclature of Chuos Formation placed at the base of Tsumeb subgroup, renaming it to Ghaub Formation after the Ghaub 47 farm near the area from which it was first described (Hoffmann & Prave, 1996).

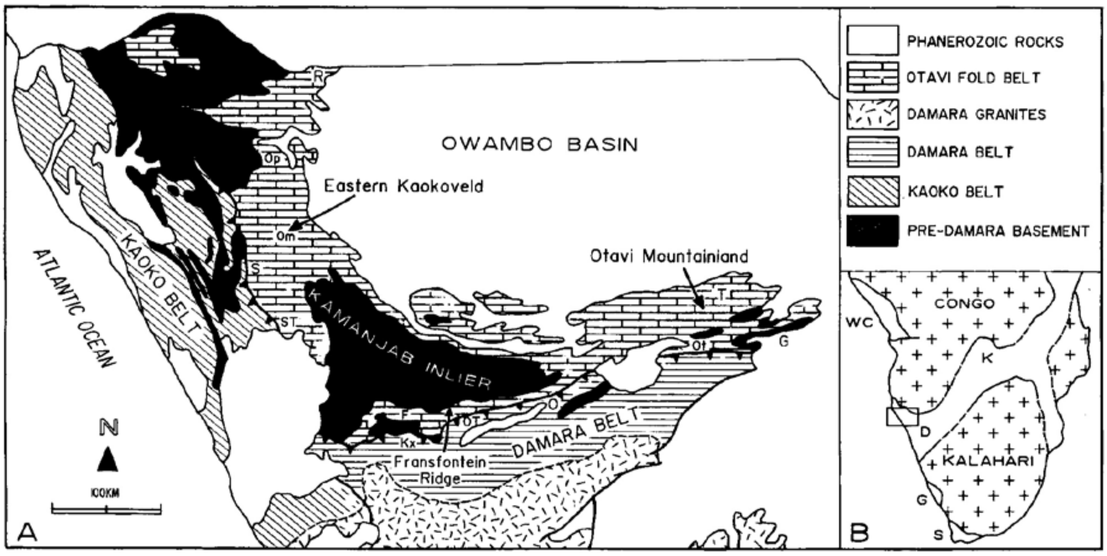


Figure 4: Map of northern Namibia showing distribution of the Otavi Group (Hoffmann & Prave, 1996)

2.2.2.1 The Abenab Subgroup

The Abenab Subgroup overlies the Nosib Group with a slight angular unconformity (Miller 1997; 2008) and is subdivided into the following formations from bottom to top by Hoffmann & Prave (1996) and Miller (2008): *Chuos Formation* (referred to as

Varianto Formation in Hoffmann & Prave (1996), was previously regarded as part of the Nosib group), *Berg Aukas Formation*, *Gauss formation* and *Auros Formation*.

2.2.2.1.2 Chuos (Varianto) Formation

Hoffmann & Prave (1996), in contrast to most other authors regarding the placement of the Chuos Formation within the Nosib Group (for example Miller (1997) and Martinez & Muundjua (2012), proposed that since the diamictites are separated from underlying rocks by a regional unconformity, the Chuos Formation should therefore be included in the lower Otavi Abenab Subgroup. In this thesis,the name *Chuos* will be adopted instead of *Varianto* following Miller (2008) and Hoak et al. (2014).

The Chuos Formation is the lower glacial interval represented by local diamictite and an associated iron-formation within the Otavi Group (Hoffmann & Prave, 1996; Miller, 2008). The diamictite reaches a maximum thickness of 130m, unconformably overlying the Nabis Formation in the central and western OML and, but is absent in the southern and eastern Otavi Mountains (Hoffmann & Prave, 1996). This unit consists of massive or crudely stratified diamictite that contains dispersed, rounded, pebble- to boulder-sized basement clasts originated from the underlying Nabis Formation (Hoffmann & Prave, 1996). The lower part of the Chuos Formation, according to Miller (1997), is made up of very poorly sorted, pebbly shale and conglomerate with a sandy, highly ferruginous argillaceous matrix but somehow better sorted interbeds of feldspathic grits, arkose, laminated shale and siltstone are also observed. Hoffmann & Prave (1996) have observed that lenticular intervals of laminated iron formation contain isolated dropstones therefore providing clear evidence that this diamictite is of glacial origin.

2.2.2.1.3 Berg Aukas Formation.

The Berg Aukas Formation is generally between 100-200m in thickness and is dominated by basal laminated and banded grey cap dolostone (Hoffmann & Prave, 1996; Miller, 2008) which is thought to have been deposited during the massive flooding event that followed the Chuos glaciation. Elsewhere, it consists of two facies: dark grey dolomite with stromatolitic reef facies and associated debris, as well as light grey, well bedded to laminated, dolomite packstone ranging from fine to coarse grained texture (Miller, 2008). The upper part of this formation consists of black to dark grey banded and laminated dolostone rhythmite that reaches at least 75m in thickness (Miller, 2008).

2.2.2.1.4 Gauss Formation.

The Gauss formation dominantly consists of massive very fine grained white to medium grey locally thinly bedded and laminated dolomicrite that reaches up to 1200m near Farm Gaus (Miller, 2008). Stromatolites and small-scale slump structures have been observed to occur locally, while crackle brecciation of the upper part of the formation is common. Towards the top, an oolite layer up to 1m thick commonly occurs.

2.2.2.1.5 Auros Formation.

The Auros Formations is composed of three to four upward-shallowing cycles of shale horizons interbedded with limestone and dolomite layers (Beukes, 1986; Miller, 2008). Most of the dolomites and limestones in this unit are mudstones, containing oolitic layers especially towards the upper part of the formation. Miller (2008) describes that the upward shallowing of the Auros Formation was caused by four periods of rapid transgression followed by gradual regression, with each cycle ending in stromatolitic tidal flat facies.

At some locations, the overlying Ghaub glacier scouring had cut deep into Auros Formation, rendering it completely absent at times (Miller, 2008).

***Depositional environment of the Abenab Subgroup*:** Local slumping structures, pinching out of basal formations and presence of clastic carbonate beds suggest deposition in post Nosib relief and marine transgression over an irregular surface. Clastic abundance in the western margin suggests uplift along that margins which caused an influx of terrigenous material. Rapid facies changes suggest variable depositional environments: limestones – brackish marine conditions; thin bedded laminated dolomites with scarce stromatolites – quiet saline intermediate depth water; oolites in the upper section of the Gauss Formation – shallow marine conditions; thin bedding, oolites and stromatolites in the Auros Formation – extensive quiet shallow conditions; interbedding of shale, limestone and dolomite – alternating open and restricted marine conditions with salinity changes (Miller, 1997).

2.2.2.2 The Tsumeb Subgroup

The base of the Tsumeb Subgroup is formed by the highly calcareous Ghaub Formation, (principally composed of tilite, pebbly shale and siltstone) which is the younger one of the two glacial units within Otavi Group (Miller 1997; 2008). Overlying the Ghaub Formation are pinkish to light grey laminated dolostone, laminated micritic limestone and banded marl to light grey dolomite mudstone of the Maieberg Formation. Upwards follows the Elandshoek Formation, comprised of massive grey dolomite and stacked cycles of well bedded grey dolomite (Miller 2008). The top of the Tsumeb Subgroup forms the Hüttenberg formation, consisting of medium to thinly bedded dolomite with chert layers deposited conformably on the Elandshoek Formation. As it appears in Miller (2008), the Tsumeb Subgroup divides into eight units from T1 to T8 based on lithology: T1 – diamictite, T2 – laminated micritic limestone, T3 – bedded, banded finely laminated dolomite, T4 – massive dolomite, T5 – well-bedded dolomite, T6 – dolomite with chert layers, T7 – bedded carbonaceous dolomite and T8 – dolomite and chert.

2.2.2.2.1 Ghaub Formation.

The Ghaub Formation cuts unconformably through the underlying Auros and Gauss formations, reaching up to 2000m of thickness in the western Otavi Mountainland but thinning out and probably absent in the eastern side (Miller 1997; 2008). It consists of diamictite (composed of 95% unsorted dolomite, limestone and quartz clasts), conglomerate, minor shale, sandstone and dolomite (Miller, 2008). The Ghaub formation is referred as to as T1 according to the lithological units division within the Tsumeb Subgroup mentioned to in the preceding paragraph.

2.2.2.2.2 Maieberg Formation

The Maieberg Formation's *Keilberg Member* forms the cap carbonate to the underlying glaciogenic Ghaub Formation. Where the glaciogenic unit is absent, this unit lies with a sharp contact on the underlying rocks, reaching a maximum of 1800m of thickness on farm Harasib 317 (Miller 2008). This unit is composed of laminated to massive pinkish to grey dolostone containing thin vertical tubes filled with quartz, dolomicrite and sparry carbonate. Where the Ghaub Formation is absent and the Maieberg Formation overlies the Auros Formation, the narrow vertical columns of stromatolites can be observed on either side of these vertical tubes, perpendicular to the bedding. When it directly overlies the Ghaub formation, the stromatolites seem to be absent (Miler 2008).

The upper portion of the Meieberg Formation is made up of laminated micritic limestone (T2) and bedded, banded finely laminated dolomite (T3). These two lithological units interfinger and grade into one another in places and the contacts between them can be observed to be either sharp, gradational or arbitrary (Miller, 1997; 2008).

Miller (2008) further noted that the T2 limestone consists of laminated micritic limestones with thin interbeds of shale or marl laminae; sometimes literally grading into dolomite. The upper parts of this unit have been have undergone karstification. There are no stromatolites or algal columns in the T2, unlike in the *Keilberg Member* below it.

According to Miller (1997; 2008) the T3 consists of bedded, banded finely laminated dark to medium dolomite mudstones and finely grained packstones. Miller (2008) further observed that at the base, the dolomite is often brecciated during deformation due to ductility contrast between it and the underlying limestone. In some parts, clasts cemented with fibrous isopachous cement of dolomicrite have been documented.

2.2.2.2.3 Elandshoek Formation

The Elandshoek Formation lies conformably on the T3 dolomite. This unit is mainly composed of extensively karsted, massive, uniform light grey dolomite (T4 and T5), reaching up to 1.5km in thickness (Miller 1997; 2008). The Elandshoek Formation makes up most of the relief in the Otavi Mountain Land.

Miller (2008) also noted that the T4 unit is composed of a massive light grey dolomite with layers of laminated dolomite. At some places, brecciation that appears to be slump related have been observed. The T5 marks the beginning of a second depositional megasequence consisting of uniform well stacked cycles of well bedded, medium to light grey dolomite mudstone and grainstone, with layers of massive dolomite.

2.2.2.2.4 Hüttenberg Formation

The Hüttenberg Formation includes the T6, T7 and T8 lithological units (Miller, 1997; 2008). The T6 overlies the Elandshoek Formation conformably, reaching thicknesses of up to 800m in in the OML and about 300m near Tsumeb. It is mainly composed of light to medium grey thinly bedded dolomite with numerous white, grey and pink (mm to 2m thick) algal chert layers. Miller (2008) observed that the lower part of the T6 contains three stromatolitic zones that begin with wavy to domal stromatolites transforming upwards into unlinked or linked branching stromatiolites, sometimes conically shaped.

The following lithological unit within the Hüttenberg Formation is the T7 dolomite. It consists of "dark grey, bedded, carbonaceous, dolomite mudstone or grainstone or alternating layers of grey dolomite mudstone or grainstone with subordinate limestone mudstone" (Miller, 2008). Minor chert bands and shale layers are also present in the T7.

As described by Miller (2008), the T8, the top unit, mainly consists of light grey massive to medium-bedded dolomite mudstones and packstones with interbedded oolite-oncolite beds with wavy stratiform, domal, bulbous and columnar stromatolites. There is at least about 30m of dolomite with chert layers.

***Depositional environment of the Tsumeb Subgroup*:** Considerable vertical relief that have aided early submarine erosion and slumping is suggested by the presence of local conglomerates, clastic grains and beds and the contorted laminae. The high content of argillaceous material in the limestones is evidence of quiet-water deposition in a basin situated far from a terrigenous source. Abundant presence of algal mats and stromatolites, clastic grains and oolitic layers in the Elandshoek Formation points to a progressive decrease in water depth in the basin. This shallowing should have continued through to the end of Otavi Group deposition as evidenced by the abundance of stromatolites in the lower parts of the Hüttenberg Formation in the upper parts (Miller, 1997; Martinez & Muundjua, 2012). Varying salinities and possibly local lagoonal conditions should have caused the deposition of limestones and thin shales in the upper parts (Martinez & Muundjua, 2012).

2.2.3 The Mulden Group

The cease of spreading (passive continental margin) between the Kalahari and Congo cratons was marked by the beginning of plate convergence and the generation of the subduction zone to the southern boundary of the passive continental margin of the Congo Craton, with associated volcanic activity. The oceanic crust of the Khomas Sea was consumed in this way, and later the collision of the conjugated passive margins of Congo and Kalahari cratons began (Miller, 1997; Hoak, et al., 2014; Gray et al., 2008; Martinez & Muundjua, 2012).

This collision formed the Damara Belt. In addition, because of the triple collision between Sao Francisco, Congo and Kalahari cratons, the Kaoko and Gariep belts were also formed (Gray et al., 2008).

The Mulden Group is a northern syntectonic molasse that was deposited during Damara orogen the deformation (Miller, 1997; Miller, 2008; Hoak, et al., 2014; Gray et al., 2008; Martinez & Muundjua, 2012). According to Miller (1997) the Mulden Group sediments were derived largely from the Kaoko Belt to the west, and were folded together with the underlying Otavi Group rocks during the final major deformation event in this region.

Three formations make up the Mulden Group: Tschudi Formation, Kombat Formation and the Owambo Formation.

2.2.3.1 Tschudi Formation

Miller (1997; 2008) describes the lower Tschudi formation in the eastern area as being composed of 30m of dark grey shales, slates, feldspathic greywackes, marls and quartzite. In the Tsumeb area, the same author describes two 2m thick conglomerate layers consisting of angular, light grey dolomite fragments set in a sericitic to marly sandstone matrix (Miller, 2008). This unit where shale predominates was drilled in Etosha 5-1A Well (See location of Wells in Figure 8)..

The upper Tschudi Formation is a thicker, upward-fining succession that consists of light grey arkoses, feldspathic sandstones and feldspathic greywackes. It is thought to reach a maximum thickness of approximately 800m in the OML (Miller, 2008) but well data from Etosha 5-1A Well shows that at least 1000m of lower Tschudi Formation was drilled.

2.2.3.2 Kombat Formation

This formation consists of sandstone, grey to black shale, siltstone and phyllite. In the Otavi valley, tightly folded dark grey phyllites and silty sandy phyllites overlie the Tschudi Formation. Miller (2008) relied on seismic data to subdivide this formation into three parts: a Lower Kombat Formation, a middle Black Shale Member and an Upper Kombat Formation. Within this three parts are four upward-fining cycles of largely fine-grained terrigenous clastic rocks that have been intersected by the 5-1A and 1-1 wells.

The Lower Kombat Formation is more of an upward-fining transition from the underlying Tschudi Formation. The Lower Kombat Formation consists of interbedded sandstones and siltstones and it reached a thickness of 300m in the 1-1Well (Miller, 1997; 2008). An overlying light to medium grey siltstone follows, that darkens and becomes more argillaceous upwards. There also exist minor grey to brown shales.

The Black Shale Member was penetrated in both, the 5-1A and 1-1 Wells, with a recorded thickness of about 93m (Miller 2008), while in well ST-1 it is believed to be several hundred meters below the well TD. It is characteristic in terms of its seismic reflection and is highly distinctive in the electronic logs, thus being a good marker within the Mulden Group. About 50m of the lower part consist of black to very dark grey, almost silt-free shales that form the top of the lowest upward-fining cycle of the Kombat Formation.

The Upper Kombat Formation consists of four upward-fining cycles of grey, green-grey and green sandstone, siltstone and shales that was recorded to reach 400m thickness in Well 1-1, where the shales account for 150m of this thickness (Miller, 1997; 2008). In the ST-1Well, the upper Kombat Formation reached 217m in thickness.

2.2.3.3 Owambo Formation

The first sandstone with extensive red coloration marks the Owambo formation, being 908m thick in the 1-1 Well and 1490m thick in ST-1 Well (Miller, 2008). Miller (1997) distinguishes three units in terms of coloration encountered in ST-1, 5-1A and 1-1 wells: the lower and upper red and grey unit, and the middle grey and black. However, the upper red and grey unit was not encountered in wells 5-1A and 1-1. This upper unit consist of several fining-upwards clastic rocks cycles capped by dolomite or limestone.

Depositional environment of the Mulden Group**:** The Mulden Group is largely composed of syntectonic mollasse sediments largely derived from the Kaoko Belt (Miller, 1997). The carbonate and chert rock fragments in conglomerate present in Tschudi Formation towards the west as well as the abundance of similar lithic grains in underlying siltstones suggest that provenance of the lower Tschudi Formation is largely from the underlying Otavi Group carbonates rocks. Abundant siltstones and shales in the lower Tschudi Formation suggest either limited sediment sources (probably lack of uplift) or distant sediment sources with quiet deposition conditions. The arkoses at the base of the upper Tschudi Formation suggest deposition during increased uplift and granite denudation. According to Hedberg (1979), the continuous upward fining of the upper Tsudi Formantion represents a period of controlled stabilization resulting either from progressive reduction of relief or larger transport distances.

The Kombat and Owambo formations are composed of finer grained sediments, suggesting either less rapid denudation or greater sediment transport distances. Sediment colors suggest continental basin deposition, probably in early stage reducing conditions (dark grey to black colors), being succeeded by alternating oxidizing and reducing conditions .

Carbonate deposition at the end of the Mulden Group suggests decreased supply of terrigenous material and reducing conditions.

2.2.4 Karoo Sequence

Following quiescence and extensive erosion, parts of the Owambo Basin were covered by lower Permian glacial, fluvio-glacial and subsequent Lower Jurassic deposits of the Karroo Sequence (Dwyka, Prince Albert and Etjo Formations respectively), as described by Hedberg (1979). In the eastern part of the basin these were overlain by the Jurassic basalts of the Kalkrand Formation. The entire Karroo Sequence is known to reach thicknesses up to 606m in the Owambo Basin (Miller, 1997; Martinez & Muundjua, 2012).

At the base of the Karoo Supergroup is the Lower Permian-age Dwyka Formation, which consists predominantly of tillites with thin interbedded shales, dolomitic siltstones, limestones and sandstones (Miller, 2008). The Dwyka tillite appear as isolated outcrops filling westward-flowing glacial valleys in the western rim of the basin (Miller, 1997). The Dwyka Formation is overlain by the Prince Albert Formation that consists predominantly of black carbonaceous shales in the lower section as well as alternating dark shales and light to greenish grey fine-grained silty and argillaceous sandstones. Both Hugo (1969) and Miller (2008) reported limited occurrences of Karoo coal, but are of the opinion that these are not sufficiently thermally mature to produce oil or gas. The upper part of the Karoo sequence consisting of flood basalts (Etendeka) and aeolian sandstones (Etjo Formation) are believed to be absent or of limited extent in the central part of the Owambo Basin (Hugo, 1969).

In the south of the basin, aeromagnetic data suggest that the Karoo Sequence is truncated by a northeast-trending fault while to the east, this group's rocks may be cut by a north-south trending fault. Continuous nearly horizontal seismic reflectors observed on the 2D seismic suggest that the Karoo Supergroup has been deposited on an extremely uniform post-Damara erosion surface.

2.2.4.1 The Dwyka Formation

The Dwyka Formation is mainly of tillite of which 158m were intersected in the Beiseb well. According to Miller (1997), clasts within this unit consist of reddish brown and white quartzite, granite, gneiss, vein quartz, siltstone, light green shale, chert, diorite, and white and grey dolomite and limestone. These clasts have an average size of 1-3cm in size (but reaching 10cm across), and are set in a matrix of grey, massive, sandy mudstone. Thin, dark grey to black, laminated pyritic shales (some of the shales are varved), dolomitic siltstones and local limestone interbedded with the tillite are also present.

In the Opuwo area, the Dwyka tillite is overlain by 100m of tan to green-grey, very thinly bedded shales and mudstones with a discrete and very consistent 2-4mm lamination.

2.2.4.2 The Prince Albert Formation

The Prince Albert shales conformably overlie the Dwyka tillite and are divided into a lower shale member, a middle shale and sandstone member and an upper carbonaceous shale member (Miller 1997). The black carbonaceous dolomitic and micaceous shale and siltstone have been drilled in the Owambo Basin wells and are found to either be superimposed by conglomerate (in ST- l) or interbedded with limestone (in Beiseb). These beds are in turn followed by dark grey to black micaceous, calcareous to dolomitic, carbonaceous, pyritic shales with minor siltstone and rare limestone interbeds. Maximum thickness of the upper member was 119m in the Okasnanakana well (Miller, 1997).

The middle shale and sandstone member reaches 100m is ST-1 well and consists of alternating shales similar to those in the lower member and light to greenish grey, fine-grained, silty and argillaceous sandstones. This unit is made up of up to 30% sandstone.

The upper carbonaceous shale member consists mainly of light to dark grey and black shales (predominantly pyritic), siltstones and sandstones, reaching a thickness of up to 65m. This unit contains coal fragments and rare pebbles, cross-bedded in places and have occasional small-scale channel structures. Interbedded lenses and beds up to 7m thick of low grade coal is present. Traces of uranium were found in ST-1, Beiseb and Okasnanakana Wells.

2.2.4.3 The Etjo Formation.

The Etjo Formation was intersected in the Nanzi Well, where it reaches a thickness of 137m. According to Miller (1997), this formation is characterized by hard, light grey to buff colored and is well-bedded sandstone that overlies unconformably the Prince Albert and Owambo Formations in the central and north-western parts of the Owambo Basin. In the Nanzi well, these sands directly overlie the deeply weathered sub-outcrop of the Owambo Formation, occurring between the depths of 257 and 394m.

Absence of Middle Permian to Lower Triassic aged rocks that should have been expected to form the upper apart of the Karoo section has been noted in the Owambo Basin. Miller (1997) suggests that they have been removed by post-Karoo erosion. However, the same author notes the absence of features suggesting significant erosion and therefore there appears to be no evidence for such erosional phase, rather a non-erosional hiatus. Since (1) there are no deep incision valley, (2) no clastic wedges containing abundant fragments of recognizable Karoo, and (3) no unconformities, it has been suggested that this absence of Middle Permian to Lower Triassic sediments can be attributed to non-deposition.

***Depositional environment of the Karoo Supergroup*:** The Dwyka tillite is a glaciogenic unit, whose glacial valleys in the west suggest that ice movement should have been from east to west in northern Kaokoland and from northeast to southwest in southern Kaokoland. Since this tillite contains granitic clasts, the ice sheet must have extended north of the Owambo Basin into eastern Angola where granitic clasts must have been sourced.

The coals of the Prince Albert formation suggest prevailing postglacial fluvio-deltaic conditions during that time.

2.2.5 Kalahari Sequence

From the Cretaceous to the present, semi- to unconsolidated continental aeolian sands and lacustrine clays of the Kalahari Sequence have blanketed the entire Owambo Basin with sediments reaching up to 601 m in thickness (Hedberg, 1979; Miller, 1997; Hoak, et al., 2014). The Kalahari Sequence is subdivided into four formations from base to top: (1) Ombalantu Formation –claystone, (2) Beiseb Formation – red conglomeratic, (3) Olukonda Formation – friable poorly consolidated sandstone and (4) Andoni Formation – sand and clay (Miller, 1997).

2.2.5.1 Ombalantu Formation

Hugo (1969), describes the lithology of this formation as sandstone or siltstone with varying amounts of clay, shale, and unconsolidated sand; finely laminated in places with small-scale, well developed cross-bedding being common. In contrast, Miller (1997) suggests that upon close examination, however, most of the red "sandstones", "siltstones" and "shales" are in fact red semi-consolidated but friable, variably silicified mudstones consisting almost entirely of clay. He further notes that these mudstones are not sufficiently indurated to warrant use of the term shale. Gypsum crystals and casts of gypsum crystals occur in the upper part of the formation.

It is suggested that deposition of the Ombalantu Formation consisted mainly of the accumulation of fine clastics in a shallow, low-energy, shallow alluvial environment in a restricted continental basin in which sufficient evaporation was present to produce gypsum.

2.2.5.2 Beiseb Formation.

The widespread Beiseb Formation was encountered in all the wells in the Owambo Basin. As described by Miller (1997), it consists of well-rounded clasts (up to 12cm in diameter) of brown and grey sandstone and mudstone and grey and black chert (some oolitic) set in a matrix of fine- to medium-grained, argillaceous, calcareous to dolomitic sandstone. It is thought to reach up to 30m in thickness. Evidence of evaporitic environment is suggested by presence of gypsum crystals up to 5cm long in the lower part of the formation.

This formation represents a period of rapid and extensive input of material into the Owambo Basin from its margins.

2.2.5.3 Olukonda Formation.

The Olukonda Formation is composed of friable, poorly consolidated, reddish brown, poorly sorted, massive sand and sandstone that contains a few thin gritty and pebbly layers, believed to be up to 120m thick (Miller, 1997). This formation is limited in extent and is only believed to have considerable elongate suboutcrop extending from the area of the Beiseb Formation in the southeast to Ombalantu in the northwest.

2.2.5.4 Andoni Formation.

This formation is the most extensive of the Kalahari succession, forming a blanketing cover for all the underlying units. The Andoni Formation consists mainly of interbedded white medium-grained sand, light greenish clayey sand and green clay.

The sand is unconsolidated, slightly pyritic and hematitic, containing numerous irregularly shaped medium-sized dolcrete and calcrete nodules. Angular to sub-rounded grains of quartz (polished and frosted) make up 90% of the sand in addition to chalcedony, feldspar and chert which are also minor components. The generally pyritic clay layers reach up to 155m and are interbedded in the sand, often sandy or silty and calcareous and contain thin laminated layers of limestone with oolites and ostracod shells.

Depositional environment of the Kalahari Sequence: Sediments of the Kalahari Sequence suggest deposition in largely arid to semi-arid conditions. Red clays and silts of the Ombalantu Formation suggest deposition into a shallow, restricted central depression in which there was sufficient evaporation to produce gypsum. A somewhat wetter period led to the introduction of coarse detritus from the basin margins to form the gritty to conglomeratic sandstone of the Beiseb Formation while the bulk of the succession thereafter is probably aeolian. Continued arid conditions are documented by gypsum and seasonal influx of sediments basin-wards from the rims.

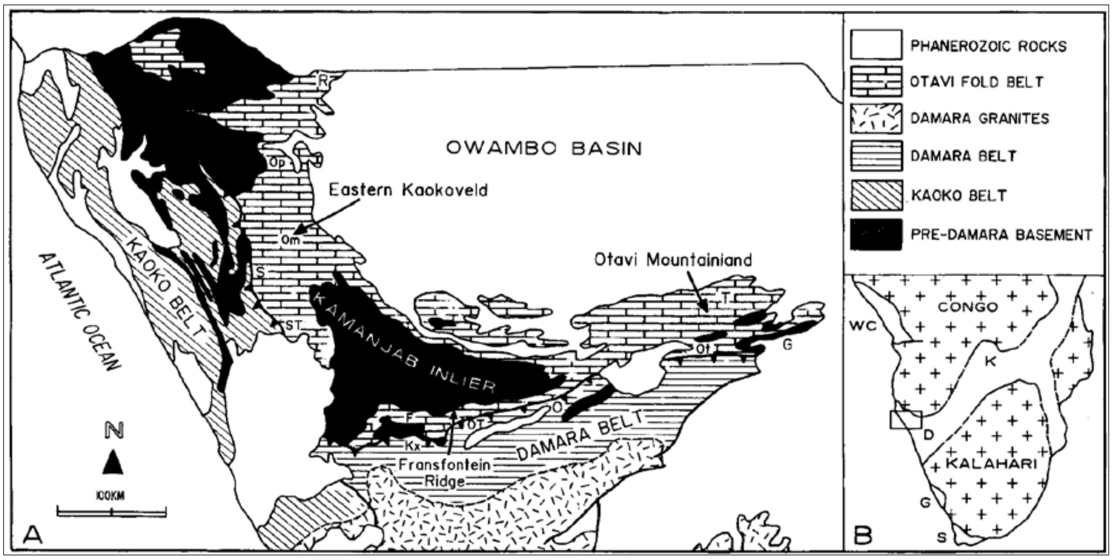


Figure 5: Present day location of the Owambo Basin in relation to the Damara and Kaoko Belts (Hoffman & Prave, 1996)

2.3 Stratigraphic Summary of the Owambo Basin

As pointed out earlier, the placement of different units within the stratigraphy of the Owambo Basin is somewhat disputed. The stratigraphy summary according to Martinez & Muundjua (2012) for example, places the Chuos (Varianto) Formation within the Nosib Group (Figure 6). These authors also include the Nanzi Formation into the Karoo Supergroup as they correlate it with the Etjo Formation sandstones found in the Nanzi Wells.

