Some Geological and Geophysical Aspects of the 2016/2017 Drilling Campaign in the Windhoek Aquifer

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Abstract: Jointed quartzites of the NW-dipping Auas and Kleine Kuppe formations together with cross-cutting faults form an interconnected, fractured aquifer network that is in part compartmentalised. The faults have a significantly higher permeability than the quartzites and large-fragment fault breccias are often highly permeably in depth. The 2016/2017 drilling programme was aimed at tapping the faults down to the depth of 400 m in localities close to existing infrastructure. Resistivity and magneto-telluric surveys perpendicular to faults were followed by the drilling of inclined, reverse-circulation probe boreholes to determine accurately the dip of faults. All boreholes deviated from their initial start orientations. Production holes were sited according to fault dip and to expected borehole deviation. Hydrothermal alteration of country rocks adjacent to the faults and mineral precipitation are ascribed to the thermal effects of the 52-Ma Aris Suite trachytes. Boreholes were sampled every metre and comprehensive records were taken. The Windhoek Aquifer is a closed system that cannot lose much water in any direction underground. It is an outstanding water reserve in times of need. However, it has been exploited at a rate far greater than the rate of natural recharge and artificial recharge is essential to replenish it and to ensure the availability of emergency water supplies during future droughts. The drilled production boreholes form part of the implementation of the Windhoek Managed Aquifer Recharge Scheme (WMARS) which is based on the premise of over-abstracting water from the Windhoek Aquifer during periods of extended drought and recharging the aquifer with water supplied from the three-dam system blended with potable reclaimed water.

Keywords: Windhoek aquifer; Groundwater; Faulting; Drilling; Water management; Auas Formation; Kleine Kuppe Formation

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Introduction

The 2016/2017 drilling campaign in the Windhoek Aquifer was undertaken to provide one source of emergency water supplies to the City of Windhoek as a result of poor inflows into the main water supply dams during the past two rainy seasons. The targets for the drilling were the depths of 350 to 400 m in the main N-S and NW-trending faults that cut the main aquifer quartzites of the Auas and Kleine Kuppe formations. Shallower boreholes drilled into these faults have provided Windhoek with water in the past and still do but a deeper slice of the aquifer was needed to provide a greater volume of water for Windhoek's massively increased population. To expedite the project and to contain costs, the deep holes were located close to existing pump and pipeline infrastructure. Although the jointed quartzites carry water, the fault breccias are by far the main, highly permeable water bearers. Individual faults vary from a few centimetres to 9 m in width and some fault zones which consist of several closely spaced faults can be up to about 40 m wide.

The faults evolved through several stages of movement and hydrothermal silicification and in outcrop many have slicken-side surfaces dipping both east and west. Consequently, it is not always possible to determine dip direction of the faults. Therefore, it was necessary to precede the drilling of the production holes with ground-based geophysical surveys perpendicular to the strike of the faults to get an indication of the dip of the faults or to locate the faults below colluvial cover. This was followed by drilling of two or more inclined probe boreholes in order to determine accurately the dip of each fault. Only thereafter could the location of the production hole be sited. A variety of problems encountered during drilling will be described below.

The drilled production boreholes form part of the implementation of the Windhoek Managed Aquifer Recharge Scheme (WMARS) which was identified in 2004 as the next supply augmentation scheme to supply water to the Central Area of Namibia. The WMARS is based on the premise of over-abstracting water from the Windhoek Aquifer during periods of extended drought and to recharging the aquifer with water from the three-dam system blended with potable reclaimed water from the New Goreangab Water Reclamation Plant when the volume of the Von Bach Dam is more than 40 %.

Geology

The geology of the Windhoek Aquifer is presented in Figure 1. This consists of rocks of the Damara Supergroup. A thin succession of the lowest stratigraphic units, the Kamtsas, Duruchaus, Waldburg and Blaukrans formations, rests unconformably on or has been thrust onto the Palaeoproterozoic basement granitic gneisses of the Hohewarte Metamorphic Complex. The next unit in the succession, the Auas Formation, overlies the lower units either conformably or with a thrust contact. The Auas Formation quartzites interfinger with and are coeval with the graphitic schists of the Blaukrans Formation. The Auas is followed successively by the glaciogenic Naos Formation with its thin lenses of siliceous iron formation, above which are the Mahonda, Gomab River and Kleine Kuppe formations. The latter consists of thick quartzite layers that interfinger with schist of the lower part of the Kuiseb Formation. Amphibolites occur in the Naos, Mahonda and Gomab River formations. The aquifer quartzites are those of the Auas and Kleine Kuppe formations. Minor quartzites of the Mahonda Formation and the dolomitic marble of the Waldburg Formation carry water. Two thrust duplicates of the Auas Formation occur in the western part of the aquifer. The thrusting has taken place on long thin slivers of the largely schistose parts of the Blaukrans, Naos and/or Mahonda formations. The dip of the succession is predominantly between 15° and 35° NW with some local variation in the amount of dip and dip direction. Thus, the aquifer quartzites dip under the City of Windhoek.

N-S, NW-trending and NNE-trending faults cut and provide hydraulic connectivity between the quartzites. Dips vary between 87° and 65° and were generally easterly in the west and westerly in the east. Some of the faults have NW-, SW- or SE-trending splays several 10s of metres long branching off them at angles of roughly 45° to the fault. Owing to breccia silicification, fairly long sections of many of the faults weather slowly and stand out in positive relief. In some instances, sections of the faults weather easily and form shallow, negative depressions that river courses exploit and follow.