A more detailed generalized stratigraphic summary of the Owambo Basin has been elaborated by Hoak et al., (2014). These authors divide the Nosib Group into Austerlitz and Naauwport instead of using solely the Nabis Formation. They do however place Chuos fFormation within the Otavi Group. The stratigraphic terminology also differs for the Karoo Supergroup where they introduce the Kaoka Formation as the top-most unit.

The following two stratigraphic charts illustrate the above outlined differences in the naming of the stratigraphic units:

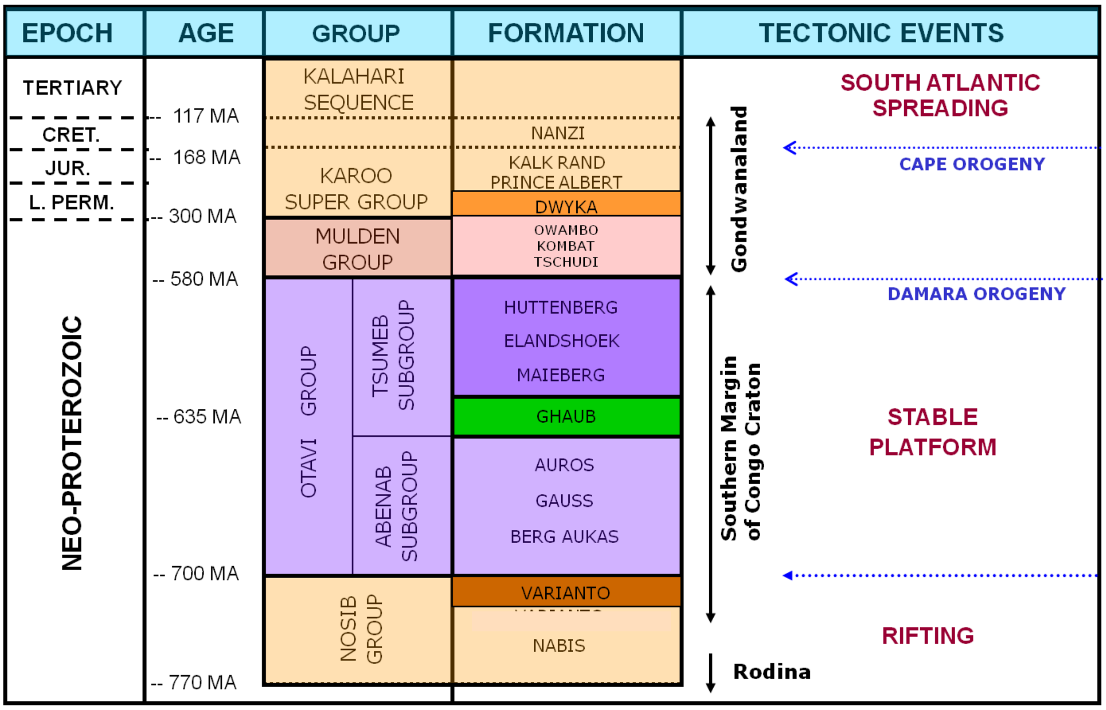


Figure 6: Summary of the stratigraphy of the Owambo Basin and the main tectonic events. Note their usage of Varianto instead of Chuos. (Martinez & Muundjua, 2012)

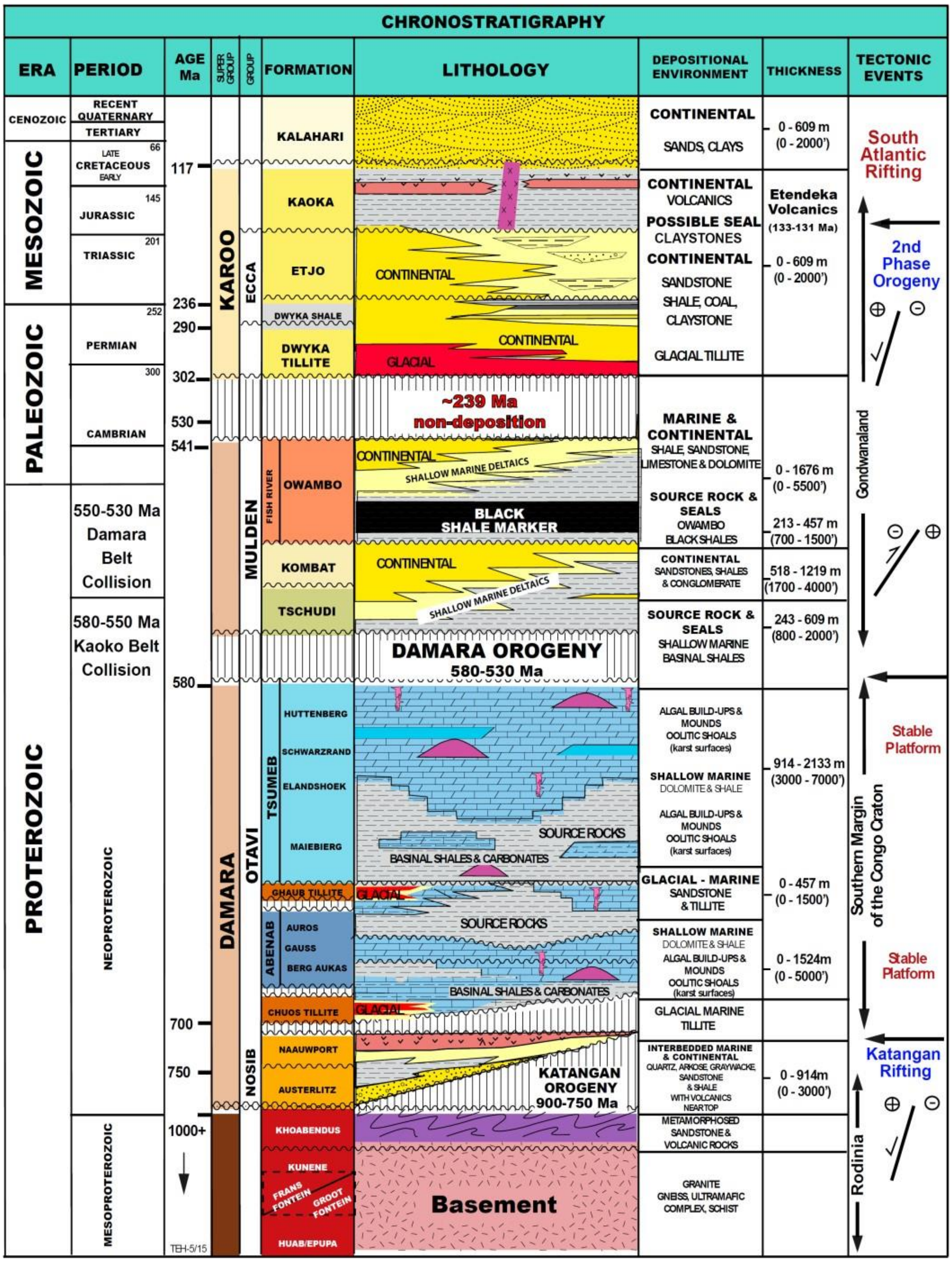


Figure 7: Summary of the stratigraphy of the Owambo Basin and the main tectonic events (Hoak et al., 2014)

2.4 Present hydrocarbon system concepts for the Owambo Basin

At the present level of understanding of the Owambo Basin from the hydrocarbon exploration point of view, two main petroleum plays concepts are understood to occur

(Hoak et al., 2014; Martinez, pers. com. June 2015; Martinez & Muundjua, 2012; Bechstädt, 2009):

PLAY 1

- *Source Rocks*: The Nosib Group and Otavi Group mobilized along reactivated basements structures during the Damara Orogeny.
- *Migration*: Basement faults that acts as conduits for hydrocarbons and potentially add fracture porosity.
- *Reservoirs*: Sandstones from the Nosib Group, carbonates from the Otavi Group.
- *Seal*: The Nosib Group and/or The Otavi Group and or Lower and Upper member shales from Kombat Formation of the Mulden Group.
- *Traps*: Carbonate build-ups in the Otavi group, intrabasinal highs with associated anticlinal structures, anticline structures from tectonic inversion.

PLAY 2

- *Source Rocks*: The Kombat Formation Group (black shales) within the Lower Mulden Group.
- *Migration*: Cretaceous normal faults which acts as migration pathways for hydrocarbons
- *Reservoirs*: Carbonates (limestones & dolomites) from the Owambo Formation within the Mulden Group.
- *Seal*: Lower and upper member shales from Kombat Formation of the Mulden Group.

- *Traps*: Drape over basement highs, intrabasinal highs with associated anticlinal structures in overlying basin sedimentary rocks especial in the Upper Mulden Group.
- *Maturity*: Maturity conditions are assumed more favorable in the deepest part of the basin (northeast).

2.5 Exploration History of the Owambo Basin

Although exploration efforts in the Owambo Basin commenced in the 1950s spanning more than 58 years, this basin had minimal exploration activity involving short periods of activity followed by long periods of inactivity. During the period before the year 1990, the political complexity of Southern Africa influenced the sporadic activity in hydrocarbon exploration both onshore and offshore Namibia. There have been 5 exploration wells (Strat Test-1, Etosha 1-1, Etosha 2-1, Etosha 5-1A and OPO-1) drilled, three 2D seismic acquisition campaigns and numerous aero gravi-magnetic surveys in the basin. In addition, several other shallow and test wells have been drilled as shown in Figure 8 below. To date, numerous hydrocarbon occurrences have been reported throughout the basin, and available geophysical data suggests the presence of both structural and stratigraphic signatures that can be associated to petroleum traps.

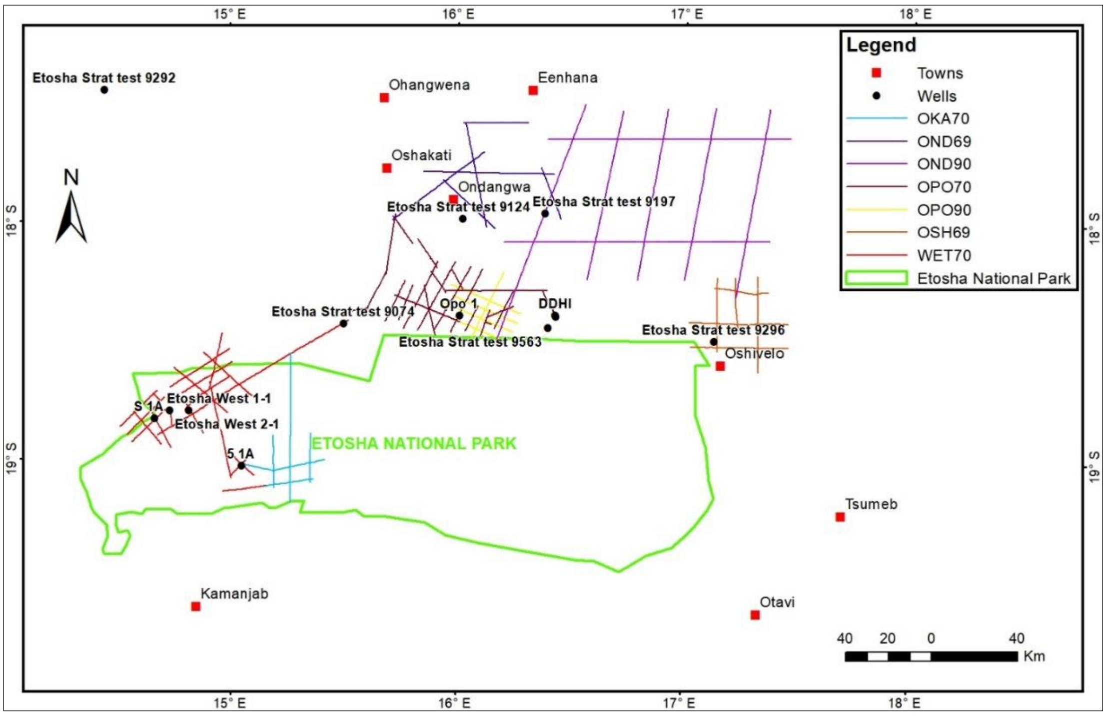


Figure 8: Location of exploration wells and 2D seismic surveys in the Owambo Basin.

However, no commercial discovery of hydrocarbons has been made in this basin up to date.

2.5.1 Period between 1959 - 1990

In 1959, Texas Eastern acquired the first exploration rights to the Owambo Basin (then called Etosha Basin). Their license covered nearly the entire Namibian half of the Owambo Basin, over which the company flew a regional aeromagnetics survey in 1962. Thereafter in 1963, Ray Geophysical acquired a ground-based gravity survey over the area. In 1964, Texas Eastern created a subsidiary company to serve as the operating company with the name Etosha Petroleum and drilled the Etosha Petroleum Stratigraphic Test #1 well later that year.

Etosha Petroleum was acquired by Brilund Mines in 1966. This merged company (Brilund-Etosha) completed a photogeology and outcrop study of the basin in 1966, which led to the 2D seismic acquisition program from 1968-1970 using Vibroseis. Seismograph Service Limited (SSL) conducted the initial seismic survey in 1968, but Teledyne took over the project in 1969. Etosha Petroleum also conducted a regional surface geochemistry study conducted in 1967 over 19,220km^2 of the basin. In 1970, Etosha Petroleum also drilled two shallow wells (Etosha 1-1 and 2-1) having their TD in the Owambo Formation, and a deeper test well (Etosha 5-1A) that reached the uppermost Otavi Group carbonates.

A period of about 20 years of significant military and political activity occurred in the Owambo region, leading to exploration inactivity in this basin until 1990. In December 1988, after over twenty years of dispute and armed conflict, South Africa signed an agreement linking its withdrawal from the disputed territory to an end of Soviet and Cuban involvement in the long civil war in neighboring Angola. Namibian independence from South African administration occurred on March 21, 1990 and this gave way to new exploration efforts in the Owambo Basin.

2.5.2 Period between 1990 – 2019

Following these ongoing political maneuvers, Brilund formed a partnership with OPIC (Overseas Petroleum Investment Corporation) of Taiwan in 1988. This partnership saw the acquisition of an additional 800 kilometers of 2D seismic and acquisition of aerogravity data using Carson Services and thereafter, the drilling of the OPO-1 well in 1991. However, OPIC left their interest in the basin in 1991.

Occidental International partnered with Brilund in 1992 as replacement for OPIC. Occidental commissioned a surface soil gas study, some TOC analyses, a limited apatite fission track analysis, and fluid inclusion work based on outcrop sampling of over 200 samples. However, Occidental left the Owambo Basin in 1993 without having drilled any wells.

After Occidental’s departure, another period of exploration inactivity occurred for the following ten years. During that time, Etosha Petroleum finally relinquished the license they had held in the basin since 1964. Commencing in 1991, the Namibian Government in collaboration with German subcontractors, acquired high-resolution magnetic data over the majority of the country, including the Owambo Basin.

In 1999, Namibia moved from the bidding rounds system and adopted the Open Licensing System that allows companies all over the world to submit application for exploration rights over any open blocks by submitting proposals containing biddable terms.

Under this new licensing regime, First African Oil was granted exploration rights of blocks 1714, 1814, 1715, 1815, 1716, 1816, 1717, 1817, 1718, and 1818 between the years 2003-2009. This company oversaw acquisition of regional airborne magnetics and gravity data of 7,627km^2. First African became a subsidiary of Circle Oil during this time. No wells were drilled during this license period.

In 2011, Preview Energy applied for and was awarded a concession area for blocks 1716 and 1816A. The company acquired a limited aerogravity survey over that area and also submitted samples for apatite fission track analysis (AFTA) from the Etosha Strat Test #1 and 5-1A wells.

Meanwhile also in 2011, Hydrocarb Energy signed an exploration agreement for the adjacent blocks 1715, 1815A, 1714A, and 1814A. Hydrocarb Energy acquired an aeromagnetics and aerogravity survey in 2013 to identify prospective areas for a potential 2D seismic survey. Additional field work in 2012 and 2013 has been done to sample outcrops for source and reservoir rocks. To date, Hydrocarb is still the holder of this license.

No seismic acquisition occurred, neither wells were drilled during the license periods of both these 2011 licensees.

In 2012, Frontier Resources was awarded a concession for blocks 1717 and 1817. In collaboration with Pioneer Energy (a local consulting company), they completed a limited soil gas survey which was reported to show the presence of anomalous levels of methane, ethane, propane, and butane. This company did not carry out further exploration activities until their license lapsed.

In June 2014, ACREP-Exploração Petrolífera (Acrep) was awarded the petroleum exploration license number 70 (PEL70) over Blocks 1718 and 1818 covering an area of of 6462km^2. Acrep acquired aero gravity-magnetic data over the license area in 2014, whose interpretation led to identification of potential structures for 2D seismic acquisition. In February 2017, Acrep contracted La Compagnie Générale de Géophysique (CGG) to conduct a seismic acquisition that comprised of 120km of 2D test lines using the Vibrosies method. Preliminary processing and interpretation showed good quality data, revealing deep seated structures in the area. However, up to date, detailed interpretation is still inconclusive and this data is yet not available for neither purchase nor public domain.

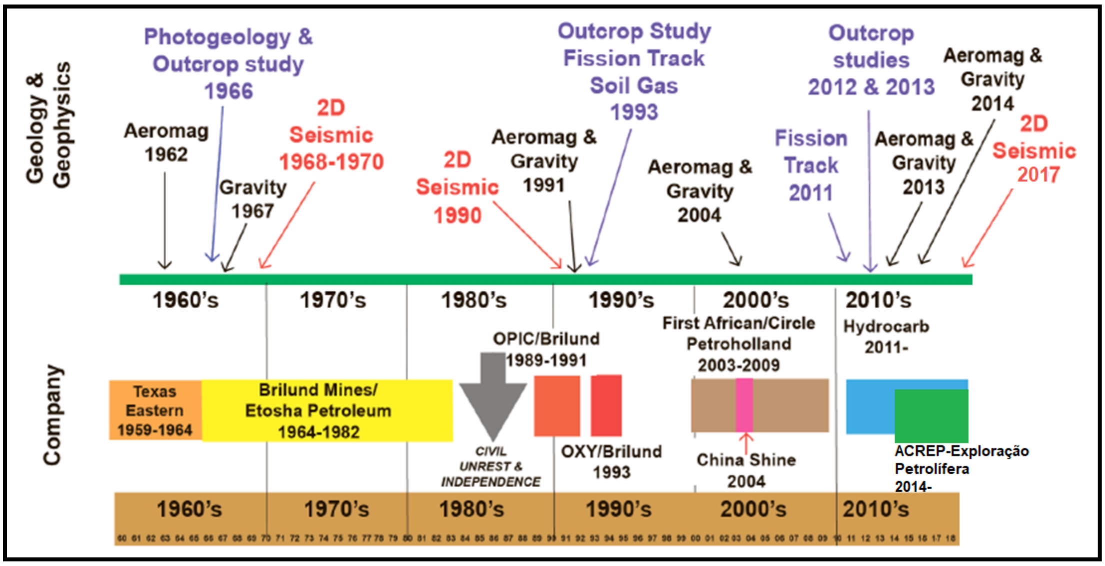


Figure 9: Summary of exploration activities in the Owambo basin (After Hoak et. al 2014)

CHAPTER 3

METHODOLOGY

A quantitative approach has been used to identify key tectonostratigraphic units from seismic data interpretation, relevant well data, potential field data and field work outcrops observations. Moreover, field work was carried out for the purpose of analyzing seismic-mapped features that may be outcropping and for on-ground verification of lithologies.

3.1 Data Collection

The data used in this project belongs to NAMCOR. The information includes one stratigraphic well and four exploration wells drilled between 1964 and 1991 in the Owambo Basin, about 2500km of vintage 2D seismic data (See Figure 8) acquired roughly during the same period and potential field data.

3.1.1 Wells Information

Well data used includes the following wells: Strat Test-1, Etosha 1-1, Etosha 2-1, Etosha 5-1A and OPO-1. The summary of the wells is shown in Table 1.

The ST-1 Well is a stratigraphic test well drilled by Etosha Petroleum in 1964. This well reached TD at 1878m in the Owambo Formation in the upper section of the Mulden Group. No hydrocarbons were encountered and the well was plugged, abandoned and classified as a dry well.

Both Etosha 1-1 and Etosha 2-1 wells were drilled by Etosha Petroleum under Brilund in 1970. Etosha 1-1 reached to a TD of 1584m and bottomed into the lower part of the Owambo Formation in the upper section of the Mulden Group. Etosha 2-1 is slightly shallower, having bottomed out at a TD of 1228m in the Tschudi Formation. Both wells were plugged and abandoned as dry holes.

The Etosha 5-1 Well was the deepest of the three wells drilled under Brilund in 1970. It reached a TD of 2509m in the Tsumeb Subgroup. It is reported that about 150-190 liters (40-50 gallons) of oil was recovered from the well while the operator was unsuccessfully waiting for a larger rig to drill deeper. Although this non-commercial hydrocarbon has been analyzed and found to be inconsistent with refined hydrocarbons, it is somewhat disputed that this well is classified as having oil shows. The Etosha 5-1 well was eventually abandoned as a dry hole.

The OPO-1 well is the only exploration well drilled in the Owambo Basin after the Namibian independence. It was drilled by Overseas Petroleum Investment Corporation (OPIC) and reached a TD of 700m in October 1991. The primary objectives of the OPO-1 were (1) to test a play type in the Oponono prospect – which is a gentle 270m relief anticline, (2) to test the expected good reservoir quality in the target tillites of the lower Karoo and (3) to collect geological information for further concession evaluation. However, drilling results indicated lack of source rock and no hydrocarbon shows were encountered.

Well	**Year**	**Operator**	**TD (m)**	**Formation at TD**	**Well Result**
ST-1	1964	Texas Eastern	1875	Owambo	Dry Hole
Etosha 1-1	1970	Brilund	1584	Tschudi	Dry Hole
Etosha 2-1	1970	Brilund	1228	Tschudi	Dry Hole
Etosha 5-1A	1970	Brilund	2509	Tsumeb	Dry with oil shows
OPO-1	1986	OPIC	700	Owambo	Dry Hole

Table 1: Summary of the hydrocarbon exploration wells drilled in the Owambo Basin

3.1.2 Seismic Data

The seismic data available for this project comprise of 2500 line kilometers of vintage 2D seismic data made up of seven (7) seismic surveys acquired between 1969 and 1990, mostly vectorised from paper copies to SEG-Y format. The surveys are listed in the following table:

Name	Year	Contractor	Reprocessed	Quality
OND-69	1969	Teledyn	Yes	Fair
OSH-69	1969	Teledyn	Yes	Fair
OKA-70	1970	Teledyn	Yes	Fair - good
OPO-70	1970	Teledyn	Yes	Fair - good
WET-70	1970	Teledyn	Yes	Fair - Good
OND-90	1990	CGG	No	Good
OPO-90	1990	CGG	No	Good

Table 2: Summary of seismic acquisition surveys in the Owambo Basin. Note that the 2017 2D seismic survey has been excluded since it is not available for use in this project.

The quality of the seismic data ranges from fair to good. However, although the surveys acquired by CGG in 1990 have considerably good quality data (OND-90 and OPO-90), reflector terminations are hardly recognizable for meaningful sequence stratigraphic applications.

3.1.3 Potential Field Data

The potential field data used in this project comprises of generated images (Figure 10) from the combined Fugro 2004 and Geological Survey of Namibia Free Air gravity. Free Air gravity was used throughout this study in preference to Bouguer Gravity due to two main reasons: (1) terrain effects in the study area are minimal due to the flat topography and (2) any assumptions about suitable Bouguer correction densities can thereby be avoided.

It is worth noting that this data does not cover the whole area, therefore presenting a data coverage limitation towards the western sector of the study area. There are also patches within the dataset where there is no coverage.

Magnetic data used comprises of aeromagnetic data supplied by NAMCOR which comprises of limited detailed Aeromagnetic Total Field image (Figure 11, upward continuation filter has been applied) and a regional Aeromagnetic Total Intensity image (Figure 12).

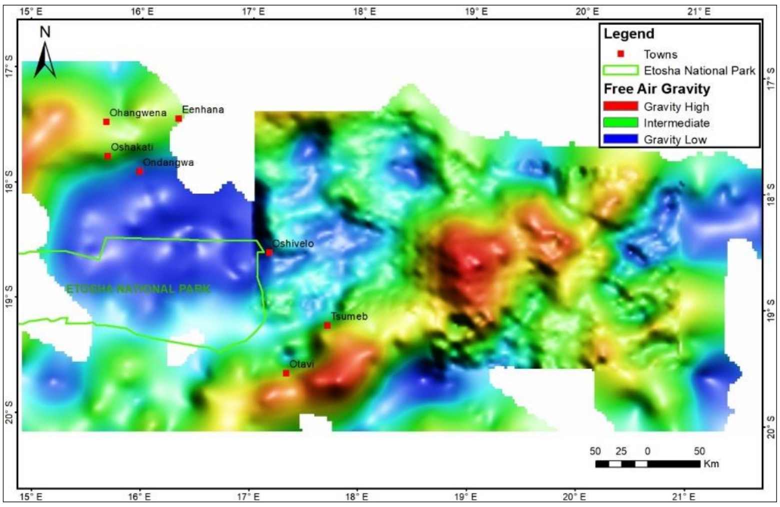


Figure 10: Free Air Gravity data combined from Fugro 2004 and Geological Survey of Namibia

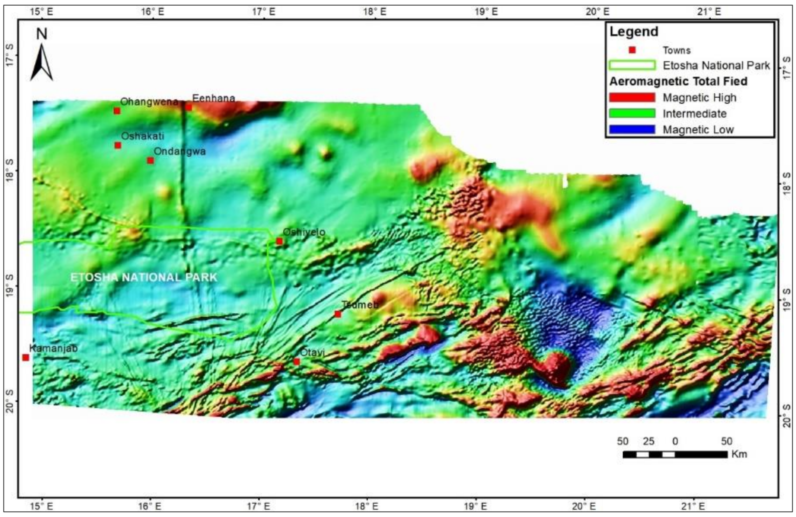


Figure 11: Aeromagnetic Total Field data used to compliment the gravity data interpretation

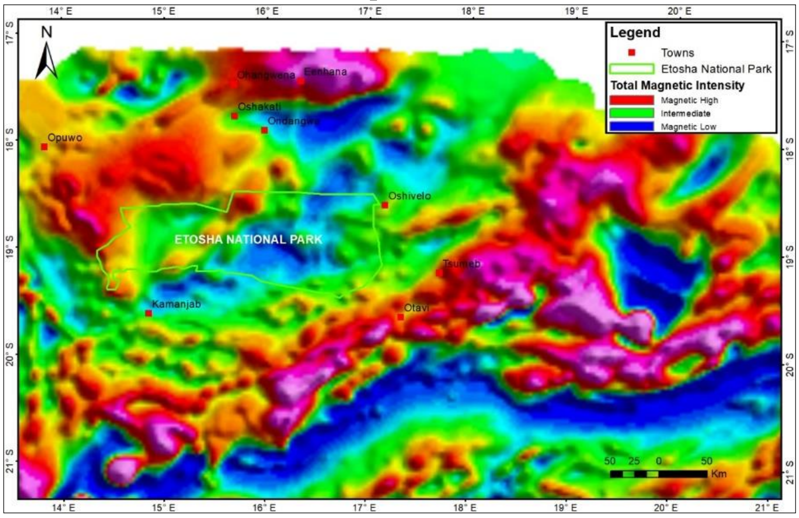


Figure 12: Total Magnetic Intensity data used to compliment the gravity data interpretation

3.2 Data Preparation

Data was acquired from NAMCOR in a hard disk drive. The initial qualitative quality control was carried out in order to verify the condition of both well and seismic data sets. Conditioning of wireline log data was not necessary since there is only one well (Etosha 5-1A) with a digital log file and QC was already done by ERLC. A Petrel project was created using WGS1984 UTM Zone 33S as Coordinate Reference System.

3.2.1 Well Data Preparation

The wells ground elevation were retrieved from the log scans and where provided their Kelly bushing was summed to obtain the final well elevation. The wells were loaded into the Petrel project. Check-shots were imported into the Etosha 5-1A well and these were extrapolated to the Etosha-1-1 and Etosha 2-1 Wells.

3.2.2 Seismic Data Preparation

The seismic data used in this project was available in SEG-Y format, however five of the seven surveys had to be previously vectorized into this format from paper copies.

The seismic reference datum for five of the surveys was retrieved from the seismic headers using Kingdom's seis-explore feature and this value has been assumed for the remaining two surveys with no seismic reference datum (SRD) data in the headers. The seven surveys were loaded into Petrel. Check-shot data from the Etosha 5-1A well was used to carry out the seismic-to-well tie of the WET-70 survey. Vertical exaggeration was varied during the working phase in order to find the optimum terminations display but this proved be of limited success. For confidentiality reasons concerning the proprietary of the data, the exact parameters and the exact location of the seismic lines are not displayed in this thesis.

3.2.3 Potential Field Data Preparation

No further preparation and processing was done on the potential fields data as this data was only made available in forms of images. Furthermore, no calculation of Bouguer gravity was necessary as discussed in Section 3.1.3

3.3 Interpretation Tools Used

Data interpretation during this project was carried out using Petrel 2015 version provided by Schlumberger to the University of Namibia (UNAM) was used for seismic interpretation and seismic to well ties. This software was also used for rendering of some of the maps presented in this project.

Other software used during this work include ArcGIS 10.5 licensed to NAMCOR for maps creation and potential field data interpretation.

3.4 Data Analysis and Interpretation

Data analysis includes reflector picking and interpretation and 3D windows in Petrel 2015 software. Composite lines were constructed to form extended section viewing and aid matching of separate seismic surveys to minimize miss-ties. Domains and trends of both gravity and magnetics data were established prior to the interpretation.

3.4.1 Seismic-to-Well tie

For the purpose of creating a tie of the wells and the seismic lines, check-shot data and well tops information has been used to create an initial tie before interpretation could be done in the time domain. Since only Etosha 5-1A well has check-shot data, this was the only well tie carried out to the WET-70 seismic survey. However, seismic-to-well tie proved unsuccessful since there is a total mismatch probably due to wrongly assigned well tops in well reports or checkshot files.

3.4.2 Seismic interpretation

Tectonostratigraphy and the effect of active tectonics on stratigraphy

The seismic interpretation in this project utilizes the tectonostratigraphic approach.

Tectonostratigraphy basically comprises distinguishing regional megasequences and their interpretation focusing on the influence of the tectonic processes on the initial stratigraphy (Nikishin & Kopaevich, 2009). Megasequences are tectonostratigraphic complexes that accumulated during the main phase of a basin's existence, often bounded by angular unconformities at the base and a combination of toplaps, downlaps surfaces or angular unconformities at the top. Formation duration of a megasequence ranges between 3 and 50 million years and corresponds to specific tectonic processes as continental rifting, continental convergence and collision, and inversion zones (Nikishin & Kopaevich, 2009). In turn, a tectonostratigraphic unit refers to all lithostratigraphic units (layers, members, formations) that were deposited at certain tectonic conditions, and the change of such units is associated to changes in the conditions.

The events of active tectonics are typically recorded in the sedimentary deposits that have accumulated at the same time. For example, for a rift, the sedimentary sequences are categorized as pre-rift, syn-rift and post-rift sequences.

Nikishin & Kopaevich (2009): “The tectonostratigraphic approach can be applied for analysis of basins of a complex tectonic evolution: rifting and post-rifting troughs, foredeeps and orogenic basin, and basins that have changed several tectonic settings during their evolution”. The evolution of the Owambo Basin was influenced by at least four main tectonic processes and therefore the tectonostratigraphic approach is suitable.

Seismic interpretation focused on the south western portion of the basin where seismic to well tie was attempted. This seismic interpretation included mapping of key horizons, unconformities, faults and seismic reflection characters to generate a geological/tectonic model. The horizons are picked according to their seismic facies (reflectors configuration, reflector continuity, amplitude, frequency and attributes); faults are picked according to offset in seismic reflectors and unconformities are picked according to termination orientation and seismic character in relation to the upper and lower reflectors. In addition, well information from Etosha 5-1A (also extrapolated to Etosha 1-1 and Etosha 2-1) was integrated and favored matching of well tops with major reflectors. Potential structures were also mapped that would represent hydrocarbon exploration leads.

The key horizons to be picked and interpreted, as well as their significance are listed in the following table (Table 3):

HORIZON	COLOR	SIGNIFICANCE

Top Mulden	**Green**	Top of the tectonic molasse (reservoir and source rock interval)
Top Otavi	**Blue**	Upper limit of the carbonates deposition cycle (reservoir and source rock interval)
Abenab	**Light Blue**	Boundary between upper and lower carbonate depositional cycles
Top Nosib	**Red**	Upper limit of the syn-rift and fluvial sediments (top reservoir). Lower boundary of glaciogenic carbonates (source).
Basement	**Purple**	Lower limit of the total sediments package in the basin

Table 3: Horizons interpreted on the 2D seismic data and their significance in terms of the hydrocarbon exploration

3.4.3 Potential Fields Data Interpretation

A. Gravity Data Interpretation

Lineament, Domain Identification and Interpretation

After a close inspection of the free air gravity maps, major and minor gravity lineaments were extracted along noticeable slopes in the gravity data. It is then assumed that these lineaments possibly reflect geological contacts, faults or folds which separate lithologies of different densities (Figure 13).

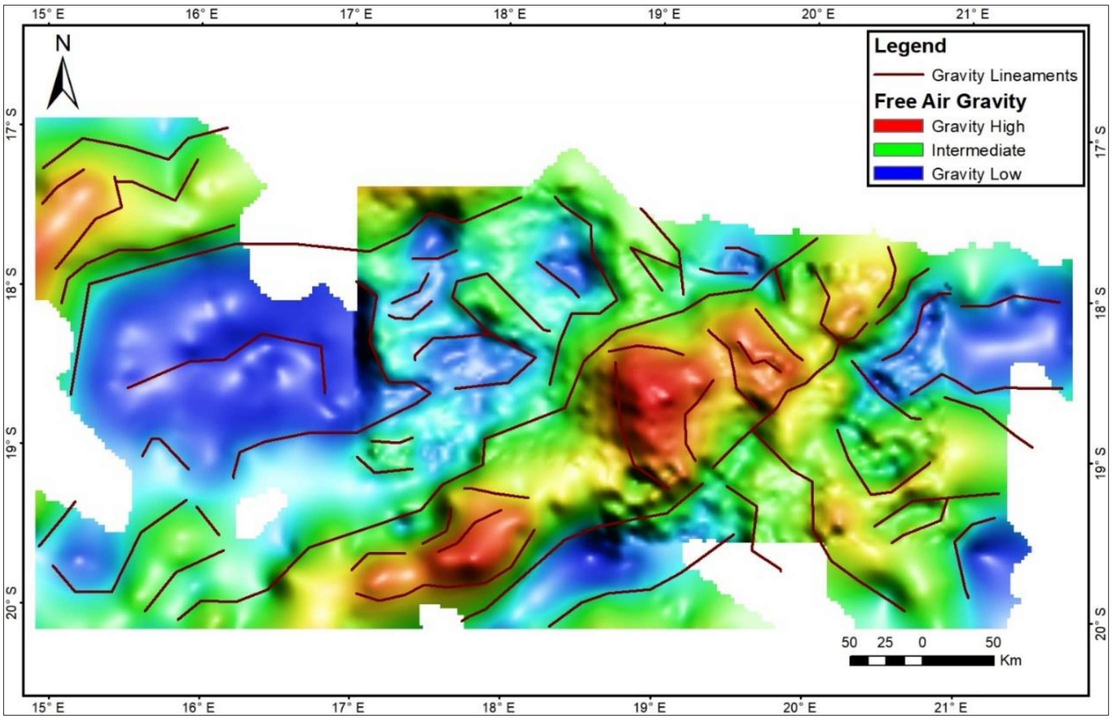


Figure 13: The main gravity lineaments in the Owambo Basin

The main gravity domains in the survey area were identified using the conventional assumption in gravity interpretation. The most intense gravity lows are as a result of the thickest accumulations of non-metamorphosed, younger sediments, which on average have lower densities than older metamorphic basement, assuming a reasonably uniform metamorphic basement density. Conversely, intense gravity highs are interpreted to be of non-sedimentary origin such as intrusions or dense metamorphic basement terrains. Different gravity domains (Figure 14/15) are most commonly bounded by contacts, faults or fold axes and therefore the domain boundaries are likely to coincide with gravity lineaments (Figure 13).

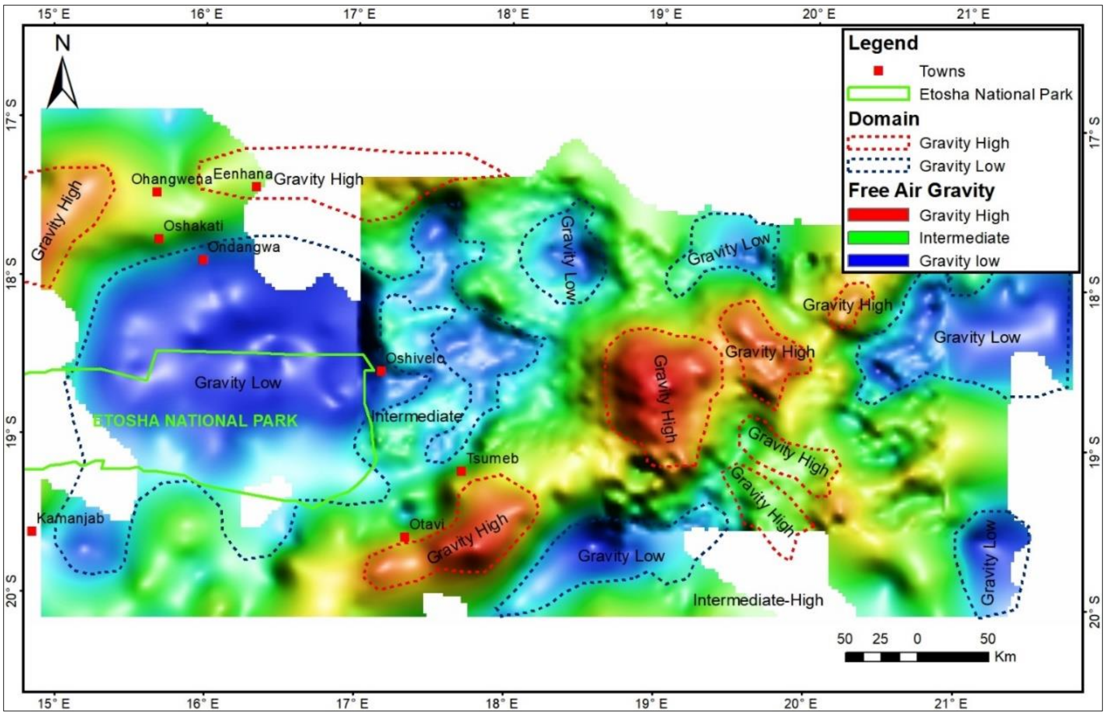


Figure 14: The different gravity domains in the Owambo Basin

B. Aeromagnetic Data Interpretation

Lineament, Domain Identification and Interpretation

The aeromagnetic data supplied by NAMCOR (Figure 11 and 12) was used to supplement the gravity interpretation. As done during gravity data interpretation, aeromagnetic lineaments were first identified and traced (Figure 15, 16). Dolerite dykes that often follow existing crustal inhomogeneities or long-lived, reactivated fault zones are recognized from aeromagnetic data and were similarly traced.

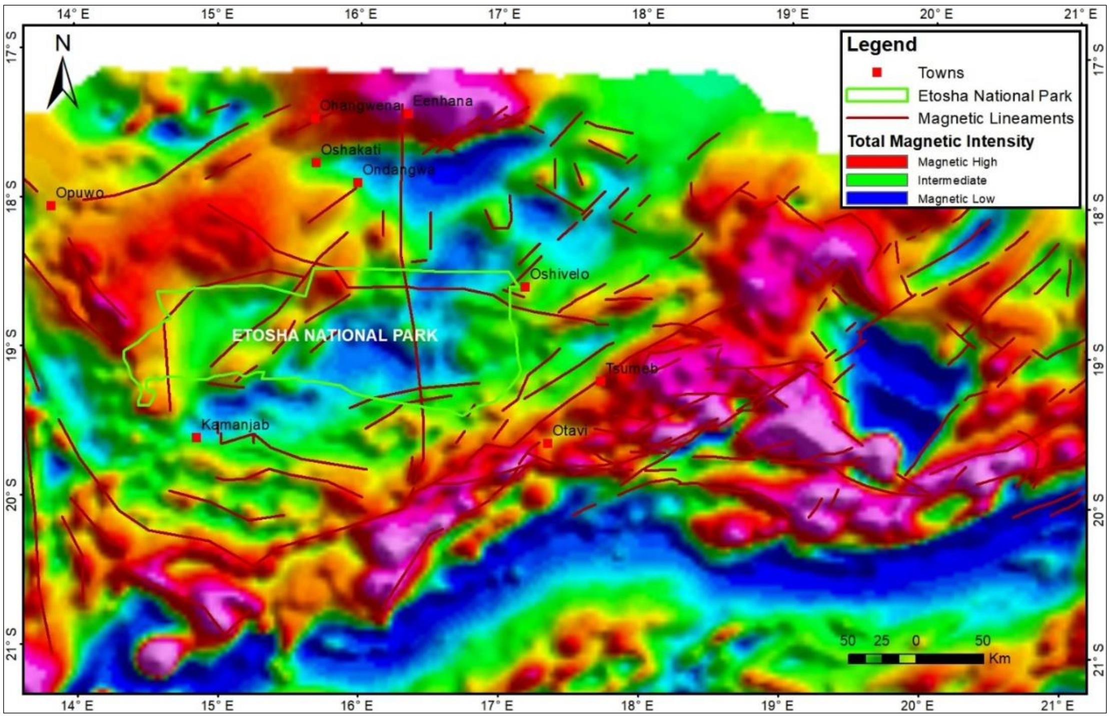


Figure 15: Magnetic lineaments in the Owambo Basin (Aeromagnetic Total Intensity)

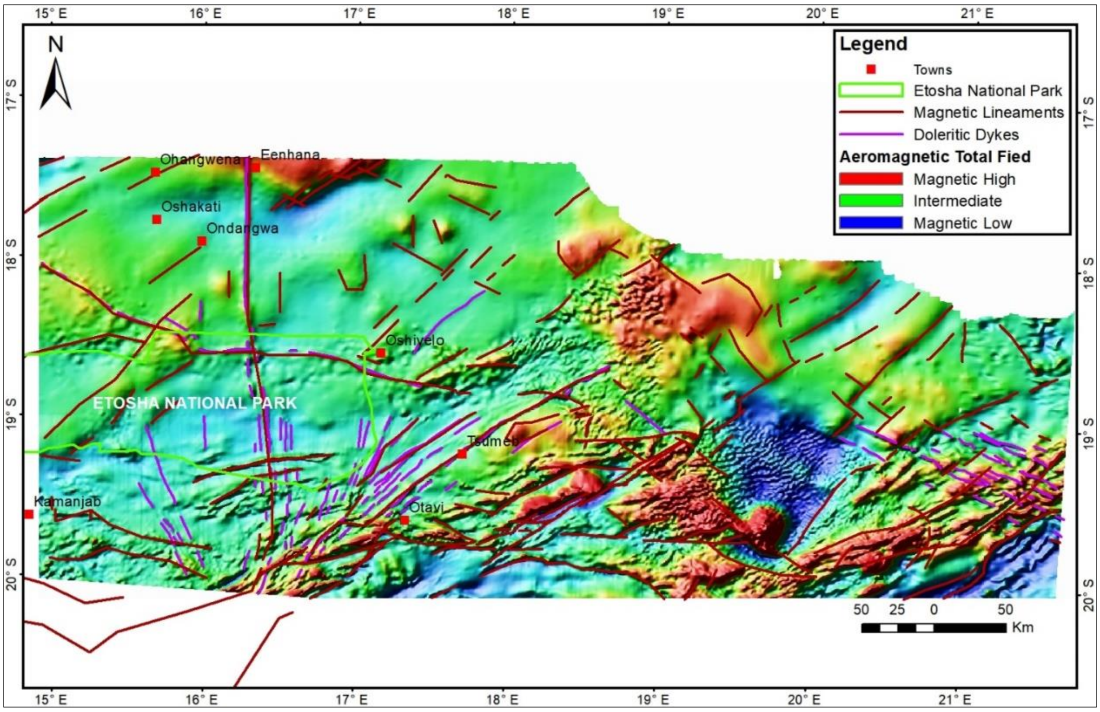


Figure 16: Magnetic lineaments in the Owambo Basin (Aeromagnetic Total Field)

Several significant magnetic domains were delineated (Figure 17, 18): discrete low frequency anomalies often caused by the magnetic mafic complexes and basement highs. Another magnetic domain identified is associated to shallow sources characterized by irregular high-frequency and often high-amplitude magnetic anomalies.

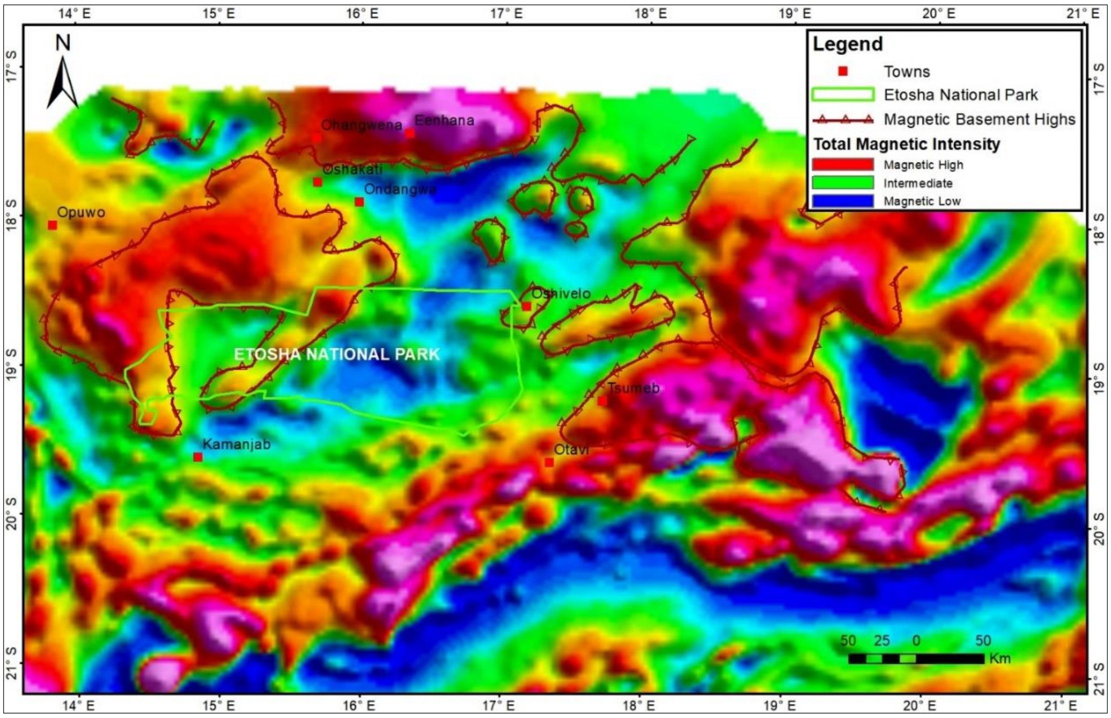


Figure 17: Magnetic domains in the Owambo Basin (Aeromagnetic Total Intensity)

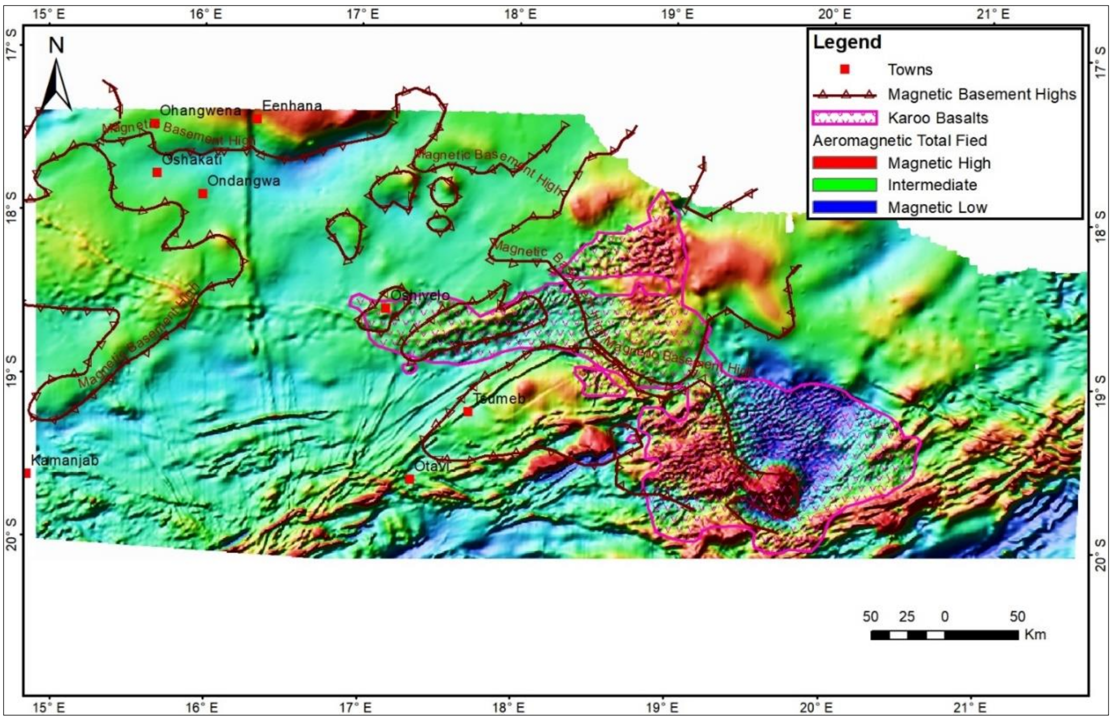


Figure 18: Magnetic domains map showing Karoo Basalts in the Owambo Basin (Aeromagnetic Total Field)

3.5 Field Work

The fieldwork trip took place between the 14 and 19 of August 2016, having field days of August 15 to 18, inclusive. The field trip was designed to have 20 stops at different outcrops in the Owambo Basin in a period of 4 days, covering a total round distance of 2500km. At each stop, a detailed description of the outcrop was to be carried out (including measurements of structural elements: strike and dip of bedding planes and fault planes), taking of pictures and GPS coordinates. Figure 19 shows the location of the outcrops observed at the field stops while Table 4 shows the dates and the GPS location of the points.

Date	Name	Latitude	Longitude	Group/Subgroup	Formation
15 August, 2016	OW1	-18.08101	13.86387	Abenab	?
15 August, 2016	OW2	-18.14619	13.92354	Tsumeb	Maieberg
15 August, 2016	OW3	-17.40650	14.24575	Nosib	Nabis
15 August, 2016	OW4	-17.40290	14.28892	Nosib	Nabis
16 August, 2016	OW5	-19.42241	15.16430	Abenab	Berg Aukas
16 August, 2016	OW6	-19.48988	15.16827	Abenab	Berg Aukas
16 August, 2016	OW7	-19.50970	15.15320	Tsumeb	Maieberg
16 August, 2016	OW8	-19.51199	15.14784	Tsumeb	Elandshoek
16 August, 2016	OW9	-19.52237	15.14685	Tsumeb	Huttenberg
16 August, 2016	OW10	-19.40537	15.92779	Tsumeb	Elandhoek
17 August, 2016	OW11	-19.03931	16.47099	Tsumeb	Huttenberg
17 August, 2016	OW12	-19.16930	17.75784	Tsumeb	Maieberg
18 August, 2016	OW13	-19.44949	17.73636	Nosib	Nabis

18 August, 2016	OW14	-19.44848	17.73731	Nosib	Nabis
18 August, 2016	OW15	-19.44142	17.73891	Abenab	Chuos
18 August, 2016	OW16	-19.43861	17.73517	Abenab	Berg Aukas
18 August, 2016	OW17	-19.43075	17.82289	Nosib	Nabis
18 August, 2016	OW18	-19.42373	17.85853	Basement	Basement
18 August, 2016	OW19	-19.41670	17.89435	Basement	Basement
18 August, 2016	OW20	-19.40357	17.91804	Abenab	Berg Aukas

Table 4: Point names and GPS data of the outcrop visited in the Owambo Basin

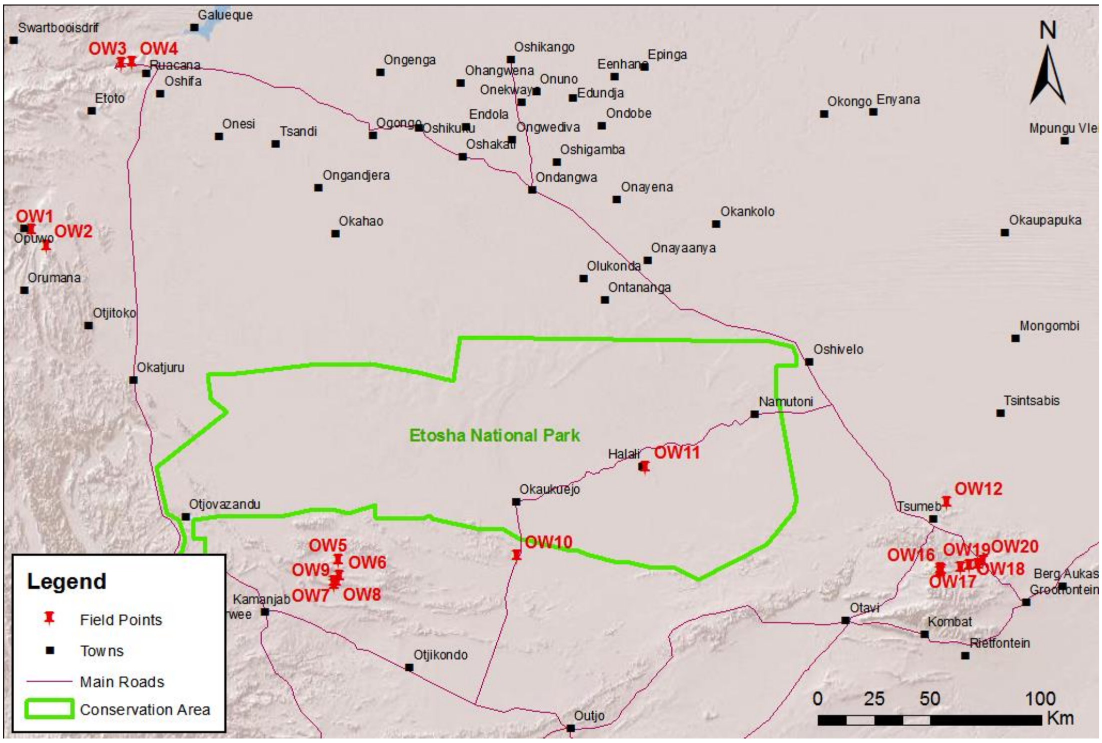


Figure 19: Location map of the field trip outcrop stop points in the Owambo Basin

3.6 Research Ethics

The conclusions contained in this work are based on data interpretations using standard approach of established scientific methods. Consent to utilize the data has been requested from the respective copyright holders where it is required and confidentiality has been adhered to as required by confidentiality agreements.