Plugs and dykes of trachyte of the Tertiary Aris Suite (52 Ma - D. Phillips and J.S. Marsh, unpubl. data, *pers. comm.*, 2006) occur in the Auas Mountains (Fig. 1) and were encountered in some of the faults during drilling.

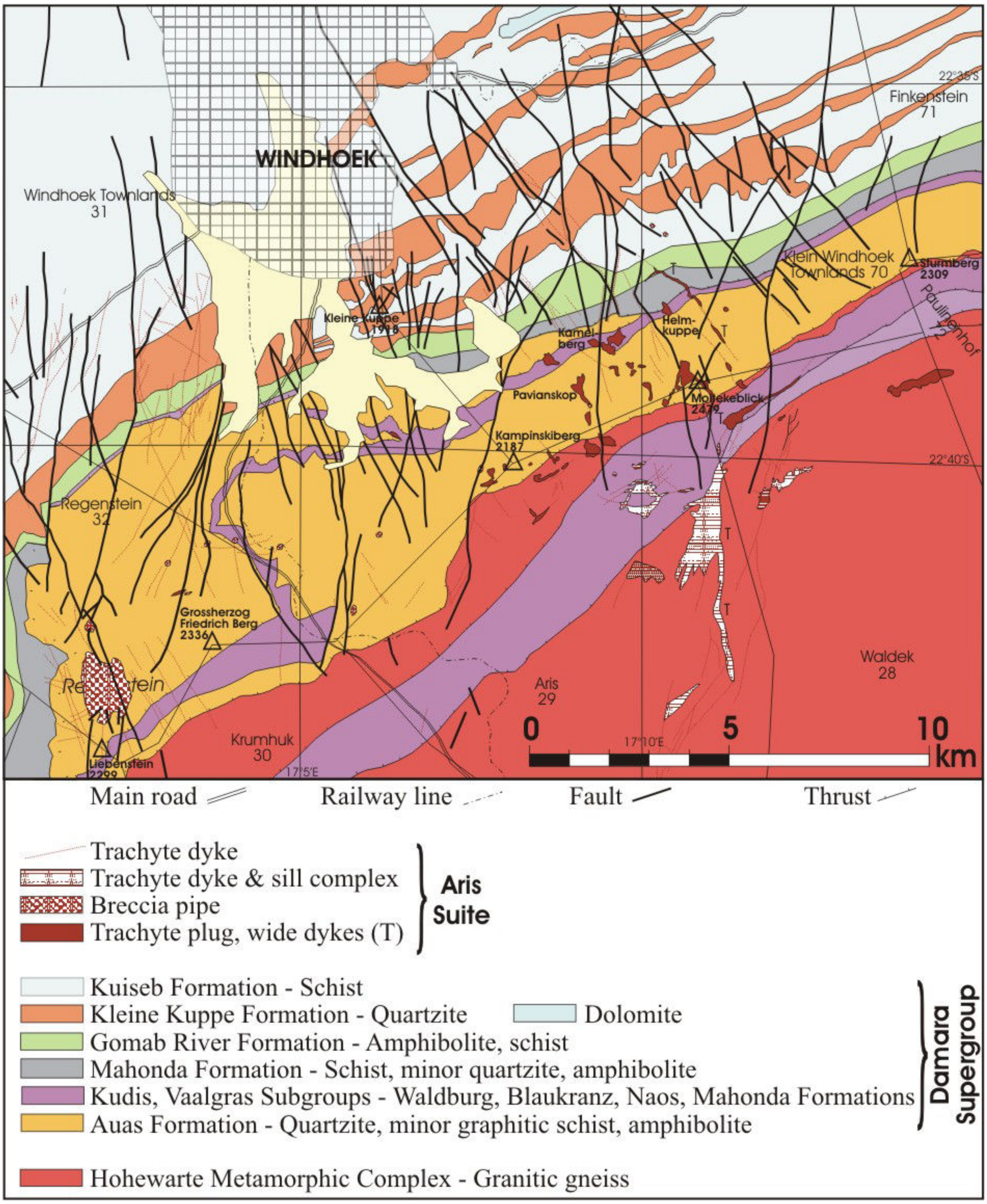


Figure 1. Geology of the Windhoek Aquifer (simplified from Gevers 1934a, 1934b; Guj 1967; Ferreira *et al.* 1979; Hoffmann 1983, Hoffmann & Schreiber 2011).

Ground electrical resistivity surveys

Deep-penetrating electrical resistivity surveys for finding underground water rely on the contrasting conductivity of solid impermeable rock lacking water and fractured, jointed or porous rocks containing water. The former has poor electrical conductivity, the latter good conductivity. If a water-bearing fault is bounded by highly jointed and deeply weathered rocks containing water in the joints, the fault does not necessarily show up very clearly. The resistivity method is thus a popular tool in the search for groundwater because of the inverse correlation to porosity. Resistivity contrasts can also be caused by changes in mineralogy of the rock. Lithologies containing graphite, sulphides and clays are typically less resistive.

Geophysical profiles

Resistivity profiles were recorded perpendicular to faults at proposed drilling targets. Two contrasting profiles are presented in Figures 2 and 3. Figure 2 shows two, closely spaced, steeply dipping, highly conductive fault zones with poorly conductive rocks between and on either side of the faults. In such a case, the depth at which an inclined probe borehole will intersect the fault can be predicted fairly accurately.