Intellectual property rights has been respected and standard methods of referring to other authors' work has been implemented. During the field work, all operations has been carried out in line with the environmental laws, especially that some parts of the area of study are located within a protected area. The research has been carried out in a manner that reduces the risk of harm to the researcher and the environment.

CHAPTER 4

RESULTS

In this chapter, the main research results are presented commencing with the seismic interpretation results and thereafter presenting the structural model. On continuation, results from the interpretation of the potential field data is presented which comprises of free air gravity and aeromagnetics interpretation results. A subsequent in-depth analysis of possible leads follows. Finally, field work results will then be presented, detailing the location and characteristics of every outcrop point focusing on hydrocarbon potential.

4.1 Seismic Interpretation Results

Key five horizons (from oldest to youngest) were successfully picked and interpreted on the 2D seismic data:

- top Basement (purple color)
- top Nosib (red color)
- Abenab? (light blue color)
- top Otavi (blue color)
- top Mulden (green color)

In addition, regional time structure maps have been created for the four horizons and are presented on continuation to each horizon. Major faults have been picked and mapped on several seismic sections that correspond with horst and graben features as expected in the syn-rift settings.

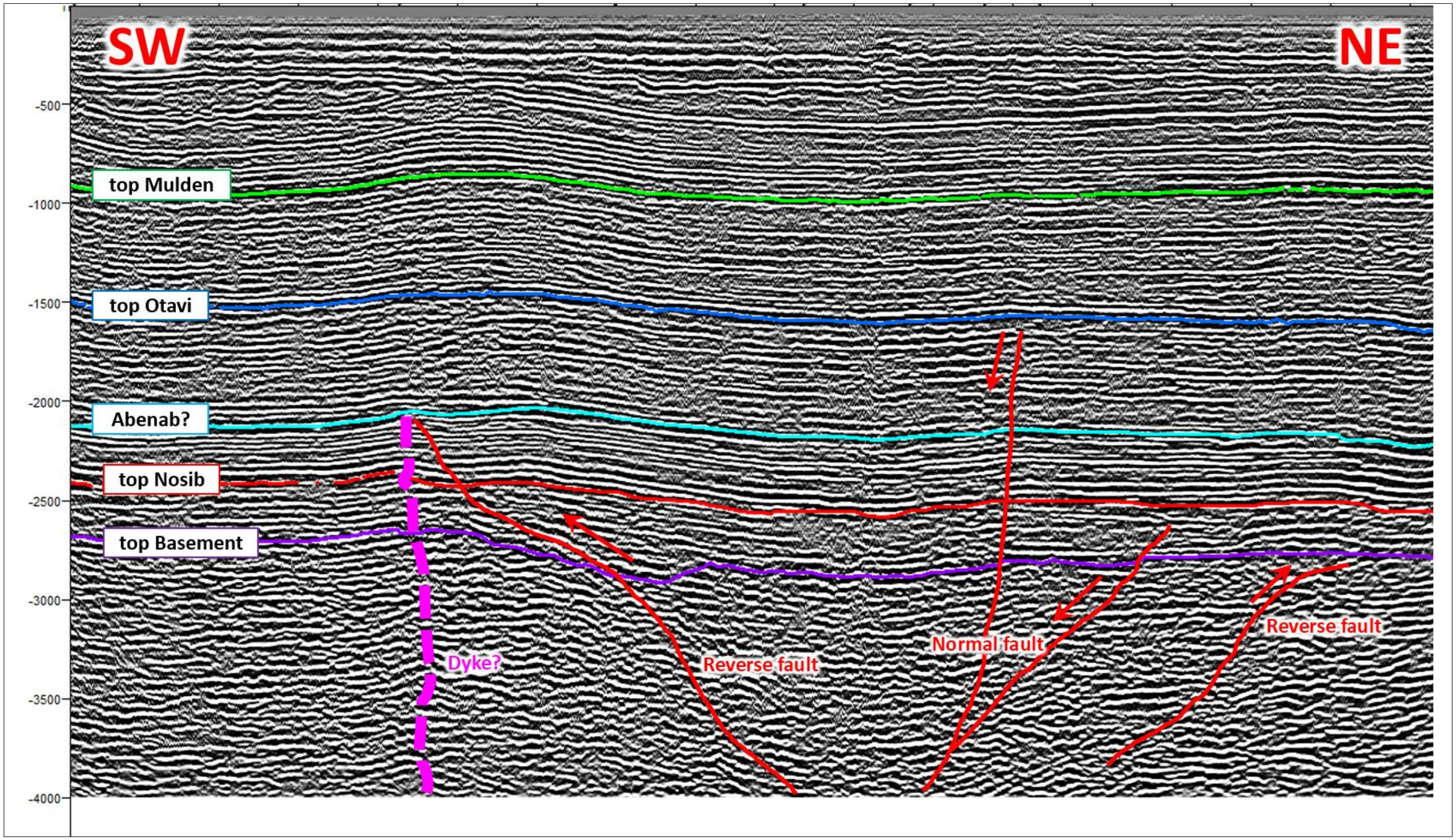


Figure 20: Seismic section showing the 5 interpreted horizons and structural elements. Note the coexistence of normal and reverse faults probably due to inversion (Line OPO-70-12)

A. top Basement:

On the seismic, the top of the basement is characterized by onlaps originating from the overlying sediments, onto what seems to be a non-sedimentary underlying unit. There is a clear distinction in seismic reflector character between the parallel to subparallel continuous, sometimes prograding sigmoidal reflectors, and the somewhat chaotic high-amplitude reflectors. The latter potentially represents the mid-Proterozoic metamorphic basement. Another feature that clearly distinguishes the basement is the normal faulting, with clear displacement of reflectors, which should be associated to the Late Neoproterozoic continental rifting. Reverse faults have also been mapped, most likely resulting from reactivation originated from the high-angle convergence between the Congo and Kalahari cratons during the formation of the Damara orogeny.

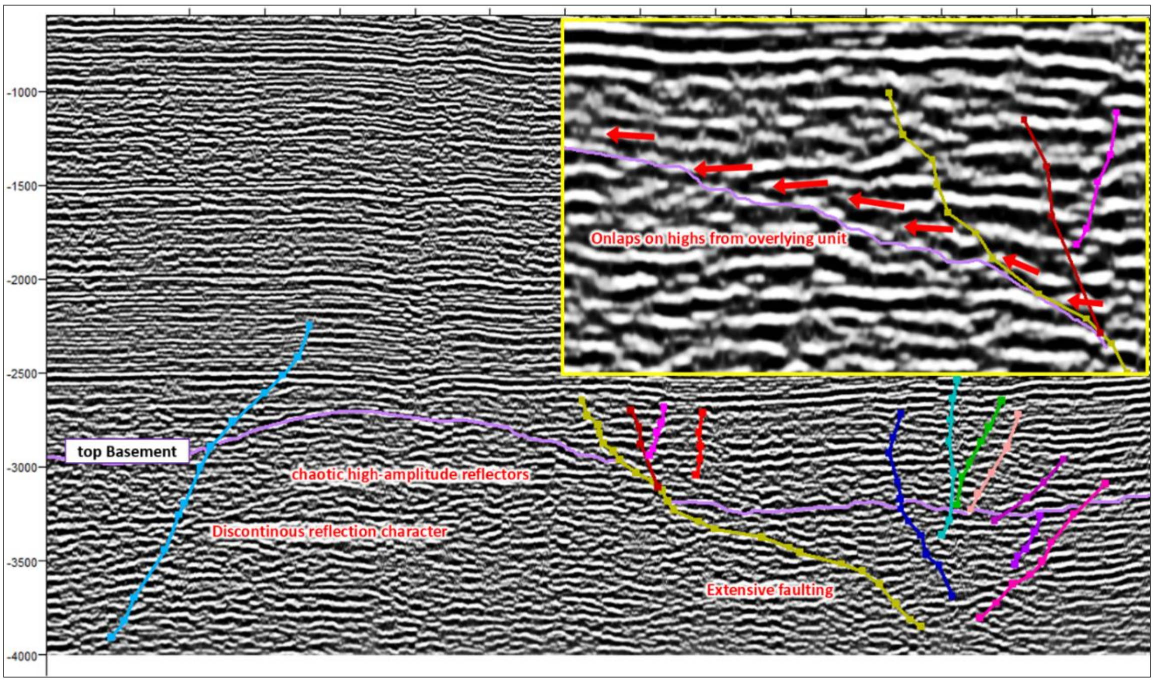


Figure 21: Seismic reflector character and distinctive features linked to the top basement pick (inset: close up on the onlaps from the overlying succession)

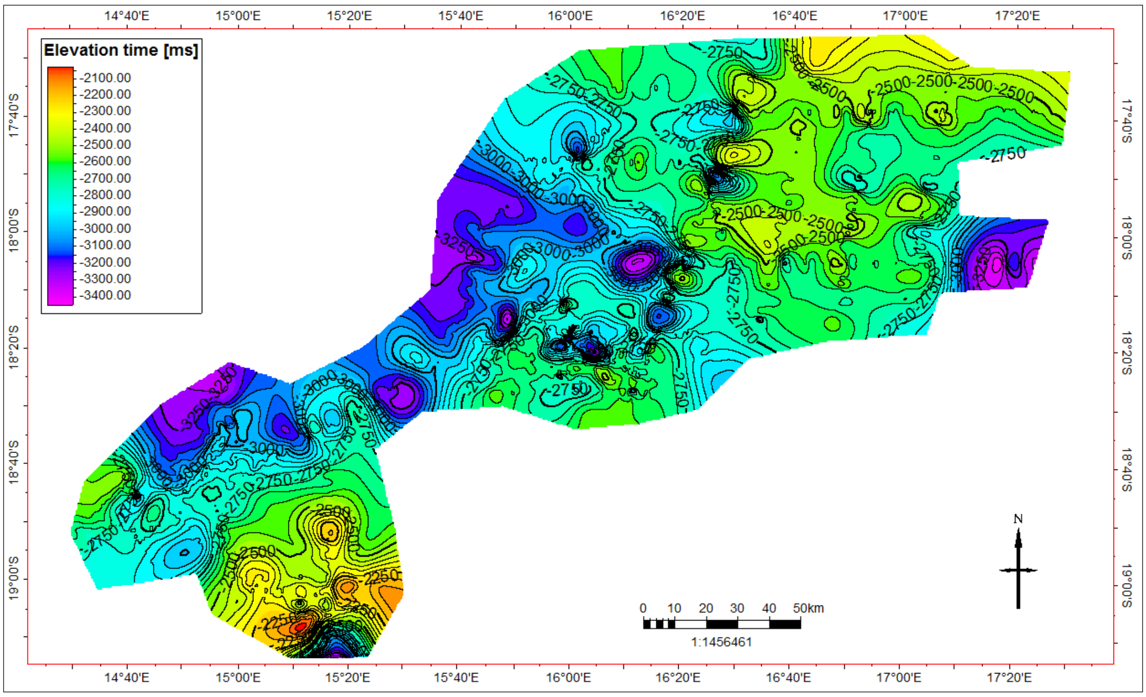


Figure 22: Time structure map of the top Basement horizon

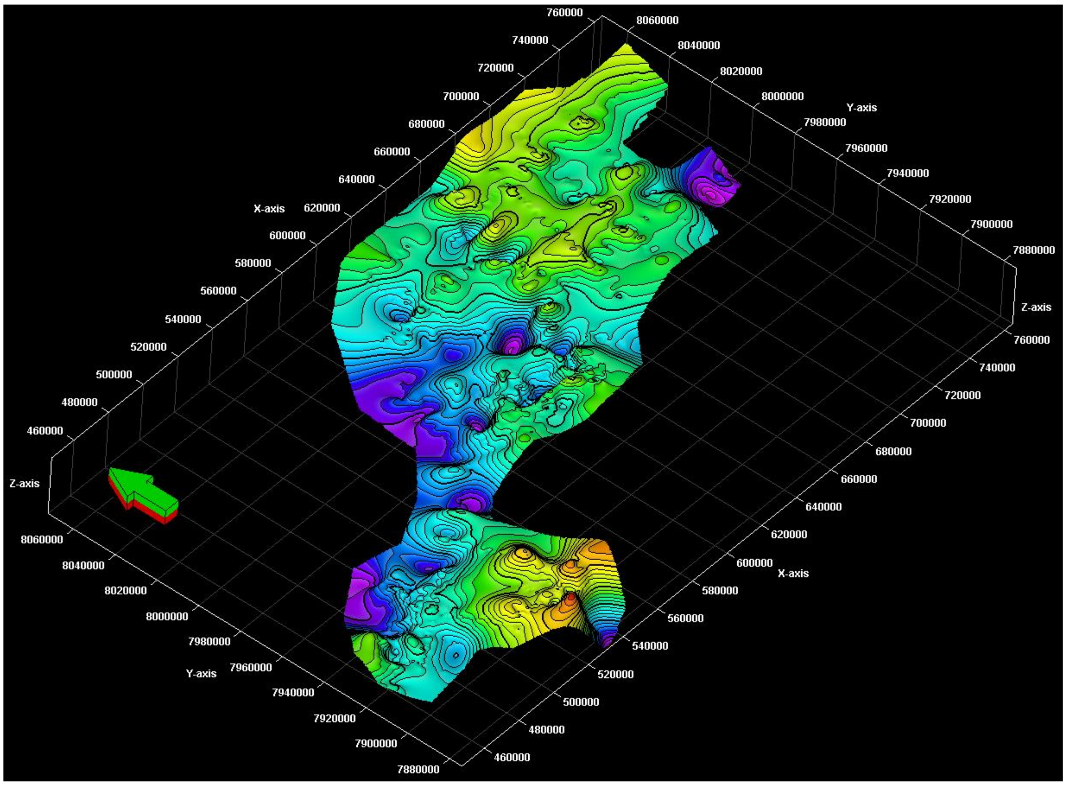


Figure 23: 3D surface of the top Basement horizon showing the morphology

B. top Nosib

The top Nosib pick follows a clear angular unconformity that clearly divides the moderate amplitude subtly discontinuous (probably moderate to high energy environment), at times sigmoidal, reflectors from the continuous parallel reflectors above. This angular unconformity suggests a typical erosional truncation (Figure 24). Clear onlaps can be observed on the lower part of this seismic package, however, sporadically these reflectors show a lower boundary concordance with basement highs.

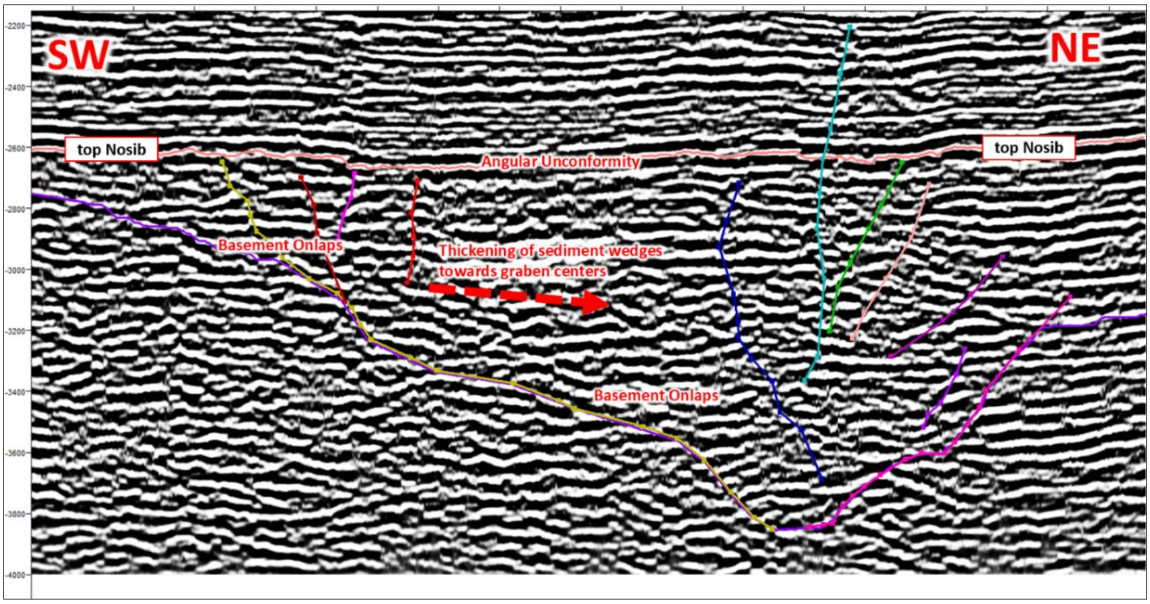


Figure 24: Seismic reflector character and distinctive features linked to the top Nosib pick (WET-70-21-C)

Areas of thicker sediment packages are present, reaching up to 800 milliseconds of thickness in what appears to be grabens bounded by normal faults that extent upwards from the basement. The seismic character of this depositional sequence points to continental derived sediments of a typical syn-rift sequence.

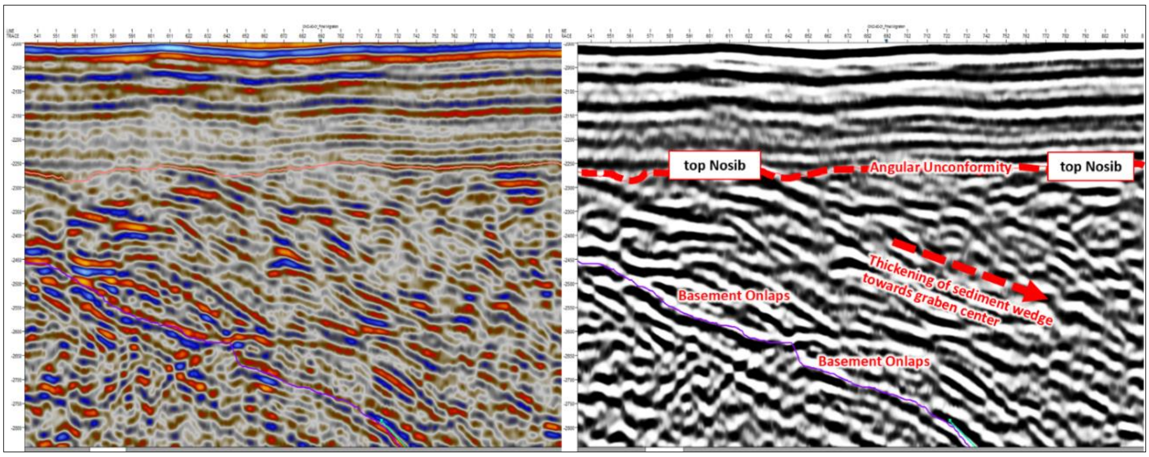


Figure 25: Erosional truncation forming a clear angular unconformity

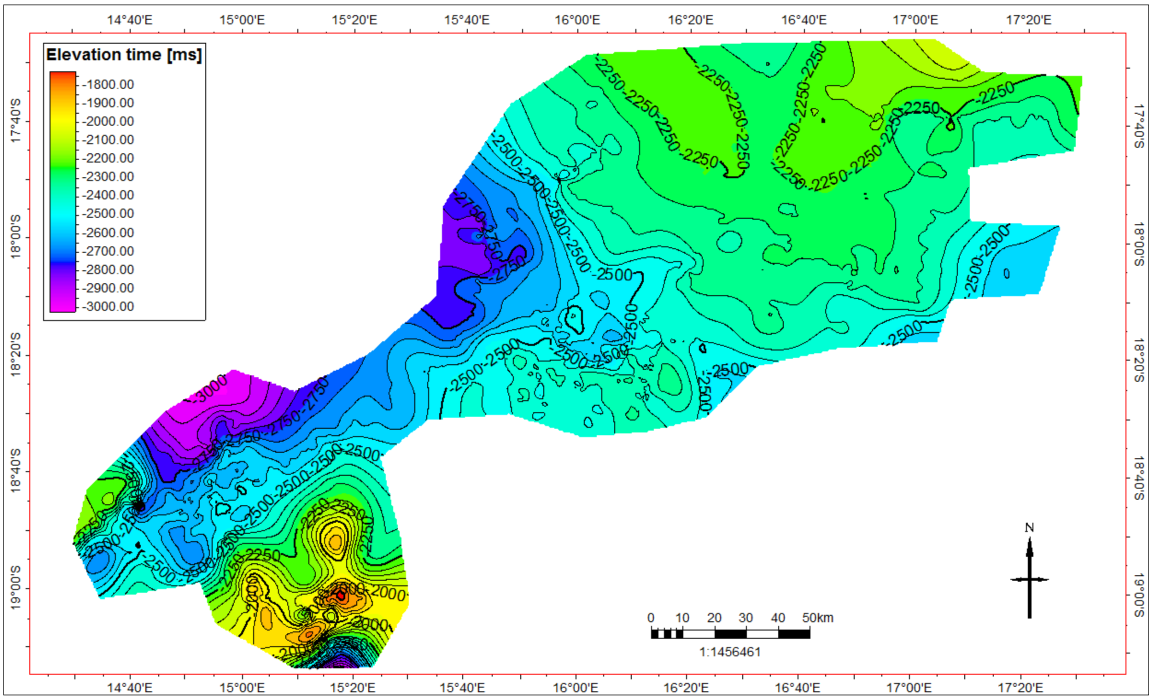


Figure 26: Time structure map of the top Nosib horizon

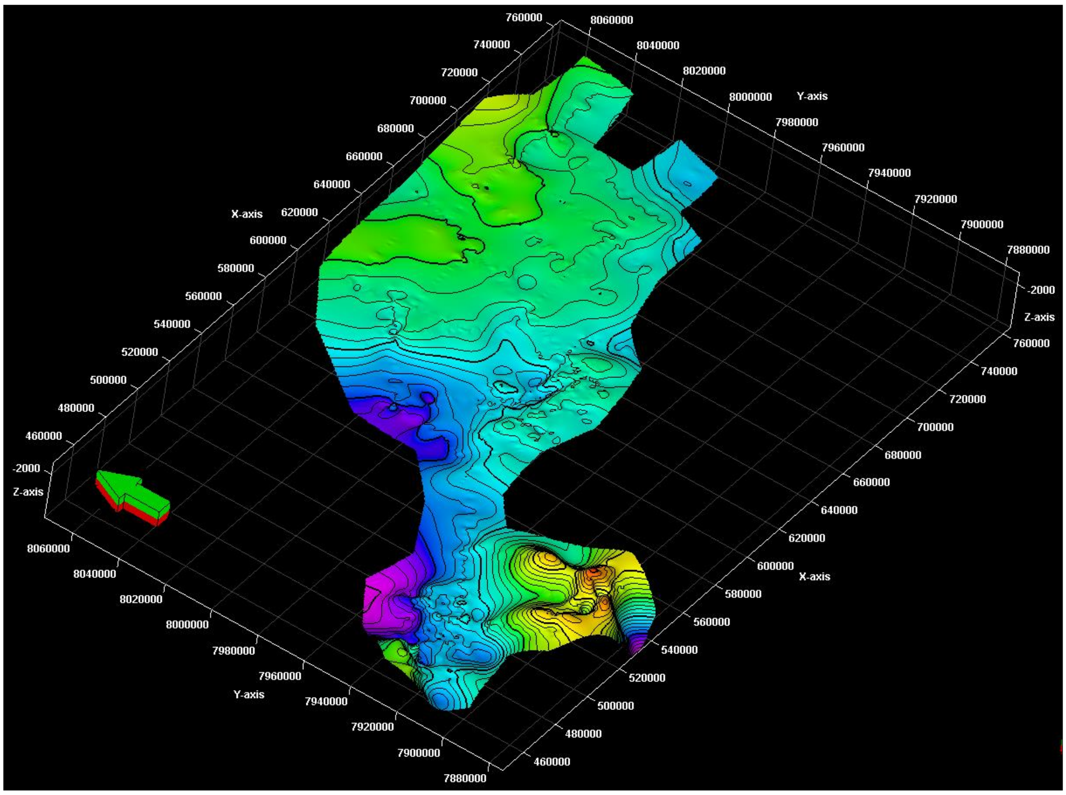


Figure 27: 3D surface of the top Nosib horizon showing the morphology

C. Abenab (?)

This pick is placed at the top of a continuous, even, high amplitude seismic facies overlying the top Nosib pick (Figure 28). Close inspection of this package shows that reflector frequency changes from bottom to top, exhibiting a steady transition from low to high frequency. The continuity of the reflectors meant that the use of a 2D seeded auto-pick tool was possible on this horizon. Reflector frequency changes of this seismic facies reflect a somewhat cyclical pattern, pointing to a varying depositional environment, alternating from a probably high energy relief-influenced base towards a quieter deeper environment – consistent with the literature descriptions (Miller, 1997) of the Abenab Subgroup.

The lower section at times exhibits lower boundary concordance with the underlying layer but this does not continue towards the upper section.

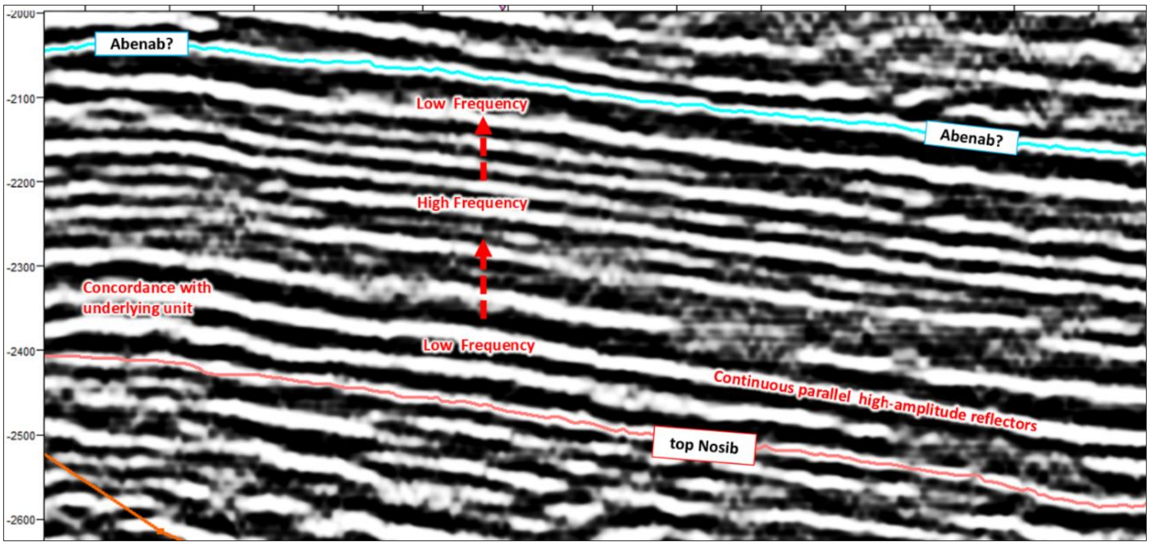


Figure 28: Seismic reflector character and distinctive features linked to the Abenab pick (note the reflector frequency change from bottom to up)

The section generally thins out toward the margins, with onlaps on the underlying succession, further suggesting initial deposition influenced by post Nosib relief.

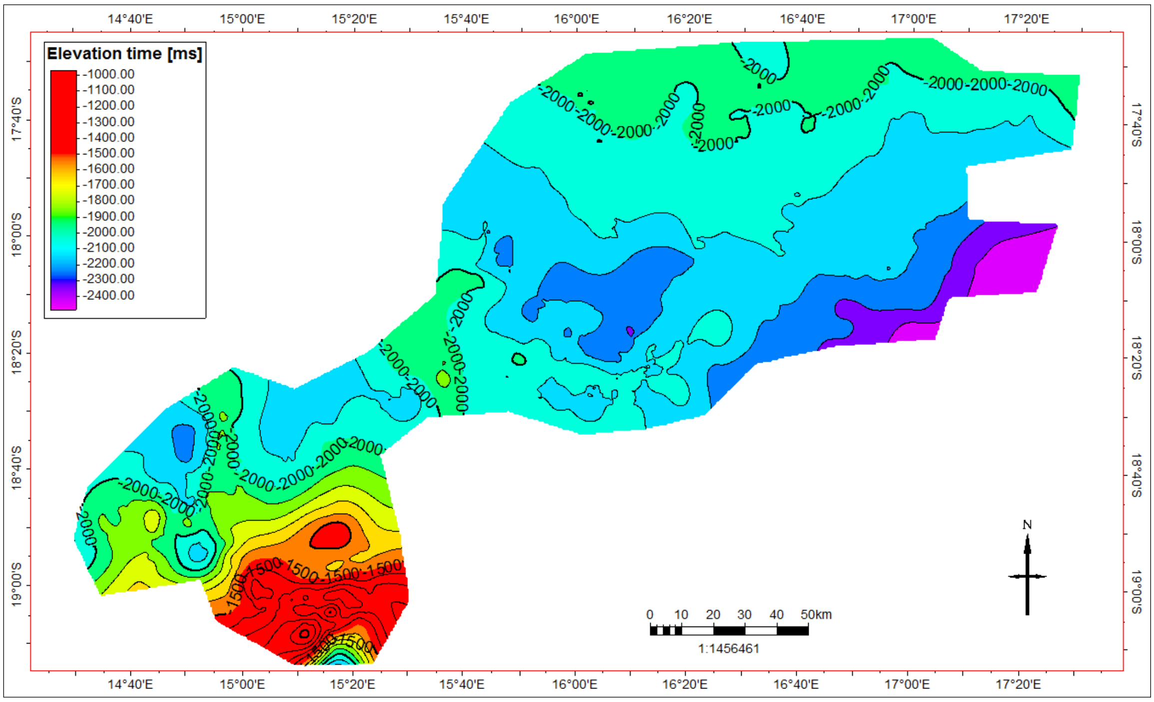


Figure 29: Time structure map of the Abenab(?) horizon.

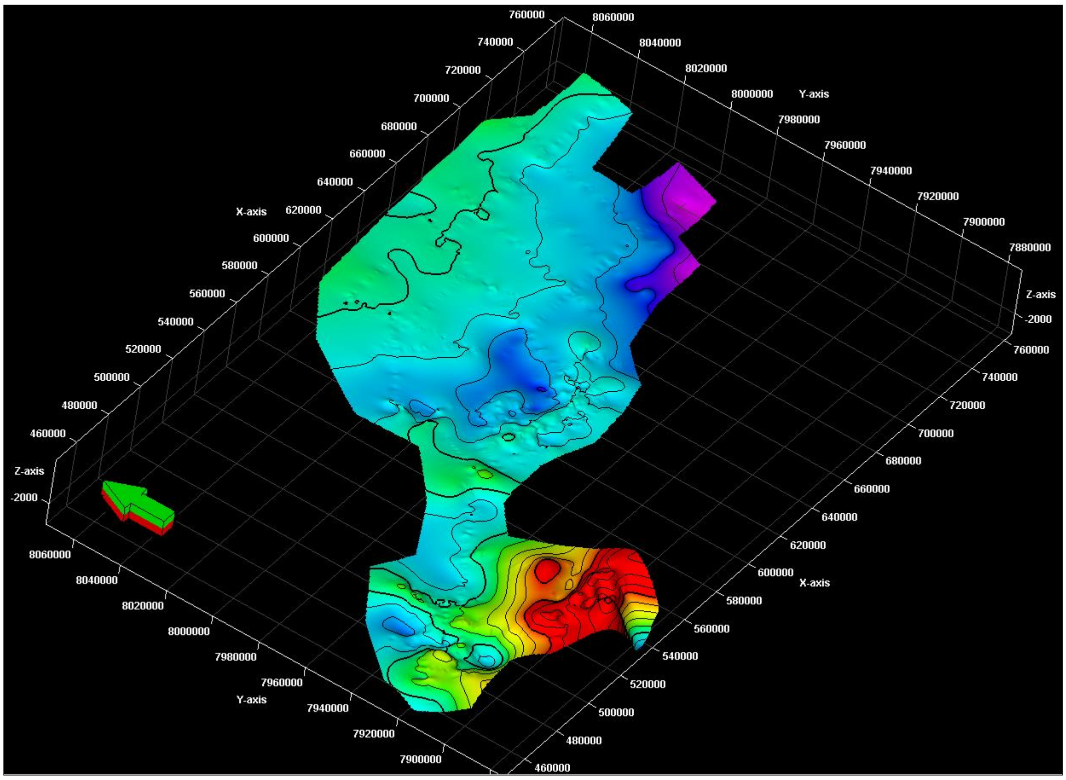


Figure 30: 3D surface of the Abenab(?) horizon showing the morphology.

D. top Otavi

The top Otavi pick bounds seismic facies characterized by moderate to high amplitude, parallel seismic reflectors. Reflection frequency does not change gradually as it was in the case of the underlying succession, here it rather remains low almost throughout the interval and only abruptly changing to higher frequency for the upper 100 milliseconds. On line OND-69-4, there is a distinct section between approximately 1800-1950 milliseconds characterized by less continuous sub parallel seismic reflector character (Figure 31).

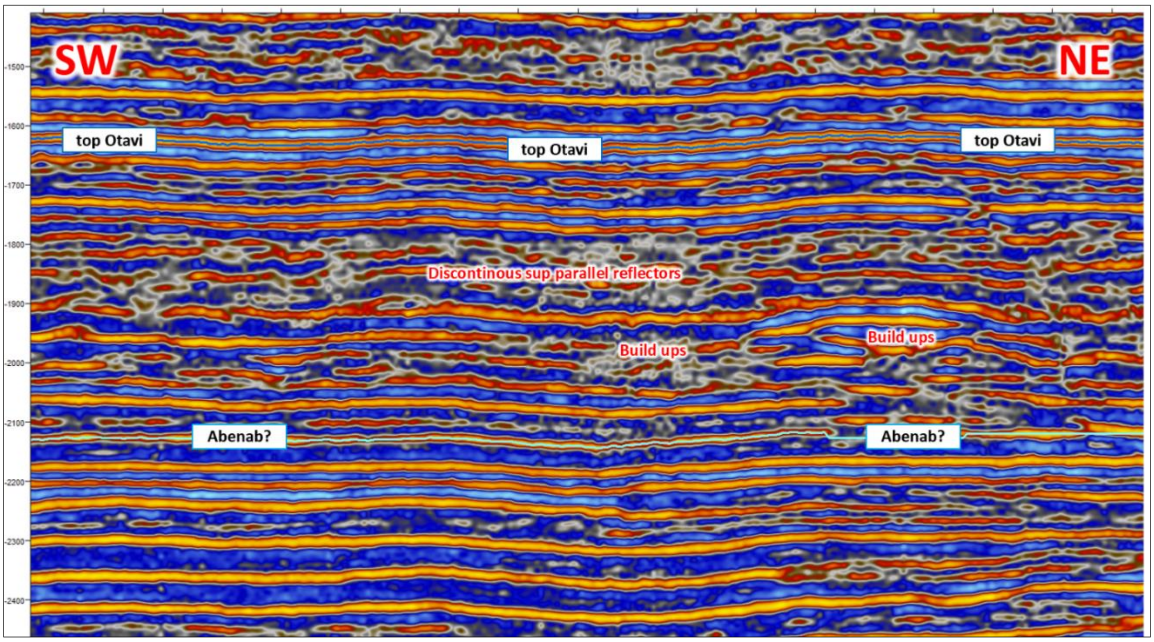


Figure 31: Seismic reflector character and distinctive features bounded by the top Otavi pick

A very distinctive feature within this package is the abundant carbonate mounts in the lower to the middle part of the interval, appearing as pinnacles with underneath velocity pull ups on the seismic sections (Figure 32).

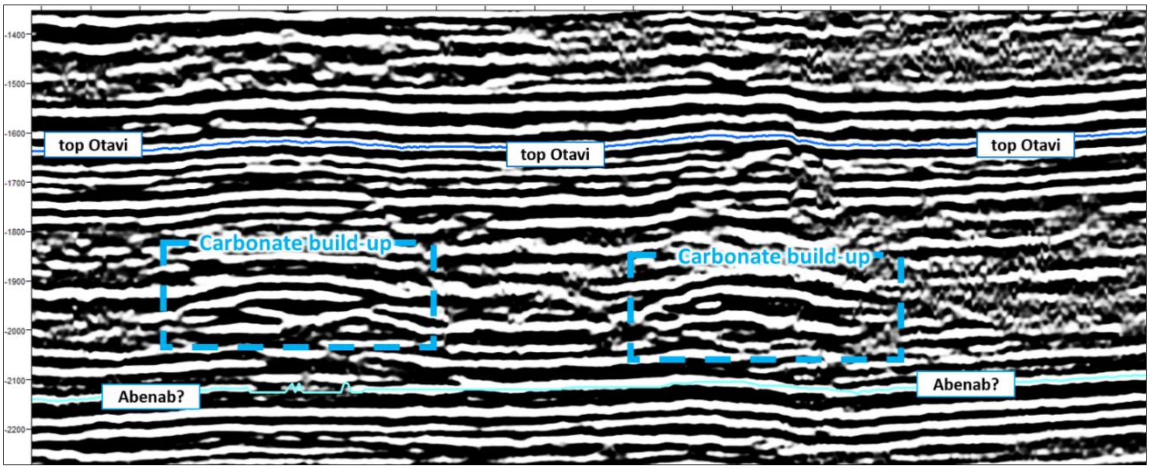


Figure 32: Carbonate build ups manifesting as pinnacles with velocity pull ups underneath

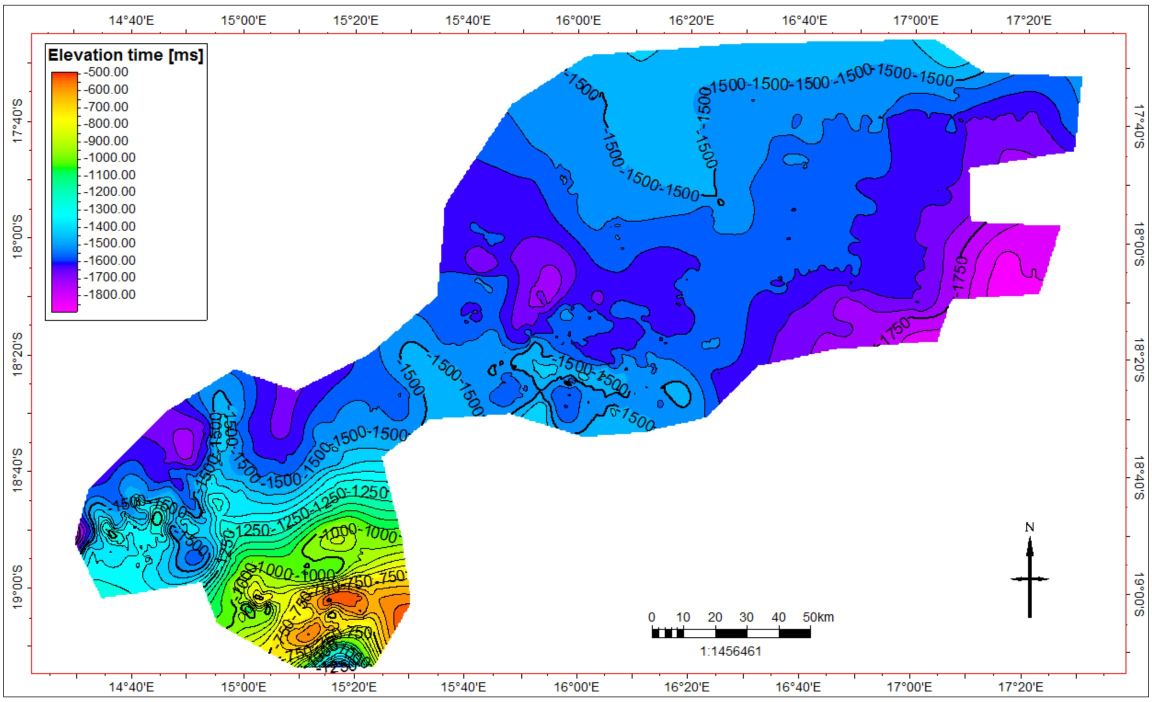


Figure 33: Time structure map of the top Otavi horizon

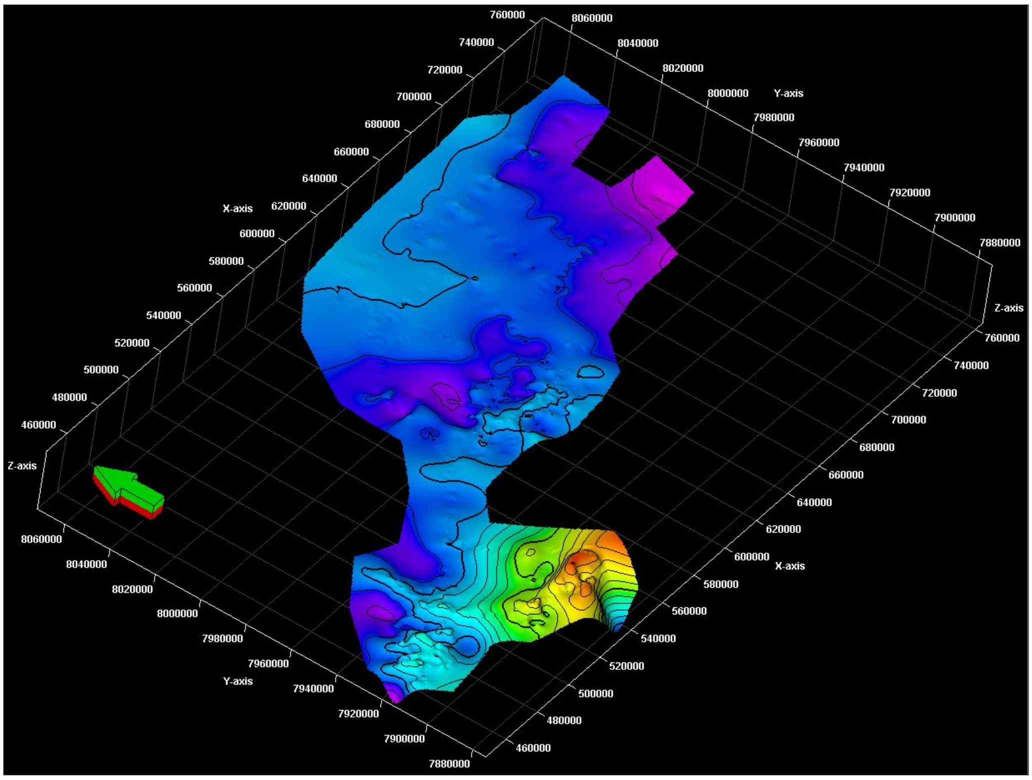


Figure 34: 3D surface of the top Otavi horizon showing the morphology

E. top Mulden

The interval under the top Mulden pick comprises of seismic facies characterized by non-uniform amplitude (mostly medium) sub-parallel medium continuity reflectors. At times there are reflector-free sections but these might be due to poor quality data. Within this package on line OND-90-02, at approximately 1350-1400ms, there is a more prominent high amplitude continuous set of 2 reflectors that seem to represent a distinctively calmer depositional environment - probably the Kombat Formation shale marker referred to by Miller (1997).

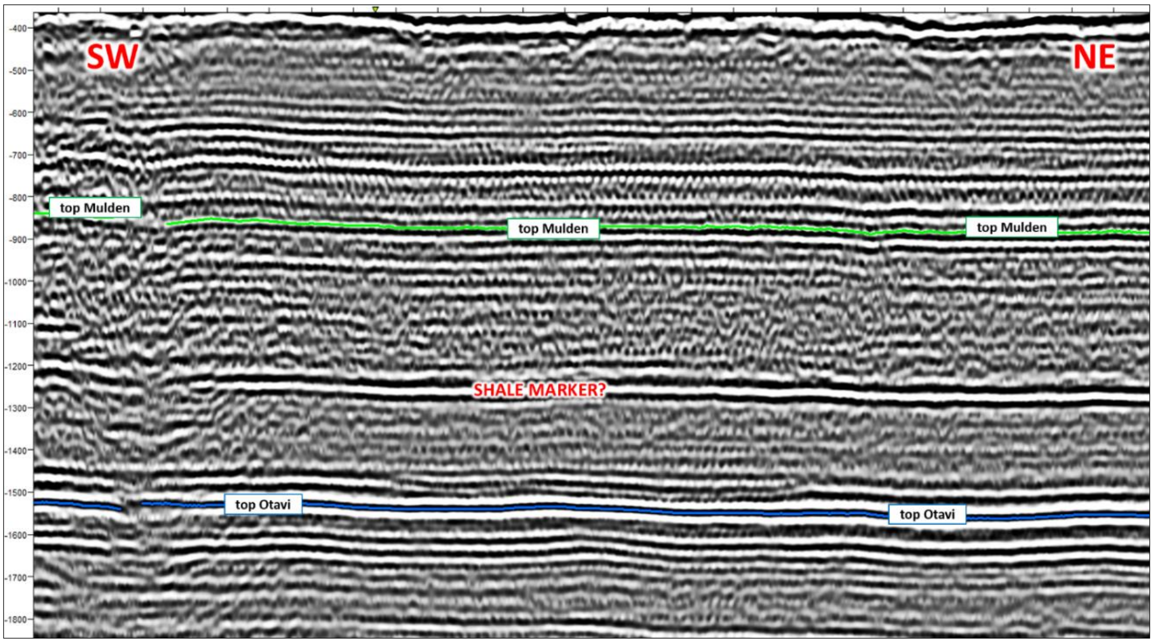


Figure 35: Seismic reflector character and distinctive features bound by the top Mulden pick (note the probable Kombat Formation shale marker)

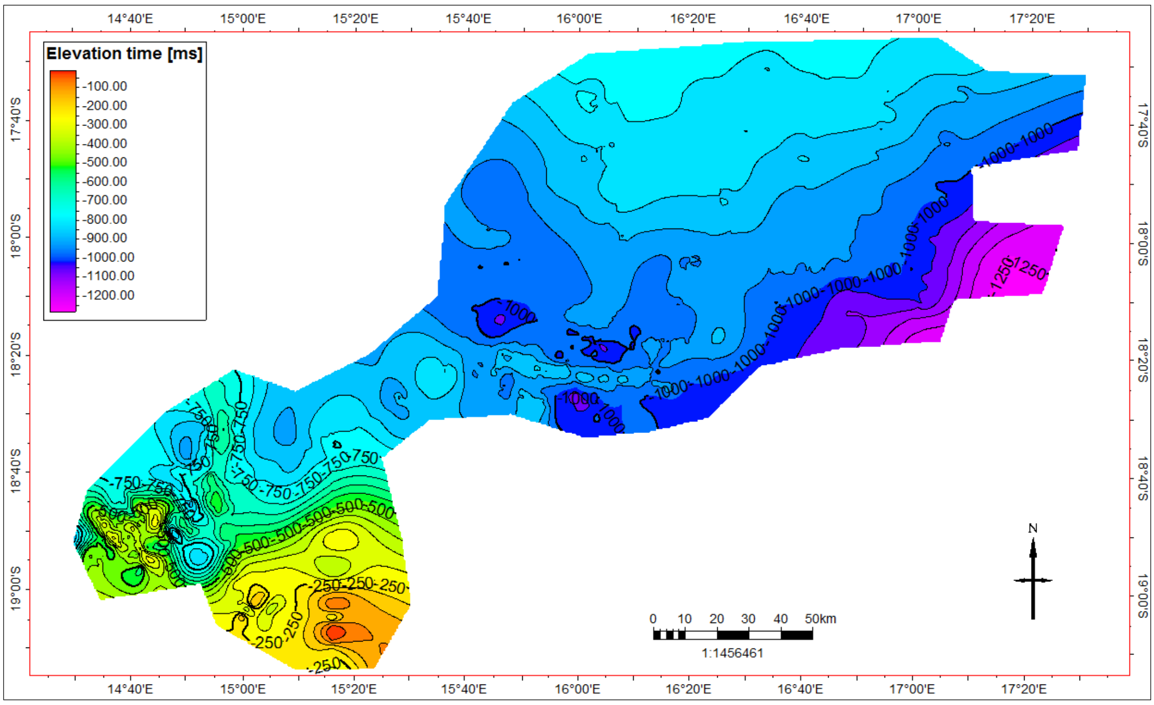


Figure 36: Time structure map of the top Mulden horizon

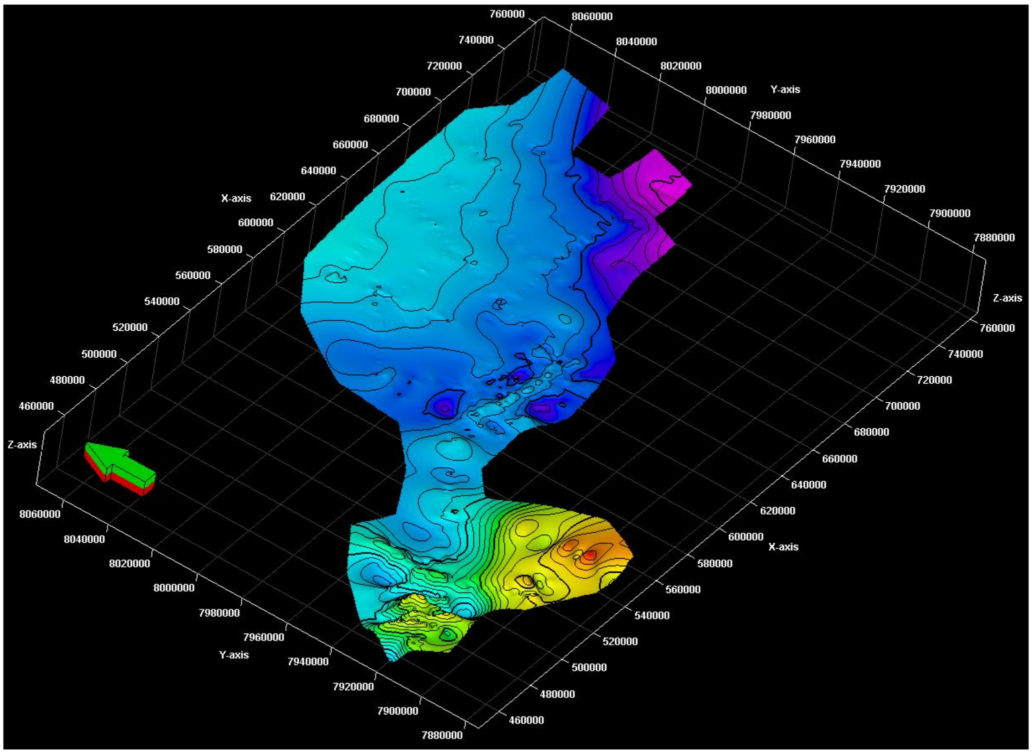


Figure 37: 3D surface of the top Mulden horizon showing the morphology

4.2 Potential Field Interpretation Results

A. Gravity Data Interpretation Results

A significant alignment of gravity lineament segments can be seen to transect the eastern half of the data area from the south-west to the north-east (Figure 38 and 39). It is clearly visible as a major discontinuity which separates three prominent gravity highs to the north-west from an area with lower and less dynamic gravity to the south-east, thus creating a considerable step in gravity.

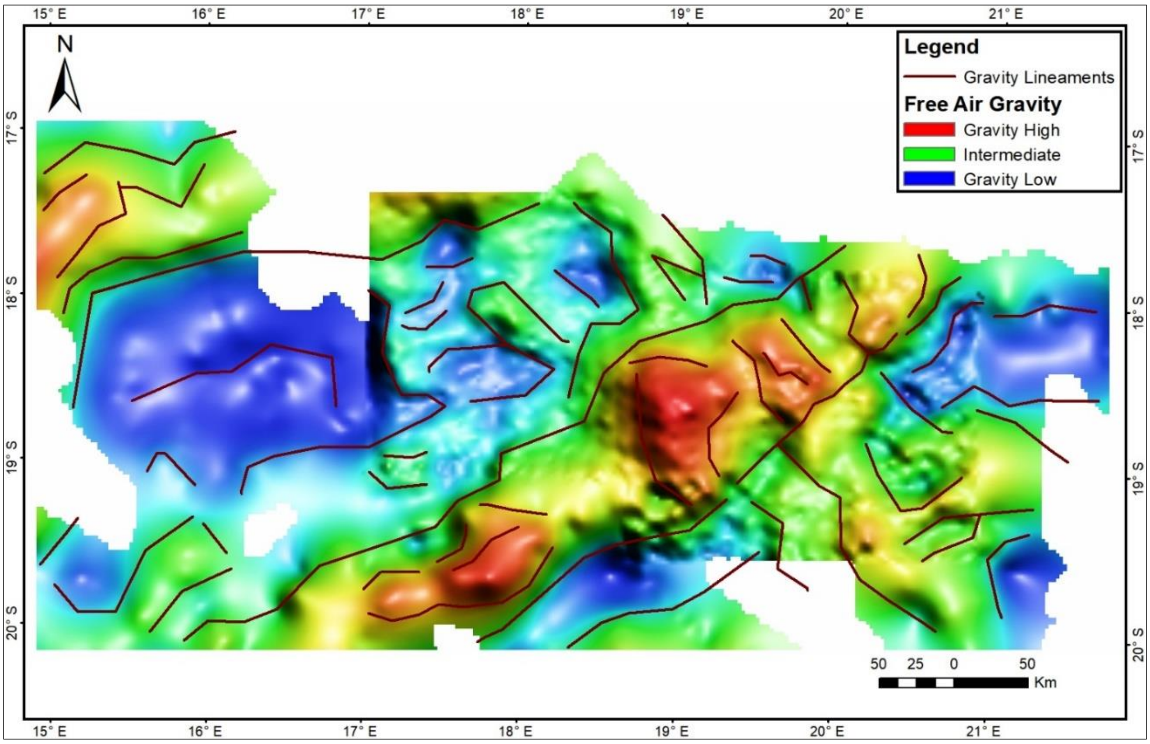


Figure 38: The main gravity lineaments in the Owambo Basin

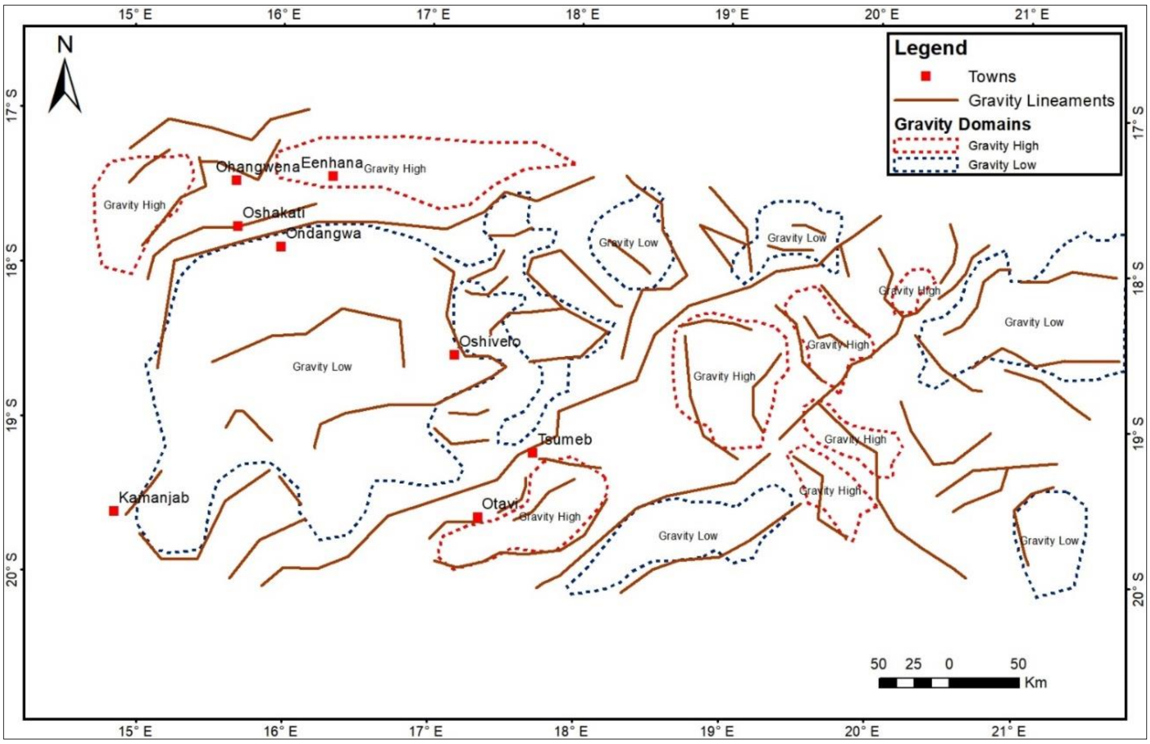


Figure 39: The main gravity lineaments and domains in the Owambo Basin

Areas of gravity lows are interpreted to be associated with the depocenters of the basin. A major discontinuity separates the middle diagonal gravity highs from the largest gravity low area on the western portion of the area, potentially representing a large depocenter (Figure 40). This implies the thickest stratigraphic thickness of the sediment fill overlying the Proterozoic metamorphic basement. Intermediate gravity values most likely represent shallower parts of the basin.