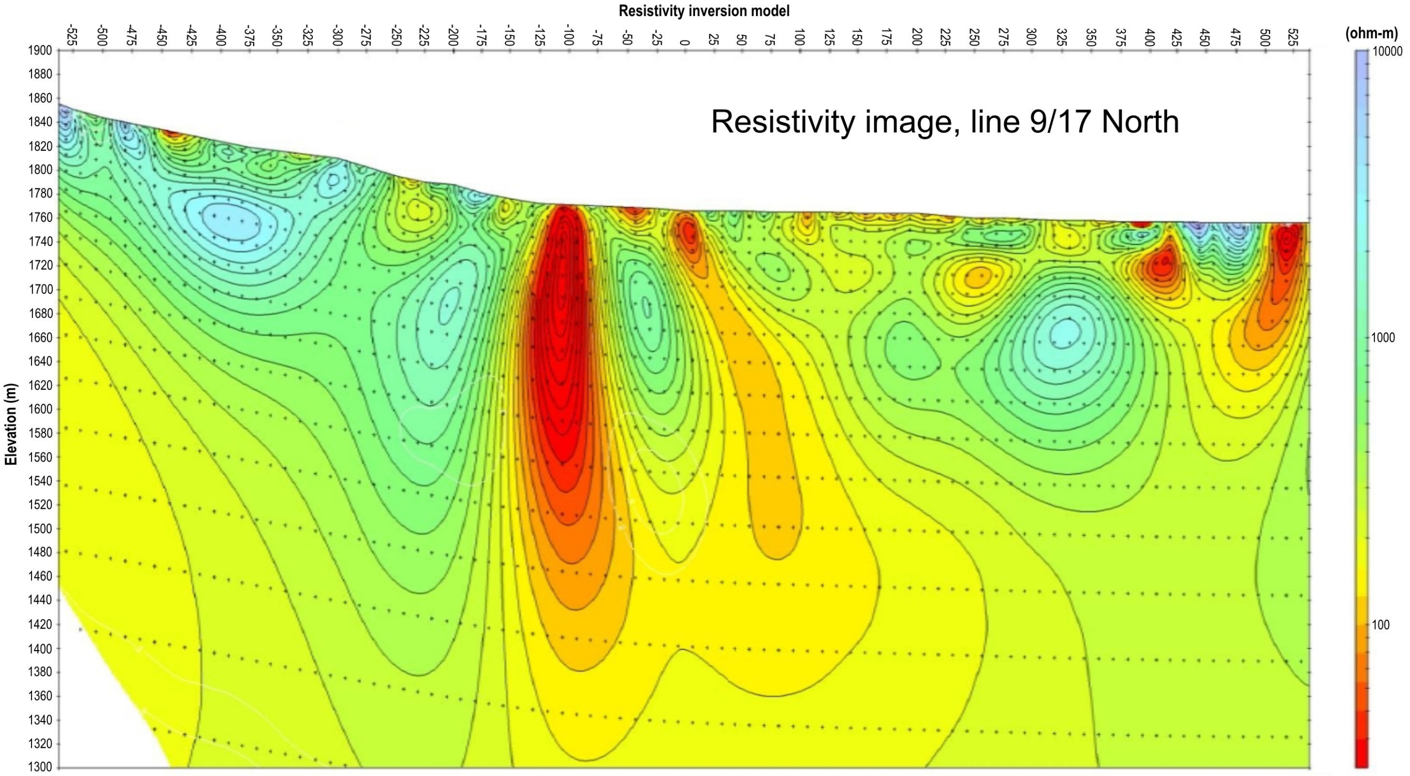


Figure 2. Resistivity depth image across two well-defined, closely spaced, steep, easterly dipping faults. The red and orange of the highly conductive faults contrasts markedly with the green and blue of the dry, poorly conductive quartzites between and on either side of the faults.

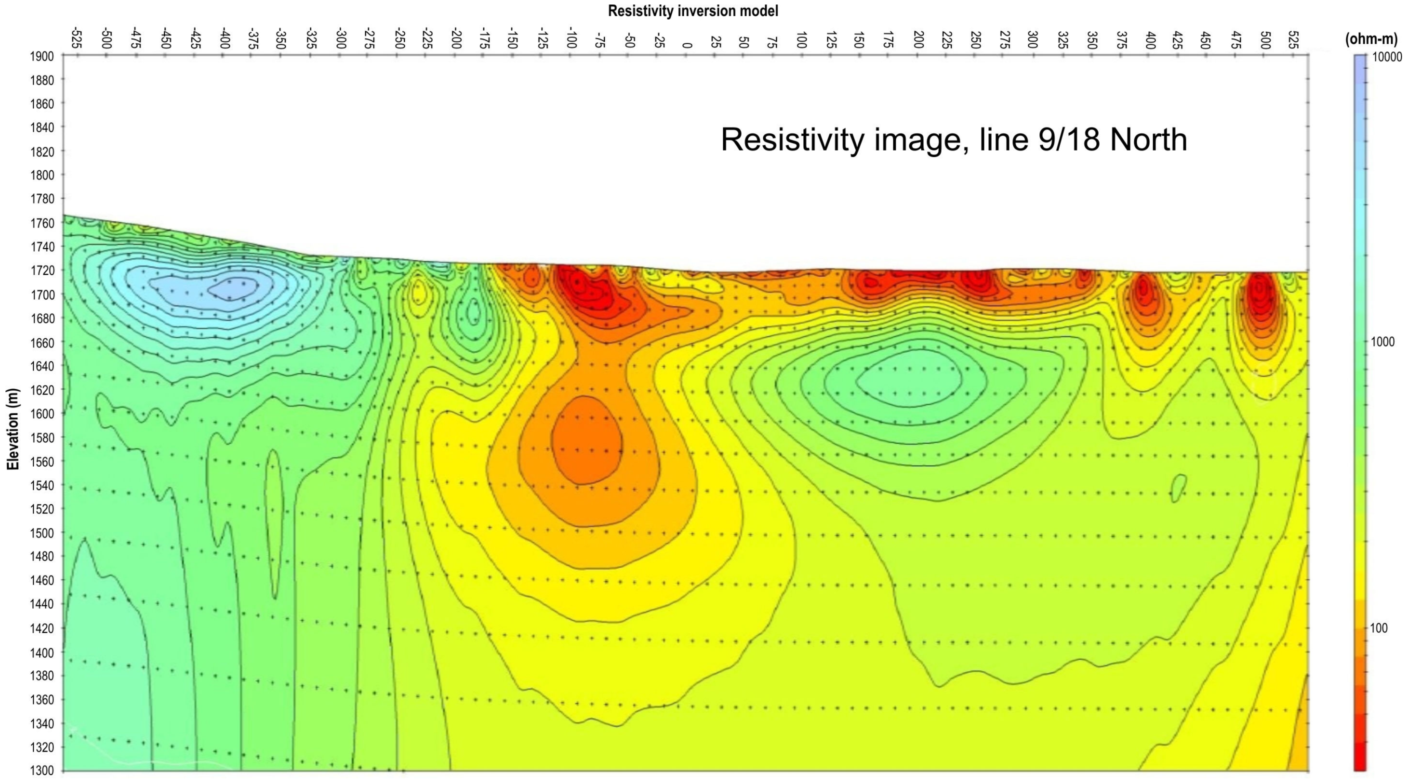


Figure 3. Resistivity depth image of a fault with a wide, balloon-shaped, high-conductivity zone in depth which makes accurate determination of the dip of the fault speculative. Note the presence of conductive overburden in this image and possible resistivity/conductivity change at the water table at a depth of approximately 80 m.

Figure 3 shows a fault zone that is clearly defined by high conductivity near surface but the conductive zone balloons in depth making it almost impossible to determine the dip of the fault. This figure illustrates a common feature of the faults where they cut through quartzites, namely, the presence of water-saturated and conductive hanging-wall and foot-wall fractures zones. Thus, the conductive zone is much wider than the fault itself and the dip of the fault can only be determined by the drilling of inclined probe boreholes.

Electrical resistivity surveys for the detection of water-bearing fault zones depends on the conductivity contrast between poorly conductive water-free and highly conductive water-bearing zones. A dry fault will not show up on a resistivity profile when the fault is bounded by dry rocks. However, the breccias of most faults in the Windhoek Aquifer contain some schist fragments which are altered to clay. This clay absorbs and holds water and shows up as a somewhat conductive zone on resistivity profiles. It is this water in the clays that is exploited by some trees, *Acacia melifera* mainly but also *Boscia albitrunca*, *Euclea undulata* and *Albesia anthelmentica*, and one often finds a tree line defining the surface trace of a fault. Similarly, it may not be able to pin-point a fault accurately in wide zones of high conductivity where bedrock saturation and/or clay development is widespread.

Drilling of inclined probe boreholes

Production holes drilled to tap the aquifer between the depths of 350 m and 400 m were expensive. It was essential, therefore, to drill inclined reverse-circulation probe boreholes with diameters of 133 mm to intersect the faults at two or more widely spaced depths in order to determine the true dip of each fault. Boreholes drilled perpendicular to the strike of bedding or schistosity will deviate into the bedding until they are approximately perpendicular to the bedding. However, in this drilling campaign, the inclined probe boreholes had to be drilled perpendicular to the faults and thus parallel or at a low angle to strike of the bedding. In almost all cases deviation of the hole was unpredictable and varied from probe to probe (Fig. 4). Once dip of a fault had been determined from the inclined probes, it was necessary to drill a vertical probe to determine how the larger diameter, vertical, production hole would probably deviate. All probe and production holes deviated from their initial orientation and it was essential to survey each and every one over its full length in order to determine the exact location of key intersections in 3D space.