Three noticeable gravity highs aligned on the western side of the Omaruru Lineament are interpreted to be dense intrusive complexes, most probably of younger age than the metamorphic basement. Another significant gravity high is clipped by the north-western corner of the survey area and is also believed to be caused by an intrusive complex extending into Angola. The central gravity highs are interpreted to represent a structural high, probably produced by an uplift in the basement.

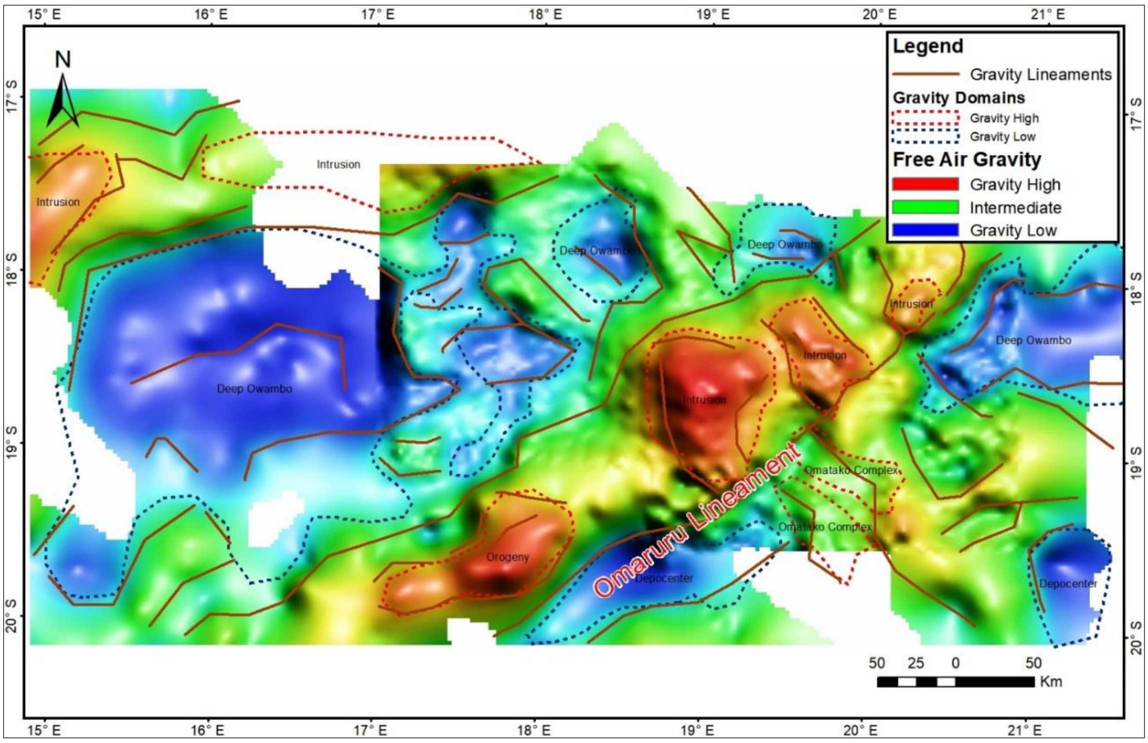


Figure 40: Interpretation of the main gravity lineaments and domains in the Owambo Basin

B. Aeromagnetic Data Interpretation

Several significant magnetic domains were delineated: a magnetic domain associated to the extensive sub-Kalahari Karroo Basalts in the Owambo Basin, characterized by irregular high-frequency and often high-amplitude magnetic anomalies (Figure 41). Other magnetic domains identified are caused by the magnetic Daneib, Omatako and Grootfontein Mafic Complexes (Miller, 2008). Remarkably, these intrusions have no anomalous gravity signature, therefore their densities must be very similar to that of the metamorphic basement which they intrude.

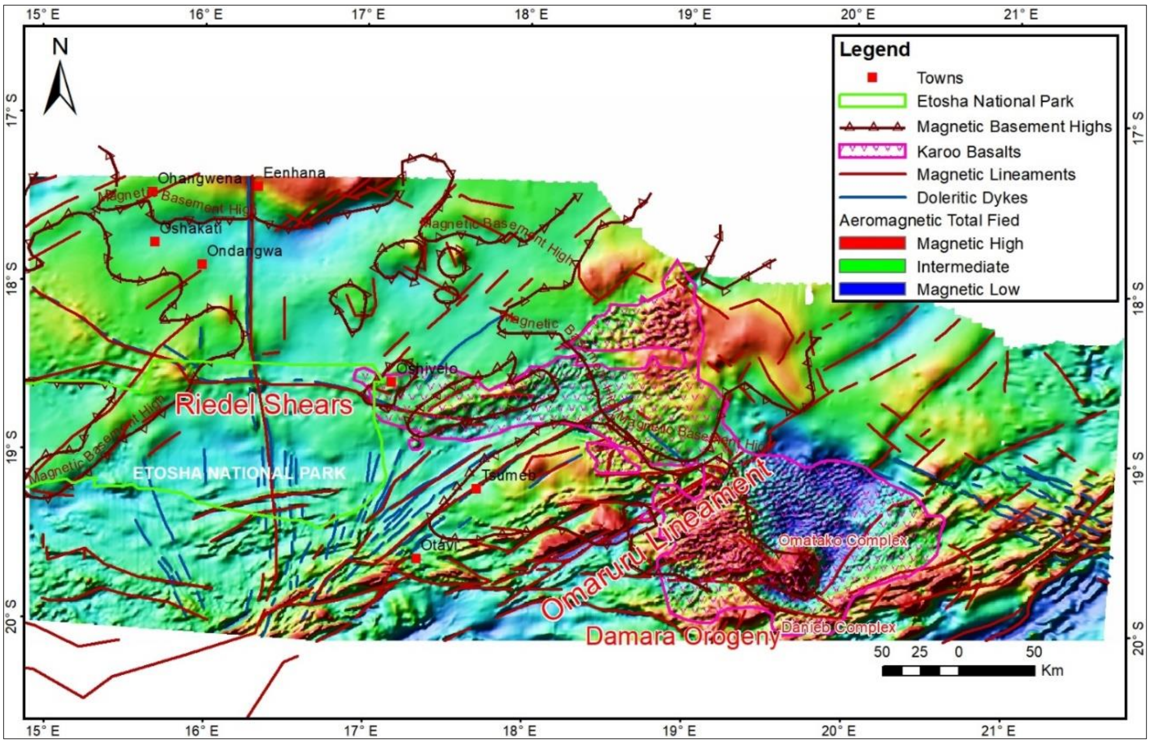


Figure 41: Aeromagnetic Total Field data with the interpreted magnetic features

Riedel System

In the southern part, typical aeromagnetic signature of intensely folded terrain is observed and is therefore interpreted to be part of the Damara Orogeny. In the western sector of the study area, transcurrent faults that represent a conjugate pair of Riedel's fracture pattern have been interpreted. The transcurrent faults also indicate that there is a major fault with a strike-slip component (caused by transpressive stress). This fault system has as well been observed in the 2D seismic data and is thought to be a result of the SW-NE Damara basement fabric that underwent shear.

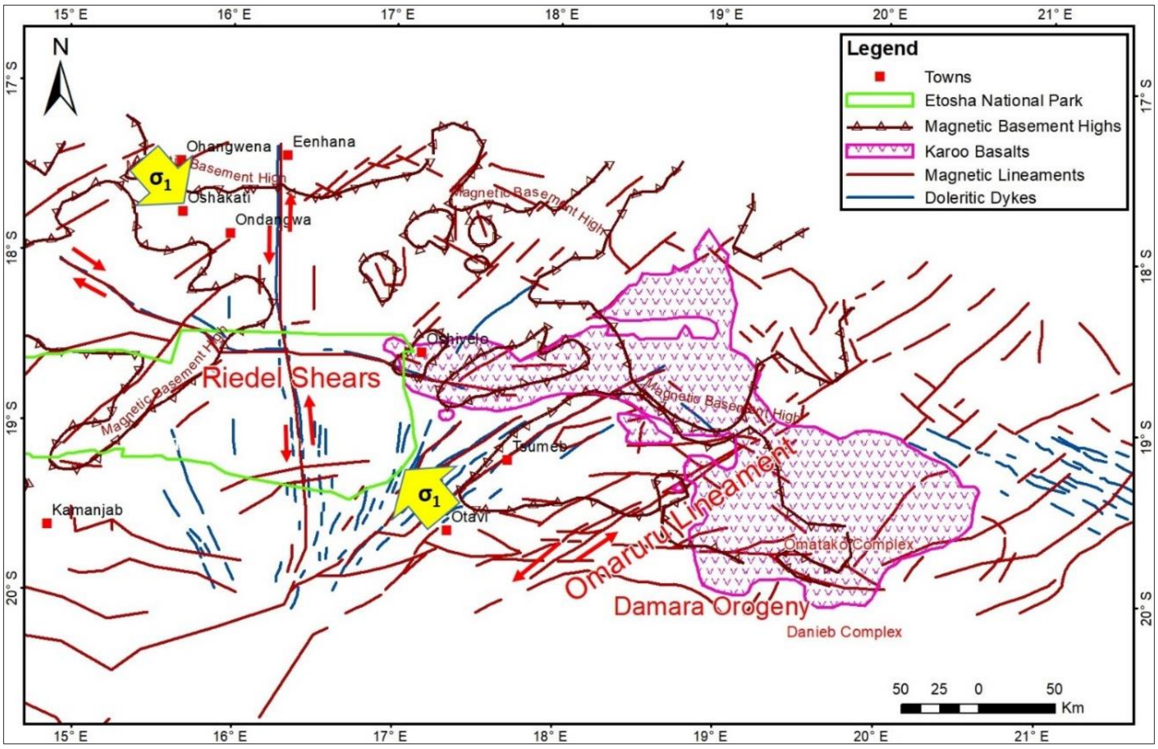


Figure 42: Interpreted Magnetic features in the Owambo Basin

The interpretation of the Riedel shears is consistent with the the angular relationship between the Omaruru and parallel lineaments with the sense of strike-slip motion and the associated Riedel shears. The principal stress (sigma 1, σ_1) is often 45° to the main strike-slip fault. This implies that the Riedel shears are some 30° degrees from σ_1, thus having an angle of 15 and 80° with respect to the main strike-slip fault, respectively, as shown in Figure 43.

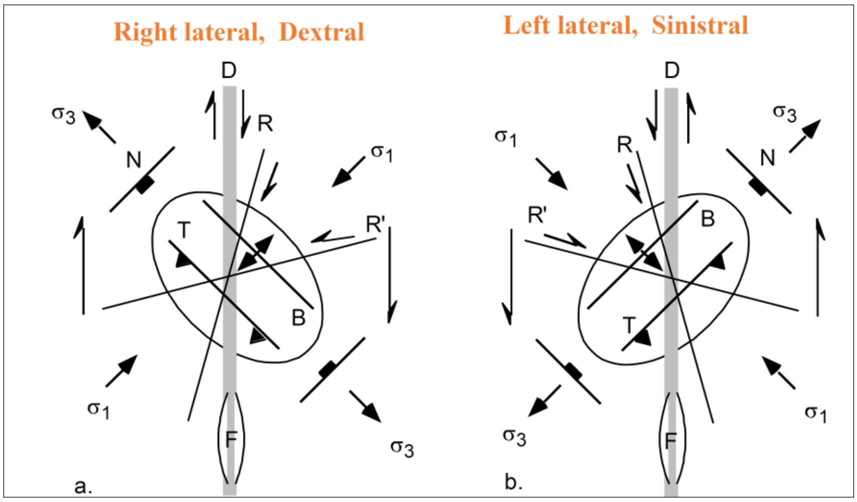


Figure 43: Angular relationships between the main strike-slip fault and the Riedel shears

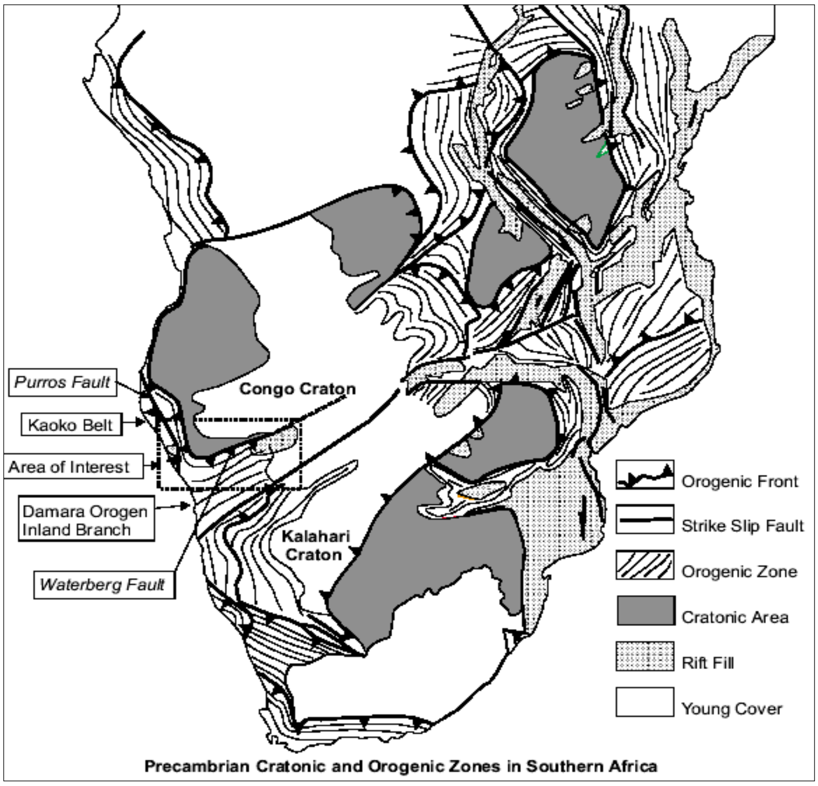


Figure 44: The Riedel shears in the Owambo Basin could related to deep rooted basement shears parallel and north of the Waterberg-Omaruru, Otjohorongo and Khorixas-Gaseneirob thrust/faults (modified from Daly et al, 1989)

The interpretation of both gravity and aeromagnetics data has been combined in order to understand the structures in the Owambo Basin with the objective of delineating potential exploration leads that could be confirmed in the seismic sections.

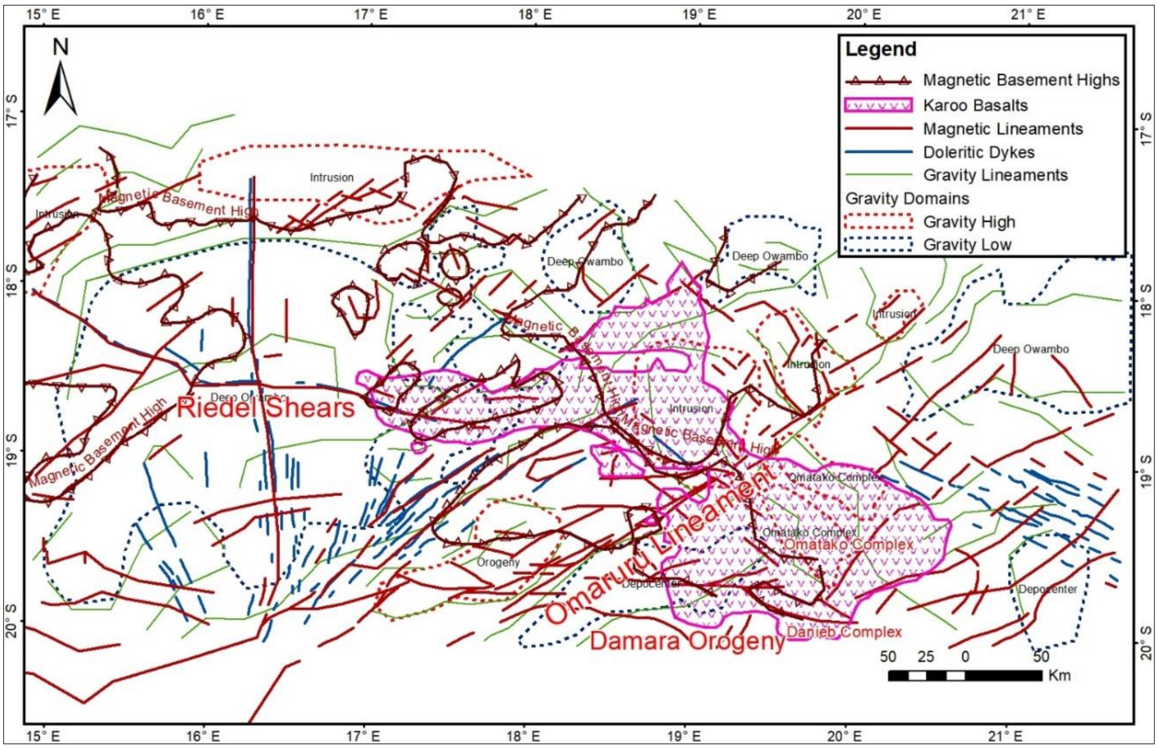


Figure 45: Combined interpretation of Gravity and Magnetic data showing the main structures

4.3 Field Work Results

During field observations stratigraphic units and associated lithologies, including their potential to act as reservoir, source and seal rocks, have been deduced. Table 5 below give a summary of the observations. The table is in stratigraphic order with oldest units at the bottom and youngest units at the top. Details including field photographs are given in Appendix 1.

Stratigraphic Unit	Outcrop No.	Location (Lat, Long)	Lithology (abbreviated)	Potential Petroleum System Element	Remarks

Tsumeb Subgroup (Huttenberg Formation)	OW11	-19.03931, 16.47099	Fractured well-laminated dark grey to black limestone with chert nodules	Source rock Reservoir	cross stratification and hummocky stratification is observed
Tsumeb Subgroup (Maiberg Formation)	OW12	-19.16930, 17.75784	Alternating dark grey to black laminated wavy bedded limestone	Source rock Reservoir	Presence of disseminated pyrite towards the bottom. Slumping features.
Abenab Subgroup (Berg Aukas Formation)	OW20	-19.40357, 17.91804	Carbonates with stromatolite features	Reservoir	Highly deformed, probably fractured reservoir
Abenab Subgroup (Berg Aukas Formation)	OW16	-19.43861, 17.73517	Dark grey carbonates	Reservoir Source rock	Overlies the glaciogenic unit
Abenab Sub-group (Chuos Formation)	OW15	-19.44142, 17.73891	Dark brown to black diamictites	Source rock	Marks the change in depositional environments
Nosib Group (Nabis Formation)	OW4	-17.40650, 14.24575	Red-brown coarse quartz sandstone	Reservoir	Cross stratification

Table 5: Summary of field observations showing stratigraphic units and associated lithologies, including their hydrocarbon potential

CHAPTER 5

INTERPRETATION AND DISCUSSION

The combination of field work with seismic, gravity and magnetic data interpretation allowed for a successful integrated approach towards achieving the characterization of the tectonostratigraphic architecture and reassessment of the hydrocarbon potential of the Owambo Basin.

Qualitative characterization of the prospective areas based on gravity and magnetics permitted the delineation of potential kitchen areas and potential structural traps. 2D seismic interpretation allowed for identification of key tectonostratigraphic units, stratigraphic mapping of the depositional sequences in the basin, deformations in these sequences, as well as identification of potential intervals of hydrocarbon exploration interest. Seismic interpretation also allowed for a consistent validation of structural features apparent in potential field data, which further led to a successful location of hydrocarbon exploration leads. Reassessment of the hydrocarbon potential is based on the integration of seismic, magnetic, gravity and fieldwork data.

By providing the detailed interpretation and discussion of the results in Chapter 4, this chapter aims to accomplish the objectives of this research project.

5.1 Tectonostratigraphic characterization based on Seismic interpretation

The tectonostratigraphic sequences recognized and bounded by the mapped horizons on the seismic reflect three main stages of the tectonic evolution of the Owambo Basin:

1. Rifting – Nosib
2. Spreading – Abenab & top Otavi

3. Collision – Mulden

Although poor quality seismic data does not allow for a detailed stratigraphic analysis and interpretation of the depositional sequences, some features were identified that characterizes each unit in relation to the tectonic condition during its deposition.

Through literature review and field work outcrop descriptions, improved understanding of the lithostratigraphic units was possible. During seismic interpretation, this proved useful in providing additional criteria for recognition and identification of the lithostratigraphic units within the megasequences based of their reflector properties and relationships with bounding units.

After the analysis of the stratigraphic summaries from the main literature documents, revision and consolidation of the stratigraphic column was possible. A revision of the stratigraphic summary of Martinez & Muundjua (2012) is given in Figure 46. In this revised stratigraphic summary, the Chuos Formation has been placed within the Abenab Sub-group, taking into consideration that the diamictites are separated from underlying rocks by a regional unconformity. In addition, the name "*Chuos*" has been preferred to "*Varianto*" following Hoffmann & Prave (1996). Furthermore, Etjo Formation has been placed above Prince Albert Formation as the top-most Karoo Super Group formation. In contrast to Martinez & Muundjua (2012) the name "*Etjo"* was preferred to "*Nanzi*" since the name "Nanzi Formation" arose from the fact that the Nanzi well intersected hard, light grey to buff colored and is well-bedded sandstone (Etjo Formation) that overlies unconformably the Prince Albert Formation. At the top of the stratigraphic summary, Ombalantu, Beised, Olukonda and Andoni were all placed withinthe Kalahari Sequence following Miller (1997; 2008).

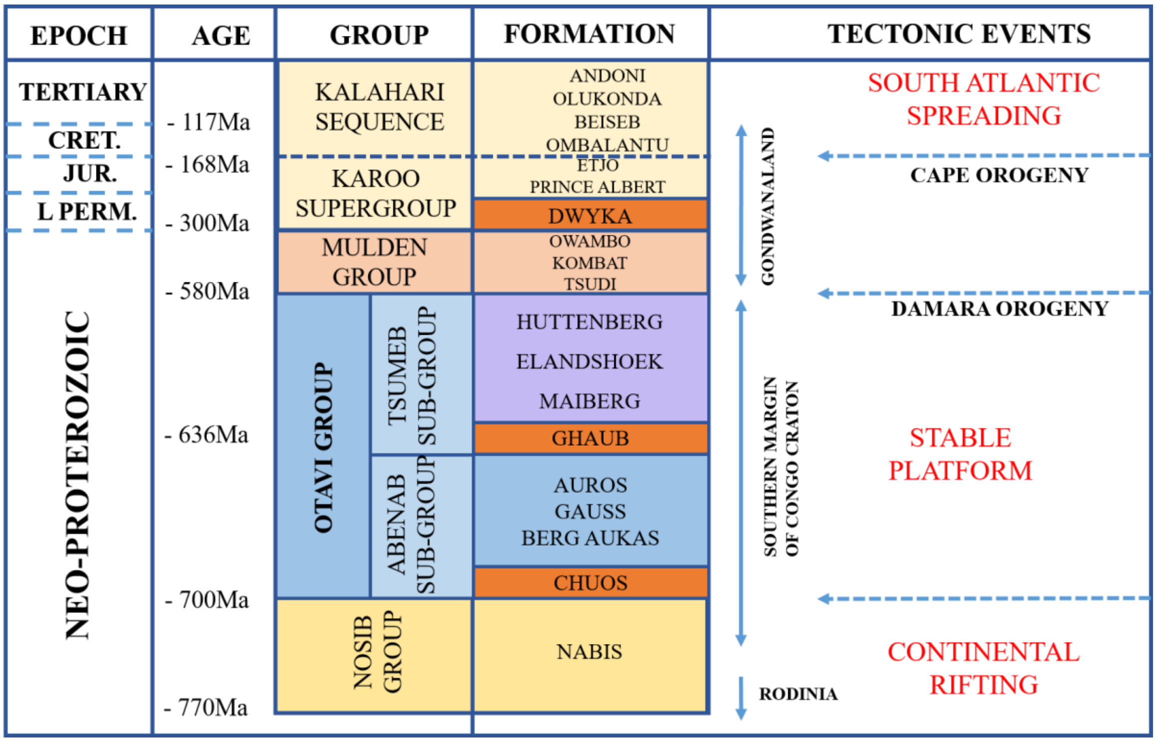


Figure 46: Revision of the stratigraphy summary of the Owambo basin and the main tectonic events (modified after Martinez & Muundjua, 2012)

5.2 Prospectivity maps based on Gravity and Magnetics

The interpretation of the gravity and magnetic data permitted the delineation of the most prospective areas in terms of hydrocarbon potential in the Owambo Basin, in terms of potential kitchen areas and trapping structures.

Free Air Gravity data interpretation allowed the delineation of deep areas that are likely to have the thickest stratigraphic thickness of the sediment fill overlying the Proterozoic metamorphic basement. These areas would be buried deep with considerable overburden to thermally mature the potential source rocks in the basin and therefore represent potential kitchen areas.

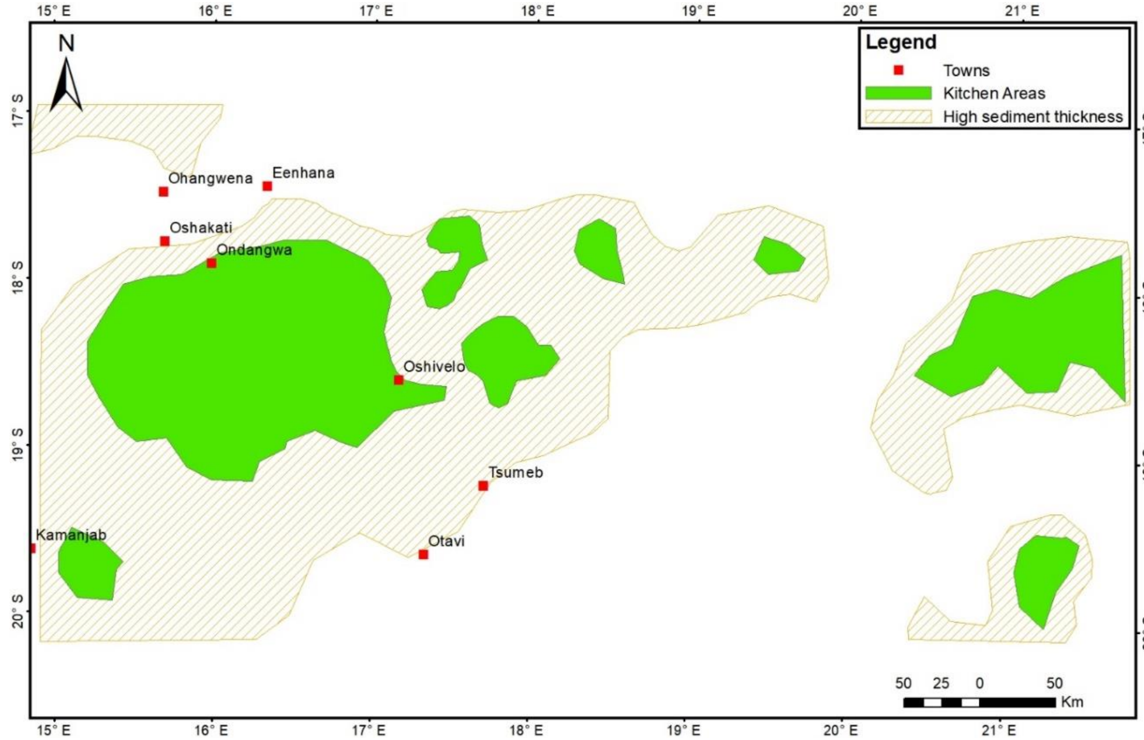


Figure 47: Prospectivity based on gravity data showing expected highest sediment thickness and depocenters (green).

In the same vein, delineation of basement highs and intrusions was possible, therefore allowing for a recognition of areas of less sedimentary accumulation, hence less hydrocarbon prospectivity, within the basin.

Superimposition of magnetic data over the gravity allowed for tracing of magnetic anomalies over the gravity lows. These magnetic anomalies most likely respond to shallow anticlines analogous to the Oponono structure (indicated in Figure 48, in more detailed described in Hoak et al). Twenty-three of these structural leads have been mapped (including the already drilled Oponono structure) and their approximate areas in square kilometers have been calculated to provide a lead ranking. To note, volumetric estimates have not been calculated, as the incomplete seismic coverage did not allow for petroleum column estimates.

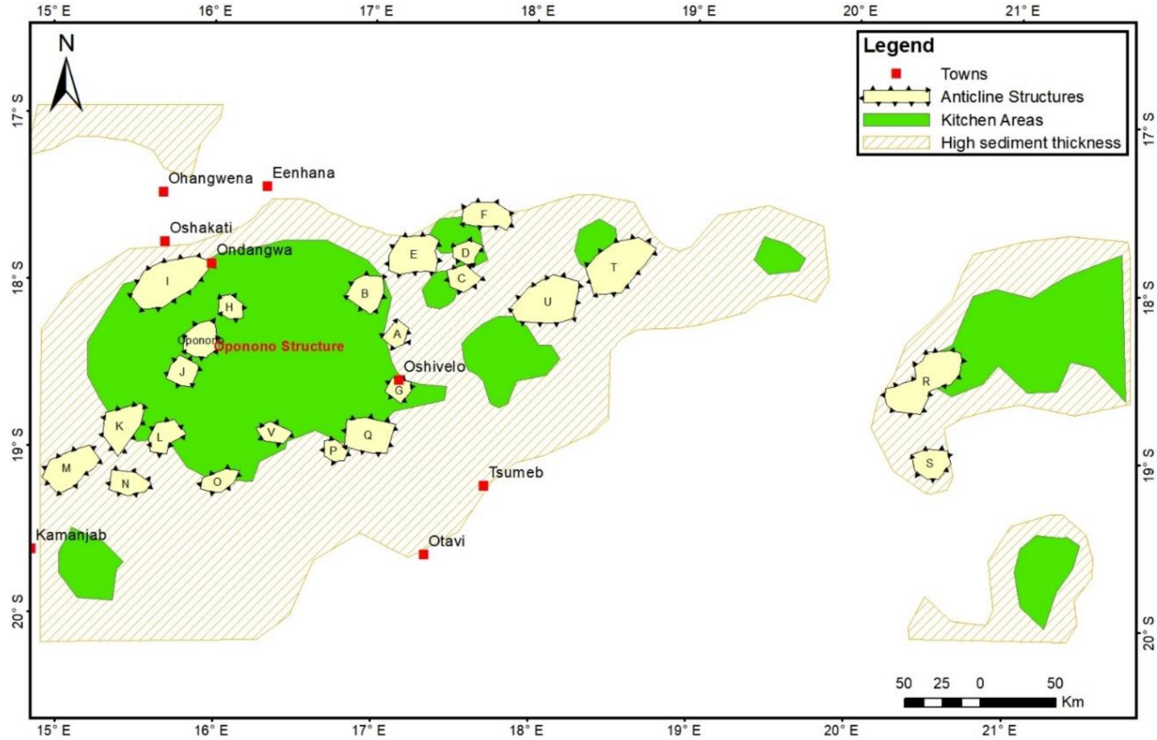


Figure 48: Structural leads identified from magnetics data superimposed on gravity-based prospectivity

The leads coincide with the Owambo Basin depocenters, with about 70% of them placed directly over the kitchen areas, increasing their chance of hydrocarbon charge where favorable conditions existed. The size of these structural leads range from 179 to just over 1100 km^2 of area, representing potentialy substantial accumulations of hydrocarbons. For reference, the already drilled Oponono structure is about $400km^2$.

Lead Name	Area (km²)
A	201
B	449
C	271
D	214
E	718
F	460
G	186
H	217
I	1136
J	302
K	584
L	345
M	700
N	339
O	271
Oponono	435
P	179
Q	641
R	1120
S	391
T	1098
U	1086
V	218

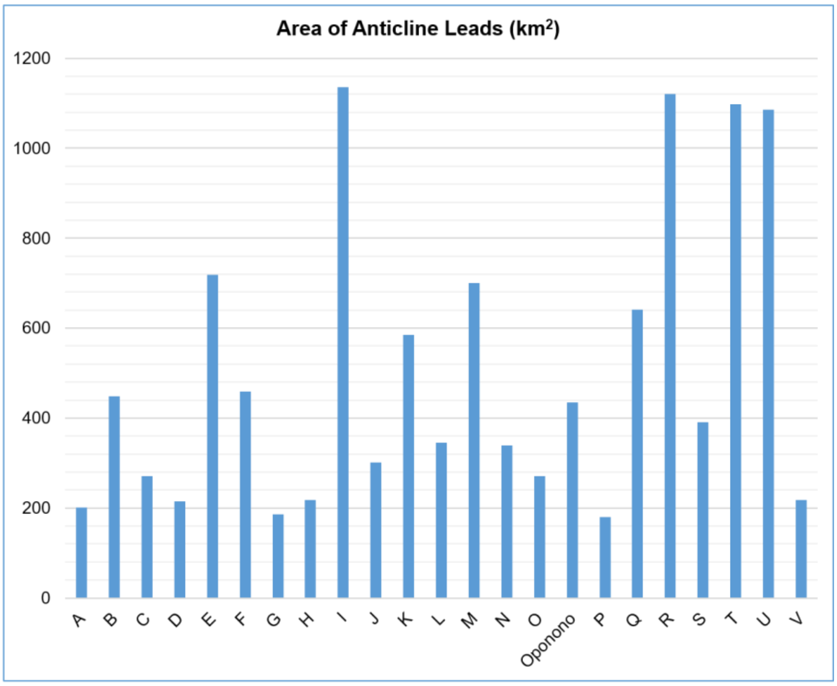


Figure 49: Approximate size of anticline leads

5.3 Integration of Seismic, Gravity and Magnetics interpretations with field data

The integration of both potential field methods with seismic interpretation allowed for superimposition ofthe results in order to refine the prospective areas of the basin. Several gravity lineaments and gravity anomalies clearly coincide and have been interpreted in the seismic sections, which further increases confidence in the results. This is the first time that integrated interpretation of the deepest section was carried out in this basin.

Superimposed onto the seismic, it is evident that most gravity lineaments follow deep seated faults that bound graben or half-graben structures.

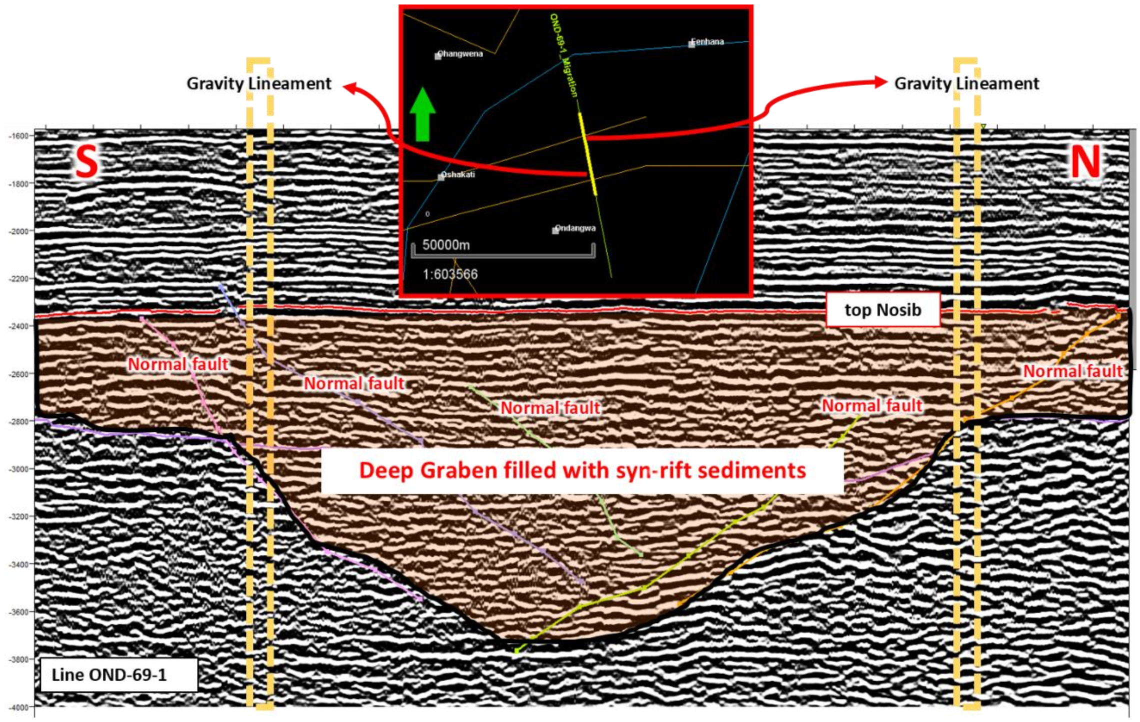


Figure 50: Gravity lineaments clearly coinciding with deep graben boundaries on seismic

These faults affect the basement as well as the Nosib syn-rift section, but at times also reach up to the lower section of Otavi carbonates. The graben faults were probably initiated prior to Nosib Group deposition during uplift in the early rift phase. During this period the faults controlled erosion of pre-Nosib basement and thereby the morphology of erosive valleys that provided accommodation space for the syn-rift Nosib Group (Figure 50, 51). In these grabens considerable sediments have accumulated, reaching up to 1000ms in some sections, therefore providing considerable opportunities for clean Nosib sandstones as confirmed by the field outcrops (see Appendix Figure 5-7 as well as Appendix Figure 21-24).

Likewise, several magnetic lineaments also coincide with edges of basement highs bounded by normal faults, clearly identified on seismic sections. These faults are also associated to deep grabens of up to 1000ms in depth, filled with syn-rift sediments.

Seismic reflector character and pattern suggest that in most of these deep grabens the sediments are not metamorphosed, however close to the basin rim seismic imaging could not provide a clear image.

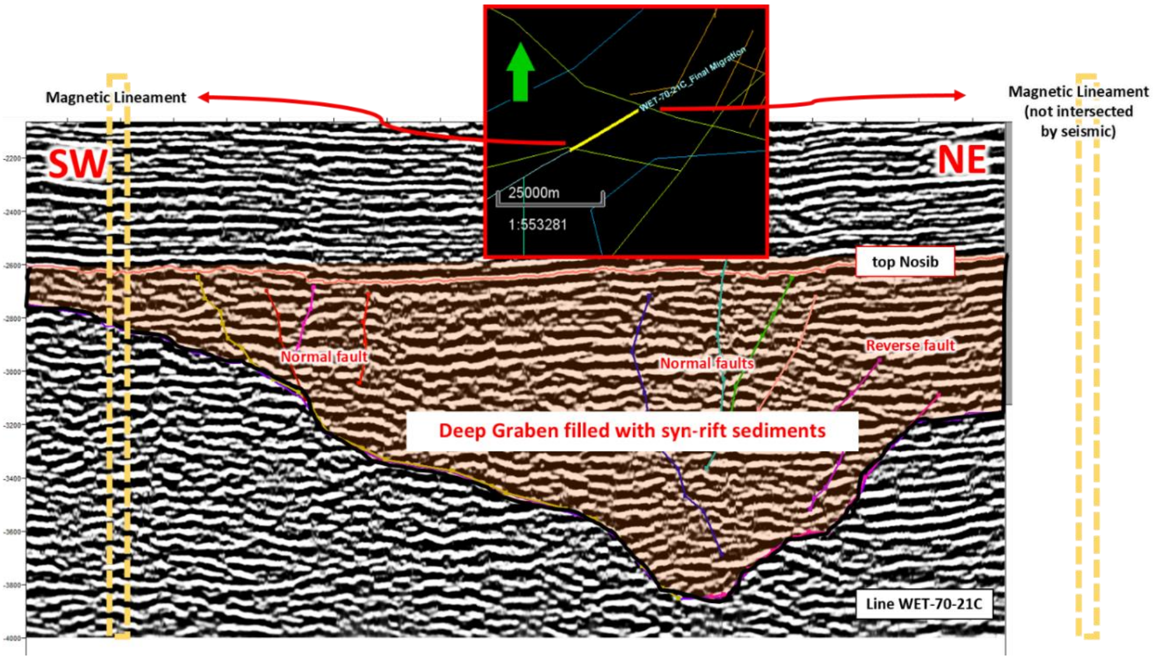


Figure 51: Magnetic lineaments clearly coinciding with deep graben boundaries on seismic

Although the absence of shales and carbonates have been documented in outcrops of the syn-rift section (Nosib), it is typical of syn-rift sequences to have lacustrine depositional phases and here it should have preceded the deposition of Otavi carbonates. However, fluviatile conditions prevailed, hence the diamictites which can also be potential source rocks. The fact that these graben structures are bounded by normal faults that reach up to the Otavi carbonates where onlaps have been mapped on the seismic represent a good opportunity for migration of hydrocarbons generated within this section.

5.4 Reassessment of the Petroleum System of the Owambo Basin

The evolution of the basin through geological time favored the conditions for the essential elements and processes of the petroleum system to be formed (i.e. source rock, reservoir, seal, trap formation, maturation, generation, expulsion and migration of hydrocarbons from source to traps). The field work results proved to be very useful in terms of verification of potential reservoir, source and seal facies as essential elements of the petroleum system in the Owambo Basin, discussed here on continuation.

Source Rock

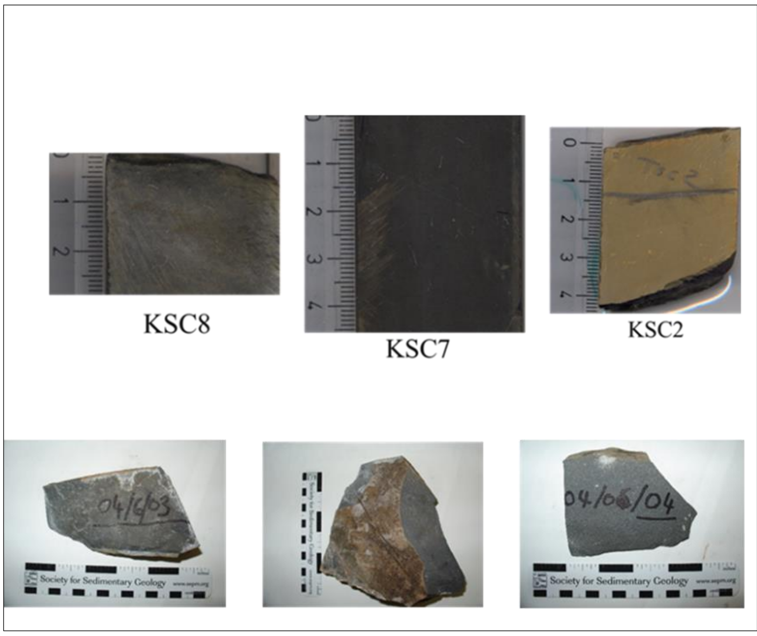
The main risk in terms of hydrocarbon prospectivity of the Owambo Basin is related to the maturity of the source rocks due to the age of the basin, which is often thought to be over mature). However, Proterozoic-sourced hydrocarbons have been encountered in analogous basins in other parts of the world: i.e. Sichuan Basin – China, Southern Salt Basin – Oman, Lena/Tunguska Region – Siberia (Grosjean et al., 2009; Korsch et al., 1991; Kontorovich et al., 1990).

Although high thermal gradients are expected to be generated by lengthy spans of thermal subsidence of this basin, there are several indications that point out to acceptable thermal levels for the source rocks. Four main intervals of potential source rocks are:

- Abenab Subgroup carbonates associated with post-glacial deposition (post Chuos Formation).
- Tsumeb Subgroup carbonates associated with either restricted intra-platform or post glacial deposits (Ghaub Formations).
- Mulden Group black shale member (Kombat Formation).

- Karoo Super-Group shales (Prince Albert Formation).

According to Bechstädt et al. (2009), hese post-glacial sediments have total organic carbon (TOC) values from 0.1 to a maximum value of 2.3% TOC in a core sample from the KH1 (Khusib Springs) well drilled in Otavi mountainland (Figures 52 and 53). Based on Littke & Welte (1992) a carbonate rock with more than 0.3% TOC can be classified as a potential source rock.



TOC & C FROM DOLOMITIC SHALE: KHUSIB SPRINGS CORE KH.

Sample	Thickness above Auros Fm	TOC	C
KSC8	46.33m	2.286	9.970
KSC7	43.13m	0.450	4.728
KSC2	16.92m	0.171	5.651

TOC & C FROM DOLOMITIC SHALE FROM KEILBERG FARM OUTCROP.

Sample	Thickness above Ghaub diamictite	TOC	C
K04-06-04	~40m	1.027	6.807
K04-06-03	~20m	1.565	8.108
K04-06-02	Immediately above	1.000	6.208

Figure 52: Potential Carbonate source rock samples of Otavi Group (Bechstädt et al., 2009).

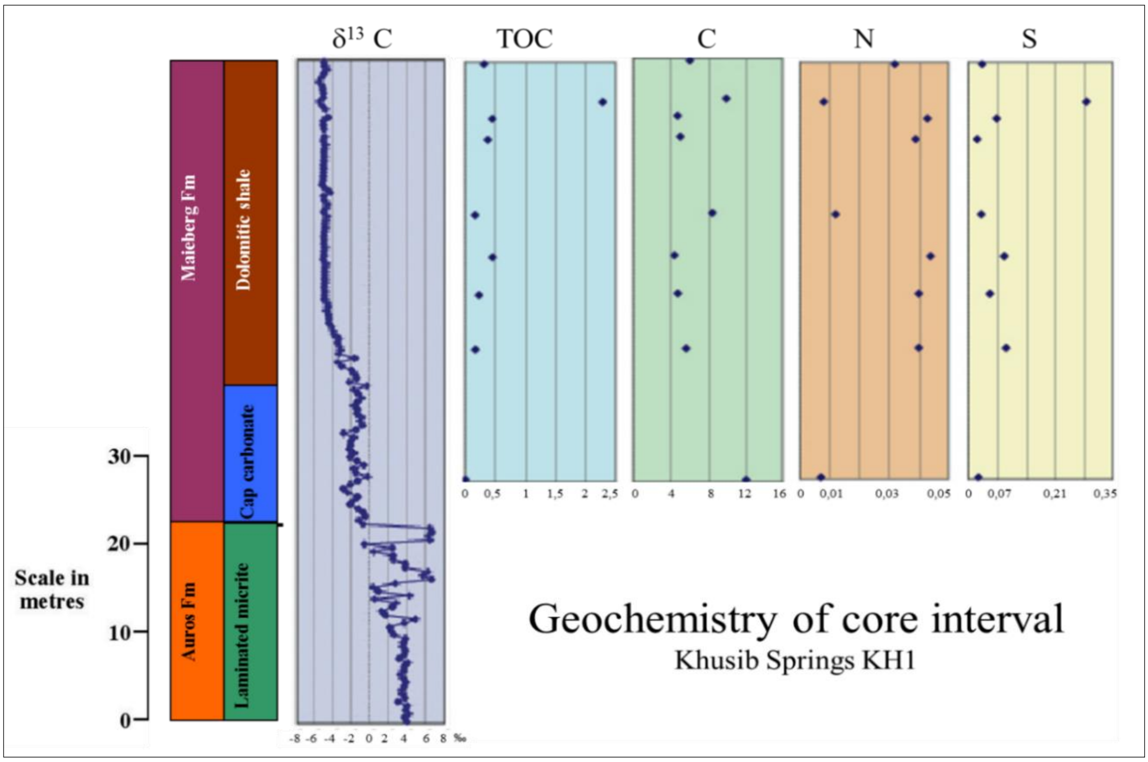


Figure 53: Geochemistry of the core interval of the Khusib Springs (Bechstädt et al., 2009).

In certain areas, Otavi Group carbonates are characterized by a deep ramp depositional environment, in which high volumes of organic matter was deposited, making these sediments good candidates for potential source rocks. The outcrop of Tsumeb-Tsinstabis Road (Point OW12 in field trip, Maieberg Fm.) is characterized by the existence of thin-bedded limestones including storm deposits, mud mounds and inter-bedded shales. The accumulation of thinly-bedded limestones is a result of both in situ accumulation of skeletal fragments, and storm-transported carbonate deposition.

The black shale member of Kombat Formation represents another potential source rock in the Mulden Group. Seven Samples from wells 5-1A, 1-1 and 2-1 averaged 2.8 wt% TOC; one of these samples contained 215 ppm extractable hydrocarbons (Momper, 1982).

The Karoo Supergroup shales are thought to be presently immature because they have not been buried deep enough. Having been drilled in some of the shallow wells within the basin, their potential is expected to be high in the deeper parts of the Owambo Basin (especially in depocenters in Figure 40) where maturity conditions can be more favorable due to burial and thermal maturity.

Reservoirs

Potential reservoir rocks in the Owambo Basin are the Nosib Group fluvial sandstones, Otavi Group carbonates and the various Mulden Group sandstones. Intra-Damara paleokarst structures may have lost of their porosity but various post-Damara episodes of karsting have produced cavernous porosity which is a major source of groundwater in the basin margins.

In the lower stratigraphy of the Owambo Basin, the units deposited during continental environments (fluvial) such as the Nabis Formation sandstones form good quality reservoirs. Moreover, these older sandstones may be thrusted above the Otavi Group source rocks especially in the southern part of the basin (Martinez & Muundjua, 2012), and as observed during field work, giving the former good opportunities to be charged with hydrocarbons.

Fractured carbonates are also believed to represent potential reservoirs in the Otavi Group, mainly associated to compressional structural traps formed during the orogeny. The carbonates penetrated by Well 5-1A are believed to be fractured reservoirs with porosities of 8-15%. These porosities might also be enhanced by secondary processes such as deep karstification due to the presence of corrosive fluids that migrated either as a pre-oil phase through the reservoir (Van Berk, et. al, 2015; Wright and Harris, 2013) or acidic fluids from volcanism.

The presence of abundant stromatolites in the lower parts (Figure 54) and oolite beds has been interpreted as a shallowing process of the basin that continued through to the end of Otavi deposition. The limestones and the thin shales in the upper parts suggest varying salinities and possibly local lagoonal conditions.

Figure 54: Stromatolite features on the Berg Aukas Foration carbonates forms potential good reservoirs

Sandstones and siltstones in the Mulden Group from the base upwards reflect removal of Otavi carbonates with their abundant interbedded cherts during erosion of the source area to the West before the underlying arkoses and basement granites and gneisses contributed to the sediment load.

Mulden Group sandstones in the Upper Owambo Formation in the ST-1 well had up to 20% porosity (Momper, 1982). According to Miller (1997), thicknesses of the Owambo Formation are recorded to be 908m and 1490 m in the Wells 1-1 and ST-1, respectively, providing enough gross thickness.

Traps and Timing

Several play types have been recognized in the seismic and potential field data as illustrated in Figure 55 below:

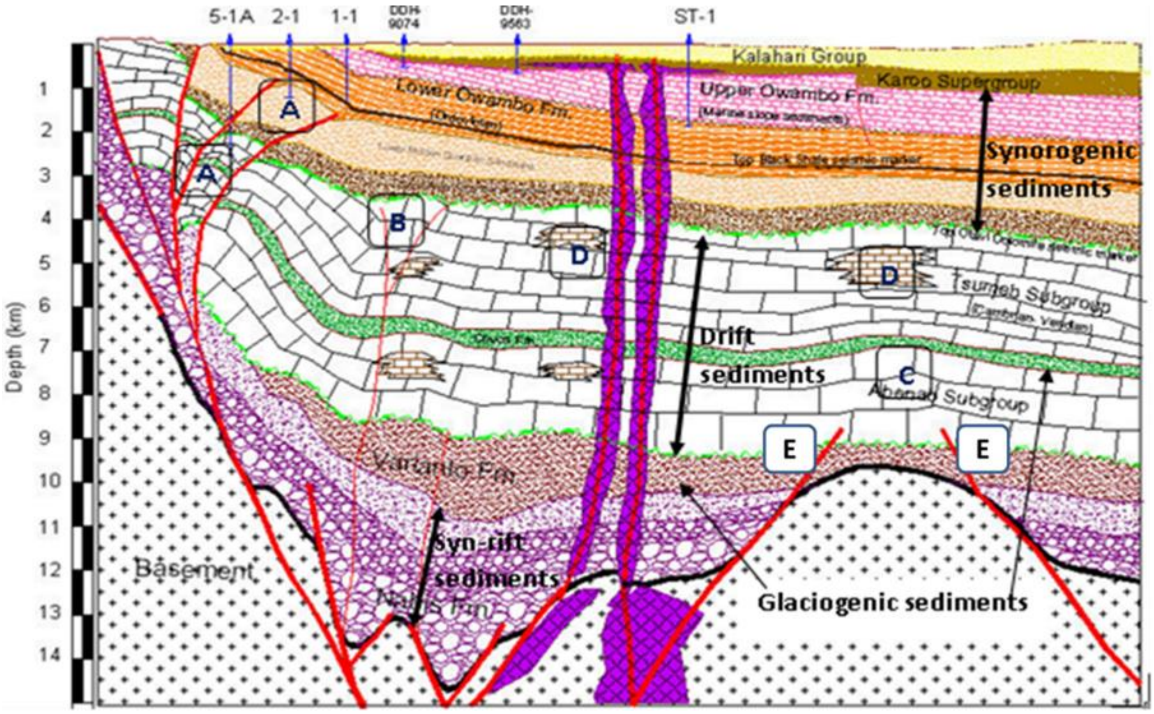


Figure 55: Play types in the Owambo basin: A=flower structure, B=anticline traps, C=drape over basement highs, D=Carbonate build-ups, E=tectonic inversion traps (Martinez & Muundjua, 2012).