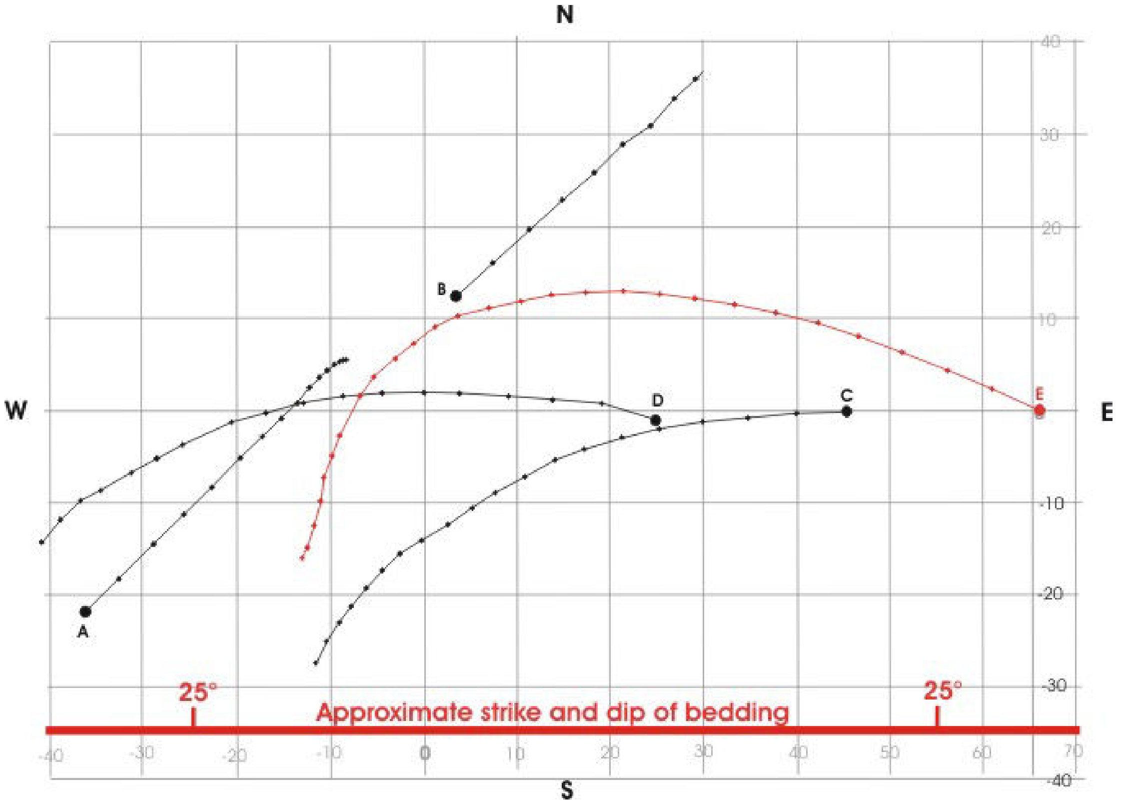


Figure 4. Plan of paths of inclined probe boreholes showing how they deviated in depth away from their initial orientation.

Fault recognition and sample collection

The surface traces of most faults are marked by tree lines, even when poorly exposed. However, where fluvial sediment covers a fault, such tree lines are generally not present. Fault outcrops (Fig. 5a) consist of coarse- to fine-grained, silicified breccia, limonite-permeated silicified breccia, chert-cemented breccia, blocky breccias, pods of varicoloured chert and large jointed blocks of the country rock caught within the fault (Figs. 5b, 5c). Such cemented breccias often have slickensided movement surfaces that in outcrop dip in different directions making is impossible to determine dip of the fault using such movement surfaces. Hanging-wall drag on the bounding quartzite or schist, when present, gives an indication of the dip direction of the fault but not the amount of dip. Fault breccias are generally well-jointed and these joints are coated with veneers of limonite, some up to 2 mm thick (Fig. 5d). Such limonite was deposited on the joints by groundwater and is, therefore, an indication of the presence of groundwater.

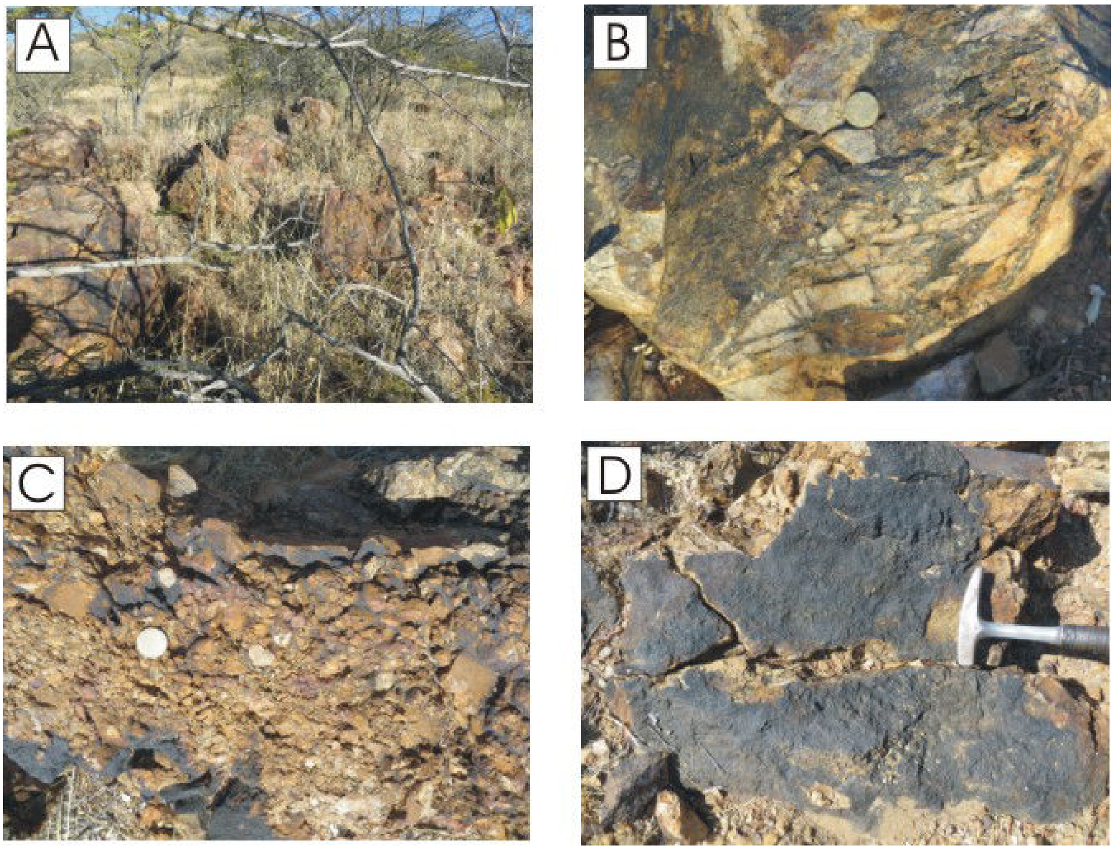


Figure 5. Fault outcrops: A. Weather-resistant outcrop of silicified and chert-cemented fault breccia; B. Brecciated quartzite with silicified and limonite-permeated matrix; C. Breccia fragments with limonite coatings on all surfaces; D. Limonite veneers on joint surfaces in fault breccia.

Joints in hanging- and foot-wall quartzites are often also coated by limonite and during drilling it is essential to distinguish between quartzites with such joints with limonite coatings and the limonite-permeated fault breccias. Samples were collected every metre and set out in a sample garden (Fig. 6a) at the drill site for immediate logging and for ready distinguishing of changes in rock type. Although cemented near the surface, fault breccias in depth often consisted of loose, broken rock fragments with limonite coatings on all surfaces of such fragments (Figs 6b, 6c). It is this intensity of limonite staining that distinguishes fault breccias from quartzites with limonite-coated joints. Below the zone of oxidation no limonite occurs and primary pyrite, the source of Fe for the limonite in the oxidised zone, is present in the quartzites, the schist and the fault breccias (Fig. 6d).

One aspect of many of the fault breccias is their unconsolidated and uncemented nature in depth. Several problems were encountered during drilling of the production holes. The first of these necessitated changing from percussion drilling to mud-rotary drilling before the water table was reached. If percussion drilling continued below this, the pockets of high-pressure air trapped in the enclosing breccia or rock formation exploded into the borehole each time air pressure was released when a drill rod was added. Commonly this threatened the collapse and loss of the borehole. But even with mud rotary drilling, collapse could still occur. Once the drill bit reached a fault the highly permeable and almost unconsolidated nature of the fault breccias resulted in total loss of the drilling mud and drilling continued without returns to the surface. Drilling in such breccias had to be continuous 24/7 without interruption so that casing could be installed quickly and before the breccia began to collapse into the borehole.

Samples were collected every metre and systematically set out in a sample garden (Fig. 6a). Fault breccias within the zone of oxidation were recognised by their intense ferruginisation (Fig. 6b, 6c). Below this, the primary iron mineral was unoxidised pyrite (Fig. 6d).