Anticline traps: these traps are formed by direct folding resulting from the stresses originating from fold belts (in the fore bulge zone of the basin) (Figure 55, *B*). Compressional regime associated to the conjugated Riedel's faults have also resulted in this type of play, as proven by the Oponono structure. These anticline traps have been largely recognized on magnetic data.

Drape over basement highs: Sediment concordance over basement highs can form large anticline structures which can be good hydrocarbon traps (Figure 55, *C*). On seismic sections, these are observed to have formed within the units following the

Nosib Group, as the latter's relief influenced the deposition of the overlying successions. Fault reactivation has also originated in this type of play as movement of the fault have been reversed, causing the bulging up of sediments and draping of the successive layers.

Carbonate build-ups: As seen on the seismic sections (Figure 31 & 32), mounds of stromatolites in Abenab and Tsumeb carbonate platforms have developed due to sedimentological processes in relatively shallow platform environment during the carbonate deposition (Figure 55, *D*). Where the reactivated faults reach this interval, the mounds can be charged from the underlying units. Close to the thrusts, these mounds may be superimposed on the Mulden Group shales as source rocks, providing good opportunity for hydrocarbon charge.

Tectonic Inversion Traps: Some of the extension faults associated to the syn-rift process have undergone tectonic inversion during the development of the orogeny (Line OPO-70-12 in Figure 20), and may form anticline structures that could be good hydrocarbon traps (Figure 55, *B*).

Generation, Hydrocarbon Charge and Seal

Hydrocarbon generation should have taken place at the late stage of the orogeny where source rock burial was considerably increased by the stacking of the thrust folds. Migration and entrapment of hydrocarbons potentially occurred after trap formation, which represent favorable timing for the charge of the traps.

Hydrocarbons potentially generated by the post glacial unit of Maieberg Formation, which should be mature at depths up to 3000 -3500 m, are likely to charge and be contained in the Tsumeb Sub-group carbonates that are overlying them at depths of

2000 to 2200 m. Otavi Group carbonates are both reservoir and source rocks and thus do not require long migration distances. Deep seated faulting seen on seismic can pose as migration pathways. The black shales of the Kombat Formation would potentially charge overlying Owambo Formation sandstones that are documented to be 105m thick in Well 1-1.

Seal rocks expected are the shales of Mulden Group or any impermeable intra Otavi Group unit.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The Owambo Basin remains a frontier area in terms of data coverage and hydrocarbons exploration. It remains a challenge to carry out a detailed stratigraphic study in the basin due to (1) to very limited seismic data in the basin and (2) due to the poor quality of this seismic data. However, seismic interpretation allowed for regional characterization of the tectonostratigraphic sequences, including some details of deep syn-rift features previously paid insufficient attention to. Integration of seismic with gravity and magnetics proved to be a useful approach on this regional scale study, allowing for delineation of high thickness sediment accumulations, potential kitchen areas and the mapping of numerous anticline leads.

It is therefore recommended that further seismic data be acquired and interpreted in order to appropriately construct a stratigraphic framework of the basin. In addition, deeper seismic imaging is required in order to properly understand the deep syn-rift sediments that appear to be non-metamorphosed, hence extending the number of play types the basin offers.

It is also recommended that several deep stratigraphic wells be drilled including acquisition of geophysical logs and checkshots that will allow for reliable seismic-to-well tie, as well as understanding the stratigraphy and lithostratigraphy in the prospective areas of the basin.

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APPENDIX

Appendix A: Detailed results of fieldwork.

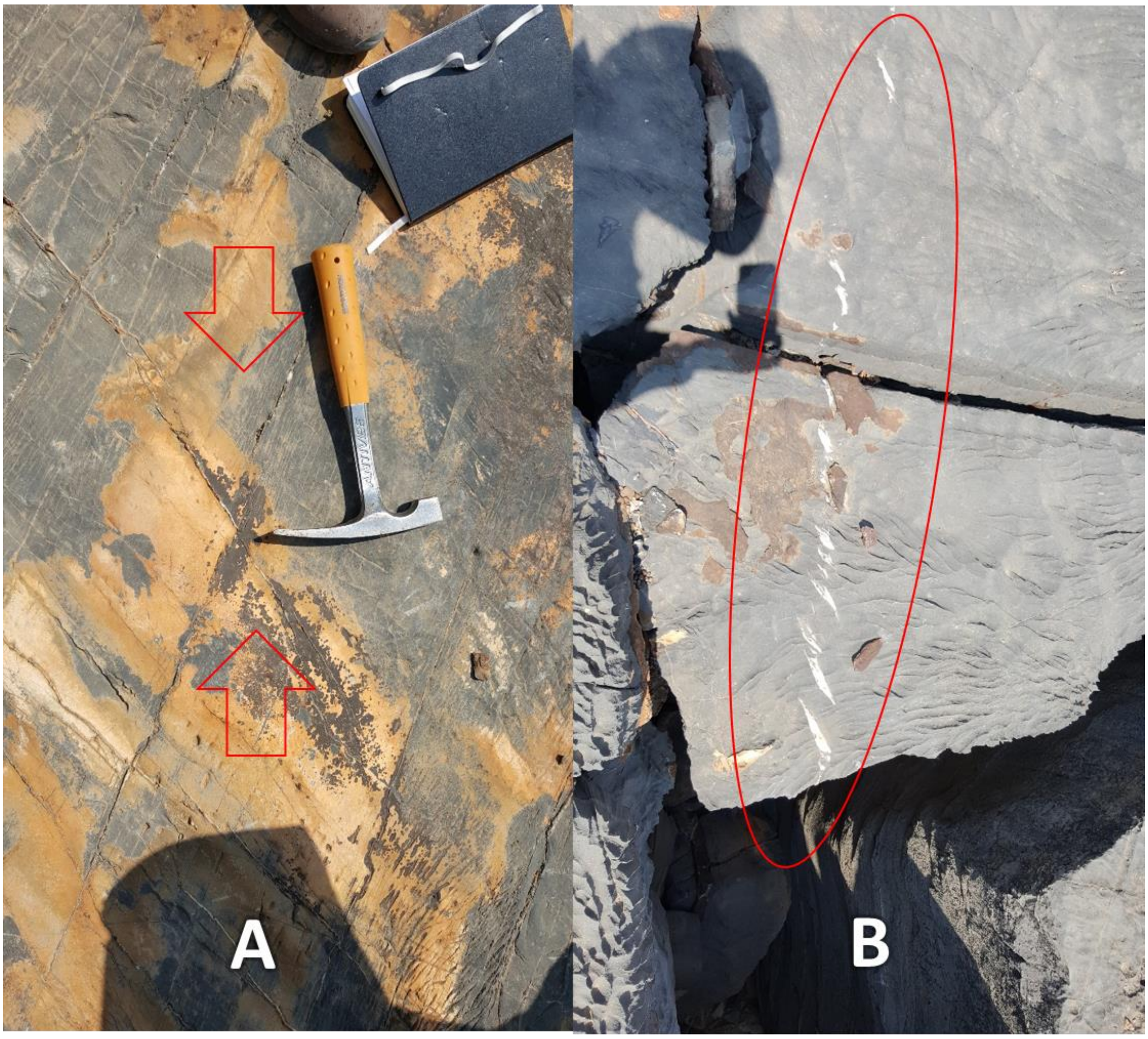
The detailed description of each outcrop is given in this appendix.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
15 08 2016	OW1	-18.08101	13.86387	Abenab	Berg Aukas

Located at 3km NE of Opuwo.

Dark-grey to black fractured dolostone with calcitic filled veins (Appendix Figure 1). Layers 30-50cm thick implying deep to medium depth water deposition. Karstified in places and filled with chert. Riedel shears (Appendix Figure 1A) and en-echelon extension fissures present (Appendix Figure 1A-B), implying strike-slip stress components. Structural readings (strike/dip of fault plane): 090°/18°

This carbonate outcrop demonstrates reservoir qualities enhanced by fractures and karstification (Appendix Figure 2). Eastwards in the basin, the Abenab Subgroup can be expected to be buried, providing good opportunities to be charged with hydrocarbons migrating up-dip.



Appendix Figure 1: Riedel shears and en-echelon structures in the Abenab Subgroup

Appendix Figure 2: Fractured carbonates of the Berg Aukas Formation. Note the karstification.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
15 08 2016	OW2	-18.14619	13.92354	Tsumeb	Maieberg

Located at 900m southeast of C41 and D3710 intersection

Dark brown to dark grey dolostone, fine grained with disseminated sulphide (pyrite), wavy bedding with syn-sedimentary deformation (breccias). Cross bedding observed (Appendix Figure 4). Stromatolites on top of the outcrop (Appendix Figure 3) indicate shallow water depositional environment. Structural reading of bedding 126°/25°.

The Maieberg formation carbonates can be good hydrocarbon reservoirs due to their framework porosity from the stromatolites.

Appendix Figure 3: Stromatolites on top of the outcrop (Maieberg Formation)

Appendix Figure 4: Cross bedding on the Maieberg Formation carbonates

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
15 08 2016	OW3	-17.40650	14.24575	Nosib	Nabis
15 08 2016	OW4	-17.40290	14.28892	Nosib	Nabis

Located at 11.5km east of the C35 and D3700 intersection, Ruacana area.

Syn-rift section consisting (Nosib Group) of conglomerate with angular to sub-rounded clasts (Appendix Figure 5), indicating close proximity to sediment source. Larger beds of conglomerate at the bottom intermittent with cross bedded sandstone towards top of section (Appendix Figure 6). Eventually conglomerate grades into coarse sandstone, occasionally with fine grained laminated layers of sandstone in between.

Cross stratification (Appendix Figure 7) suggests a high energy environment, probably fluvial to deltaic.

Towards the NE at stop OW4, recrystallized grains suggest slight metamorphism in the red brown sandstone, although the sedimentary features are still visible (Appendix Figure 8). Shear zones can be observed within packages of quartz sand.

The Nosib Group sandstone has excellent reservoir characteristics. However, in the Owambo Basin, it might only be applicable to exploration where it could be thrusted over potential source rocks, most likely near the basin rim.

Appendix Figure 5: Conglomerate and sandstone beds of the Nosib Group

Appendix Figure 6: Close up of the angular to sub-rounded conglomerate section

Appendix Figure 7: Cross stratification suggests a high energy environment, probably fluvial to deltaic

Appendix Figure 8: Shear zones within the packages of quartz sand

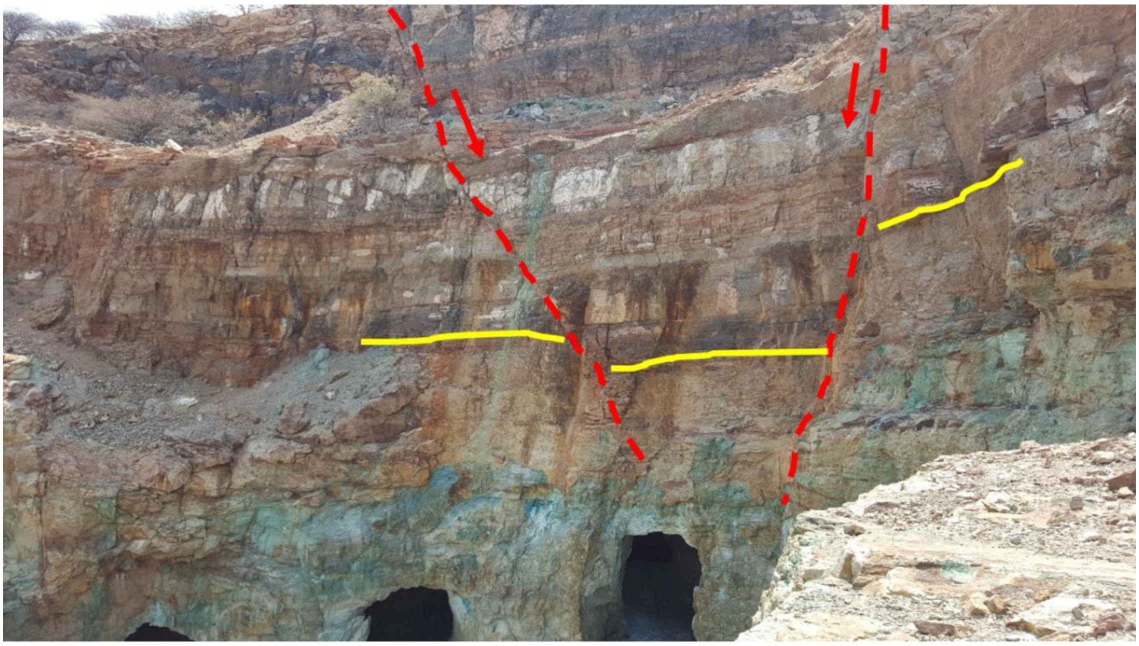
Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
16 08 2016	OW5	-19.42241	15.16430	Abenab Khoabendus	Berg Aukas Synrift

Located in an old mine 41km northeast of Kamanjab, south of Etosha National Park.

Near the top of the section, cap dolostone of the Berg Aukas Formation is observed (Appendix Figure 9). The dolostones are dark grey to black in color with thin laminations. The laminations and parallel horizontal bedding of the dolostone suggest deep water deposition below storm wave base.

Towards the bottom, conglomerate, metasedimentary and metavolcanics sediments (Appendix Figure 10) which form the basement to the Otavi group in this area, forming primary host rocks for malachite mineralization (Appendix Figure 11) at Kopermyn. This area is likely to have undergone intense fracturing due to the junction between Kaoko and Damara belts. Basement related normal faulting can be observed and a graben with differential displacement in normal faults can be observed (Appendix Figure 55).

Appendix Figure 9: Conglomerates and metasediments of the Khoabendus group. Note the Berg Aukas Formation carbonates towards the top of the section.



Appendix Figure 10: Graben structure associated to basement-related normal faulting. Note the green color of malachite mineralization towards the bottom.

Appendix Figure 11: Close-up view of the carbonates alternating with conglomerates towards the top of the section.

The deep-water deposited carbonates can be potential candidates for source rock interval. The synrift section sandstone can be a good reservoir where it overlies any potential source rock with charging capacity.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
16 08 2016	OW6	-19.48988	15.16827	Abenab	Berg Aukas

Located southwards of point OW5.

Dark grey carbonate/dolomite (Appendix Figure 12), strongly reacting with HCL. This carbonate is typically lighter in color than the Maieberg formation carbonates.

Appendix Figure 12: Dark grey carbonate of the Berg Aukas Formation

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
16 08 2016	OW7	-19.50970	15.15320	Tsumeb	Maieberg

Located at 300m southwest of the D2671 and D2695 intersection

Steeply dipping laminated grey carbonate/limestone of the Maieberg formation, with clear folding and wavy pattern. It can be observed that these carbonates are significantly darker than those observed at the previous point.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
16 08 2016	OW8	-19.51199	15.14784	Tsumeb	Elandshoek

Located at the Bloukrans Hill on Skeins Farm

Highly fractured black, wavy bedded laminated carbonate with significant cementation (no apparent porosity). Slight reaction with HCL.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
16 08 2016	OW9	-19.52237	15.14685	Tsumeb	Huttenberg

Located at about 1km NE of OW8.

Highly compressed shallow upwelling carbonates with chert. The sedimentary patterns point to a shallow depositional environment. Reacting with HCL slightly stronger than Elandshoek carbonates observed at previous point.

No picture available for OW9.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
16 08 2016	OW10	-19.40537	15.92779	Tsumeb	Elandhoek

Located near entrance of El Dorado Camping Lodge.

Contact between Tertiary calcrete (Kalahari Group) and grey carbonates (dolostone) of the Elandshoek Formation.

Appendix Figure 13: Contact between Kalahari Group and Elandshoek Formation.

Appendix Figure 14: Distant view: contact between Kalahari Group and Elandshoek Formation.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
17 08 2016	OW11	-19.03931	16.47099	Tsumeb	Huttenberg

Located at Halali water point in the Etosha National Park

At the upper section of the outcrop, highly fractured well-laminated dark grey to black limestone with nodules of chert (Appendix Figure 15). The chert nodules are mainly rounded (Appendix Figure 16) but layered form is also present.

Towards the middle of the outcrop, truncations, cross stratification and hummocky stratification is observed (Appendix Figure 17). There is also evidence of slumping (Appendix Figure 18), indicating deposition in gravitationally unstable part of the platform. Some evidence of reworking may point to periods of high energy environments.

Appendix Figure 15: Laminated dark grey to black limestone with nodules of chert (Huttenberg Fm)

Appendix Figure 16:Round chert nodules within the carbonates)

Appendix Figure 17: Truncations, cross stratification and hummocky stratification in the middle of image.

Appendix Figure 18: Slumping features indicate deposition in unstable part of the platform.

The depositional environment for this outcrop corresponds to proximal deep ramp. The deepening trend observed from the upper section of the outcrop (laminations - deeper water facies below storm base) towards the bottom of the outcrop (hummocky cross stratification and truncation - shallow water facies) suggest a transgressive environment.

The Huttenberg deeper water carbonates can be candidates for source rocks if they persevere high TOC in the subsurface.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
17 08 2016	OW12	-19.16930	17.75784	Tsumeb	Maieberg

Located on Tsumeb-Tsintsabis Road, about 10km north of Tsumeb

Alternating dark grey to black laminated wavy bedded limestone capped by medium to dark grey dolostone (Appendix Figure 19), weathered to pinkish brown color. Presence of disseminated pyrite towards the bottom. On the southern side of the road, red brown carbonate has undergone deformation and evidence of slumping is present (Appendix Figure 20).

The Maieberg formation was preceded by the glaciogenic sediments of the Ghaub Fm. These carbonates should probably have the highest source rock potential within the Tsumeb Sub-Group.

Appendix Figure 19: Alternating dark grey to black laminated wavy bedded limestone

Appendix Figure 20: Evidence of slumping in red brown carbonate

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
18 08 2016	OW13	-19.44949	17.73636	Nosib	Nabis

Located on Guestfarm Ghaub

Basal conglomerate of the synrift section of the Nosib Group (Appendix Figure 21).

Well rounded medium- to large-sized clasts (5-10cm) indicate likely fluvial transportation over considerable distance. It is worth noting that in the Otavi mountains area, the conglomerates clasts are more rounded compared to the Ruacana area.

Appendix Figure 21: Conglomeratic synrift section of the Nabis Formation (Nosib Group)

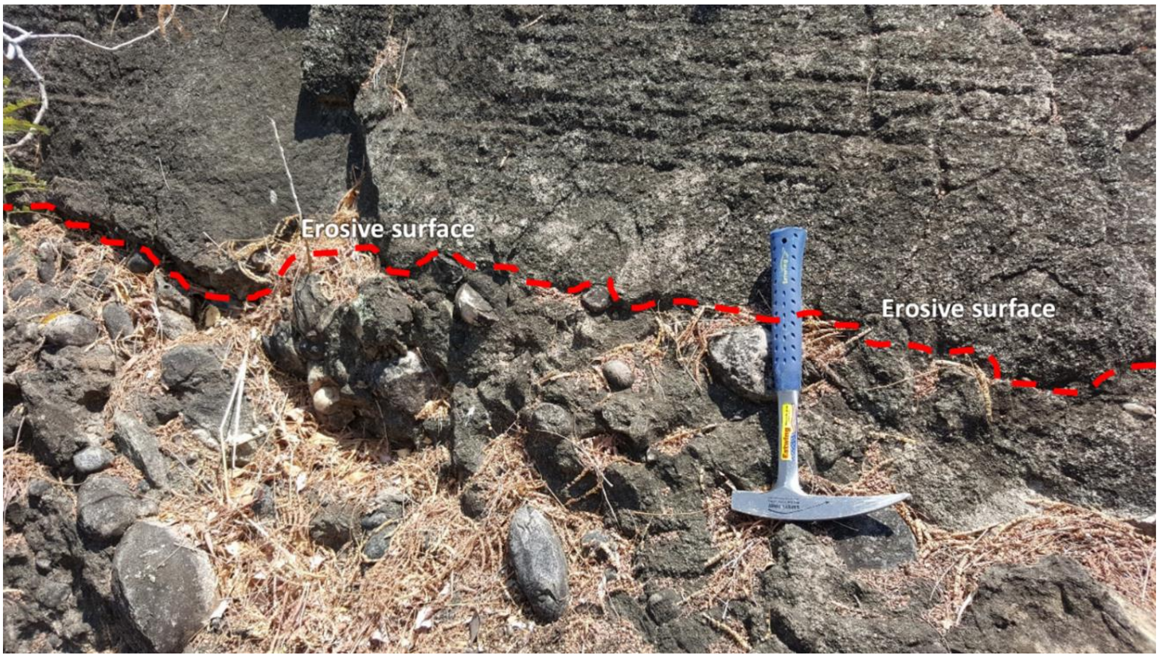
Appendix Figure 22: Different sized rounded clasts in the conglomerate

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation

18 08 2016	OW14	-19.44848	17.73731	Nosib	Nabis

Located about 200m north of OW13

Contact between basal conglomerate and about 1.5m medium to coarse sandstone unit (Appendix Figure 23) which is overlain by a thinner conglomerate section (Appendix Figure 24). There is a clearly visible erosive surface between the two units (Appendix Figure 23).



Appendix Figure 23: Erosive contact surface between basal conglomerate and sandstone

Appendix Figure 24: The sandstone unit is in-turn overlain by another thin conglomeratic section

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
18 08 2016	OW15	-19.44142	17.73891	Nosib	Chuos

Located about 300m north of point OW14

Dark brown to black diamictites of the Chuos (Varianto) Formation (Appendix Figure 69). The contact between The Nabis and Chuos formations is not clearly visible due to limited outcrop exposure between points OW14 and OW15. However gradual increase of diamictite sediments and reduction in conglomerate pebbles is apparent northwards between the two points.

Appendix Figure 25: Dark brown to black diamictites of the Chuos (Varianto) formation

The Chuos Formation marks the change in depositional environments in the Owambo Basin about 700ma (Lower Neoproterozoic). Mostly fluvial sediments of the Nabis Formation were overlain by the glaciogenic tilite of the Chuos/Varianto Formation, clearly making the deepening of the basin to shallow marine and probably change in climate condition to warm/tropical.

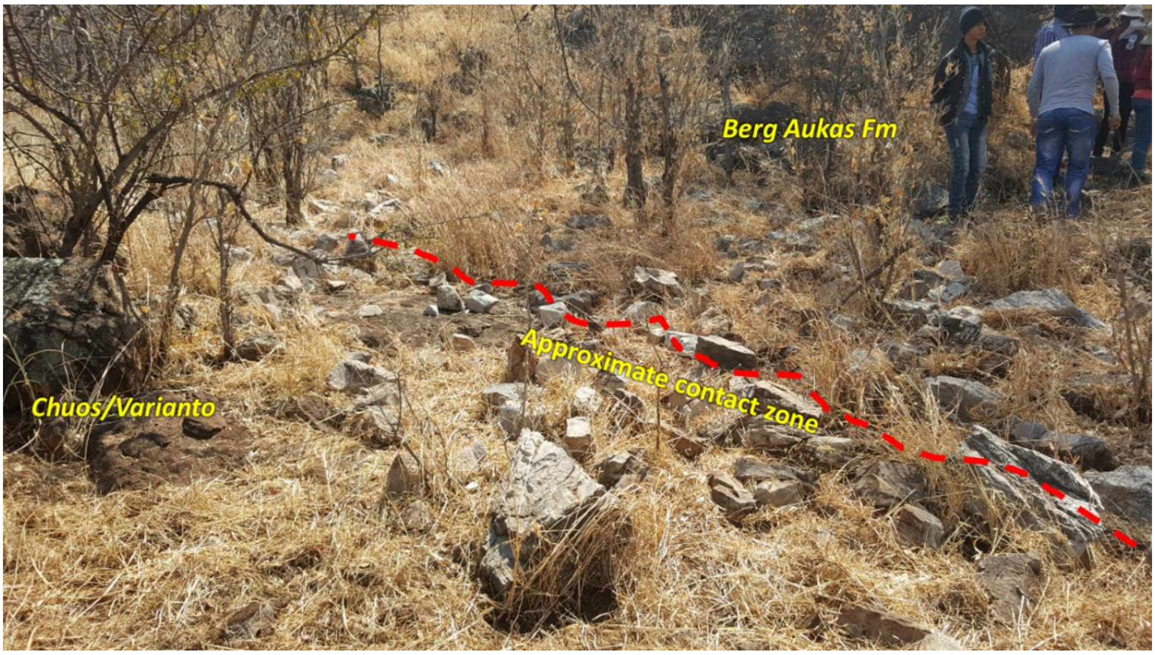
This change to shallow marine conditions has important significance in the petroleum exploration context as this marks potential deposition of source rocks belonging to the lower part of the Abenab Sub-group, that give rise to opportunities to charge the overlying Berg Aukas carbonates.

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
18 08 2016	OW16	-19.43861	17.73517	Abenab	Berg Aukas

Located about 1km northwest of point OW15

Dark grey carbonates of the Berg Aukas Formation (Appendix Figure 26). This carbonates immediately overlies the glacial sediments, suggesting deposition in shallow to medium depth marine conditions. Contact with the diamictites (Chuos/Varianto Formation) should be within 15m south of point OW16 as rock blocks and clasts from both formations can be observed at this point (Appendix Figure 27).

Appendix Figure 26: Dark grey carbonates of the Berg Aukas Formation



Appendix Figure 27: Approximate contact between Chuos/Varianto and Berg Aukas formations

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation
18 08 2016	OW17	-19.43075	17.82289	Nosib	Nabis

Located about 90m north of D3022

Light grey medium to coarse sandstone (Appendix Figure 28). This sandstone demonstrates good reservoir qualities as observed at points OW13 and OW14. However, the conglomerate section is not outcropping at this point, but it is expected to be a few meters below this sandstone section as observed at the previous points.

Bedding structural readings: 334°/22°

Appendix Figure 28: Medium to coarse sandstone of the Nabis formation

Date	Point Name	Latitude	Longitude	Group/Subgroup	Formation

18 08 2016	OW18	-19.42373	17.85853	Basement	Basement
18 08 2016	OW19	-19.41670	17.89435	Basement	Basement

Located along D3022, about 3.5 and 7 kilometers east of point OW17, respectively.

Control points. Weathered and foliated light grey granite basement, part of the Huab Metamorphic Complex. This basement is overlain by the Nabis Formation observed at the previous points.

No pictures available for these basement outcrops.

Date	**Point Name**	**Latitude**	**Longitude**	**Group/Subgroup**	**Formation**
18 08 2016	OW20	-19.40357	17.91804	Abenab	Berg Aukas

Located along C42 (Tsumeb-Grootfontein Road)

Highly deformed and fractured carbonates with stromatolite features (Appendix Figure 29). Fizzing with acid suggests a dolostone.

The stromatolitic features (Appendix Figure 30) suggest a shallow depositional environment. For reservoir consideration, these carbonates would be classified as a fractured reservoir. However, the Abenab Sub-group carbonates are usually tight and would not be good reservoirs where fractures are not prominent.

Appendix Figure 29: Highly deformed and fractured carbonates of the Berg Aukas Formation

Appendix Figure 30: Stromatolite features on the Berg Aukas Foration carbonates