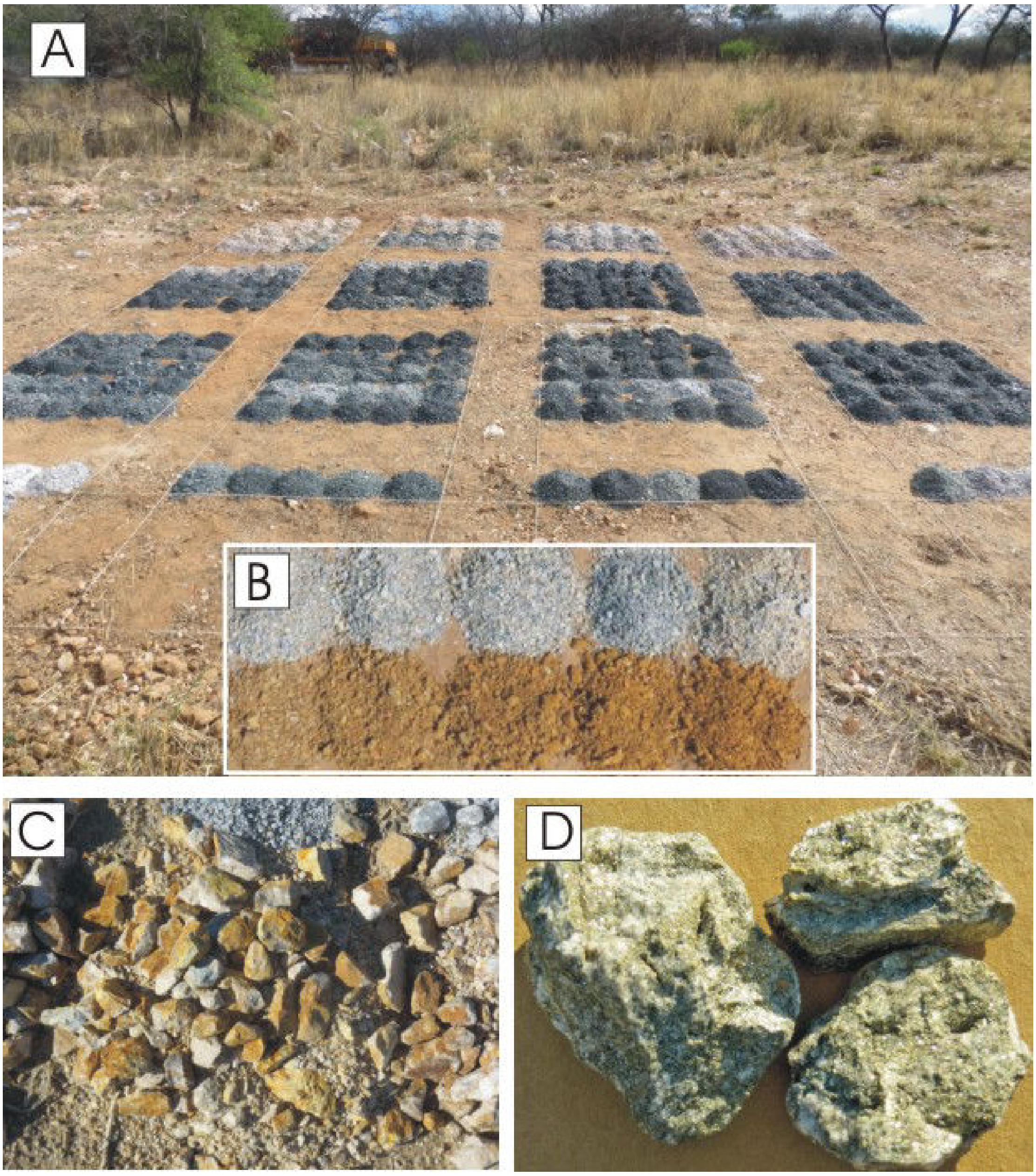


Figure 6. Sample garden and fault recognition: A. 1-m samples set out in rows of 20 samples and four spaced columns of 5 samples each. Once five rows are complete, i.e. 1-100 m, a space is left before the next 100 m is started; B. Five samples of red-brown, limonite-stained fault breccia contrast with the pale grey unstained hanging-wall quartzite; C. Loose quartzite fragments forming a coarse, blocky fault breccia in which all fragments are coated with brown and yellow limonite and goethite; fragments 2-3 cm long; D. Fresh, unaltered pyrite coating fault breccia fragments below the zone of oxidation, fragments 2-3 cm long.

Hydrothermal alteration caused by heat from the Aris Suite trachytes

Windhoek's erstwhile hot springs attest to the deep groundwater circulation from the main recharge area in the Auas Mountains down-dip towards the city (Murray, 2002). The age of faulting is uncertain. Some fault movement may be Karoo in age (300 - 180 Ma) but it is likely that much of the hydrothermally induced silicification and rejuvenated faulting of the silicified breccias took place during intrusion of the Aris trachytes. Immediately after the intrusion of the trachytes, water temperatures in the aquifer and particularly along the faults will have been higher by 100°C or more than at present. At such temperatures, hydrothermal water dissolves minerals (silica, iron, sulphur), reacts with and alters rocks it comes into contact with and, as it cools, deposits its dissolved minerals. Such hydrothermal fluids dissolve significant amounts of silica from their surroundings.

Hydrothermally deposited pyrite occurs in depth. Higher up, in the zone of oxidation, this has altered to limonite. Nearer surface, as rising hydrothermal waters cooled, they deposited silica as silica cement and chert in the fault breccias.

However, silica also replaces or cements some of the country rocks. Splays branching off faults into the enclosing schist consist entirely of fine-grained, quartzite-like silica. These splays appear to be more silica-rich than the unaltered quartzites in the region and can have a slightly glassy appearance in places (Fig. 7a). The splays and the quartzite-like silica gradually pinch out in the enclosing schists. Under the magnifying glass, this quartzite-like silica contains a fine, closely spaced foliation, a relic from the schist foliation that the silica has replaced. Since such a rock is not an originally metasedimentary rock but is the result of hydrothermal replacement, it was termed "pseudoquartzite" in the report on an earlier drilling programme in the aquifer (Windhoek Aquifer JV Consultants, 2011). This term has been retained in the present paper. Pseudoquartzite also often occurs in the immediate hanging wall of faults where it has replaced either schist or quartzite and is a good indication that the borehole is about to intersect a fault. Some breccias included fragments of pseudoquartzite. Such pseudoquartzites are normally white to grey in colour (Fig. 7a).

In some cases, hydrothermal waters have altered hanging- and foot-wall schists to soft grey clays that were recovered during drilling as soft grey clay sausages (Fig. 7b). In others, amphibolites were totally altered to the swelling clay montmorillonite which, when it came into contact with the drilling water expanded to such an extent that drill rods became blocked and the fault breccia began to collapse into the hole (Fig. 7c - 7f).

The aquifer quartzites and aquifer structure

The Windhoek Aquifer is a fracture-hosted aquifer. The jointed, positively weathering quartzites of the Auas and Kleine Kuppe formations form one component of the Windhoek Aquifer. The Auas Formation forms the Auas Mountains and most of the Kleine Kuppe quartzites form their own individual ridges. The cross-cutting faults are major conduits for groundwater flow in the aquifer. These faults provide across-strike and vertical connectivity between the quartzites and the joints and fractures in the quartzites provide lateral connectivity between faults. Thus, the jointed quartzites and faults form and an interconnected aquifer network. Nevertheless, monitoring of water levels in the older boreholes has shown that the aquifer is divided into several compartments across which there is little connectivity (Murray, 2002).

Natural recharge takes place predominantly on exposed, jointed quartzites and where rivers cross or run along faults or break through quartzite ridges. The quartzites of both formations pinch out to the east and west so little water is lost to the east or west. The gneissic basement on the southern side of the high Auas Mountains is relatively impermeable so little water is lost to the south. The brecciated Kuiseb schist in the faults north of the Kleine Kuppe quartzites is so highly altered to clay that the faults become blocked by this clay and they lose their permeability and almost no water is lost to the north. Thus, hydraulically, the Windhoek Aquifer behaves like a closed system within which almost no water is lost in any direction. Subsurface flow of the water in the quartzites is down dip to the northwest and into the aquifer that the boreholes tap. Being underground, no water is lost to evaporation.

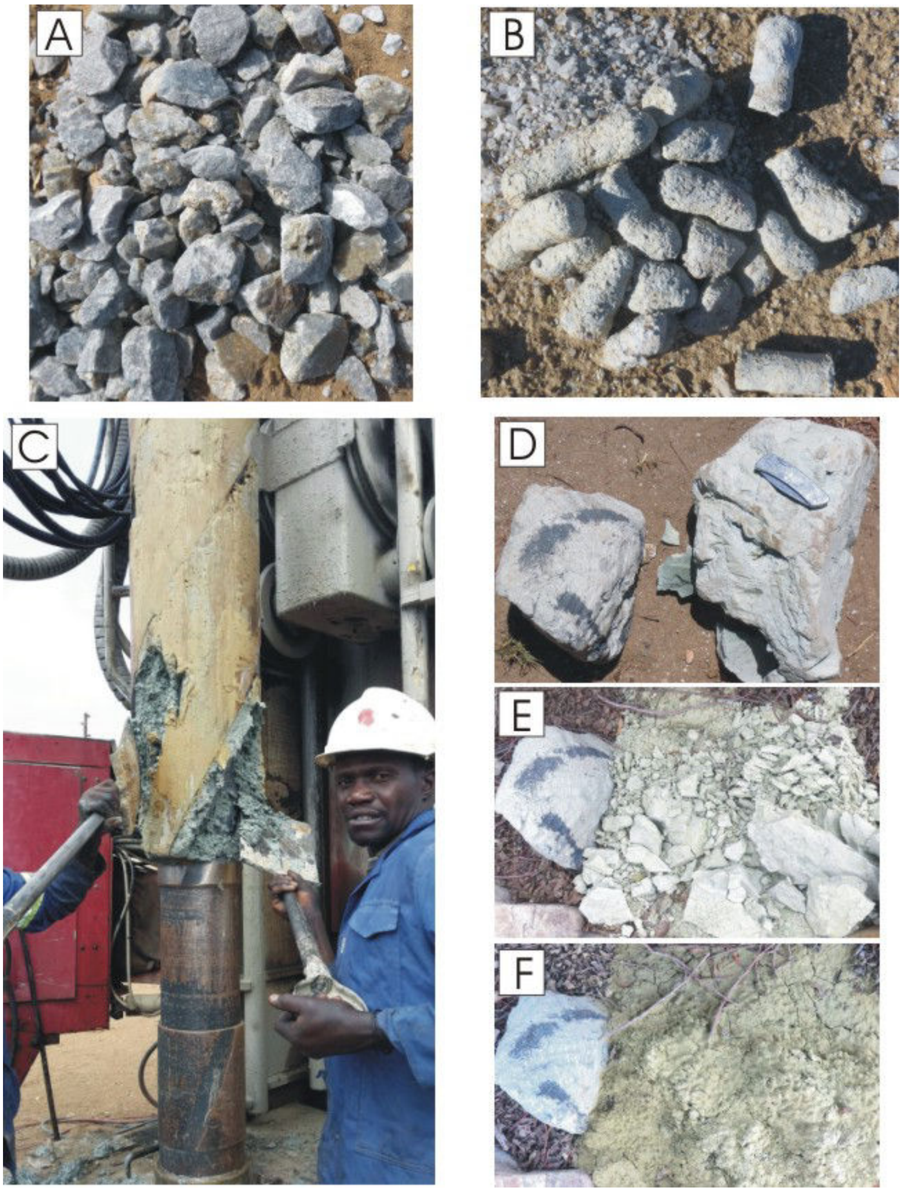


Figure 7. A: Slightly brecciated pseudoquartzite; B: Sausages of soft, hydrothermally altered, clay-rich schist in the immediate hanging wall of a fault; C: Montmorillonite clay clogging the spaces between the gently spiralling blades of drill rod centralisers; D; Blocks of quartzite (left) and montmorillonite (right) recovered with pieces of broken drill bit from the borehole in photograph C; E: Same montmorillonite block two weeks later - water vapour absorbed from relatively dry air has caused partially disintegration of the block; F: Same montmorillonite block after the first rains.

A comprehensive report on the drilling has been submitted to the City of Windhoek authorities. For better comprehension of the geology, the report on each probe and production hole includes a Log-and-Design page with colour-coded lithology and joint columns (Fig. 8) and a photo collage of the samples as laid out in the sample garden (Fig. 9).

Conclusions

The rate of natural recharge to the Windhoek Aquifer is low (with a maximum in the Auas Formation of ~2.5 % of the annual rainfall - Murray, 2002), and the rate at which the aquifer has been pumped over the years has far exceeded this. Exploitation of the water in the aquifer at a far greater rate than the rate of natural recharge has resulted in a falling piezometric level (water table) but since almost no water is lost through lateral seepage or evaporation, the aquifer is an ideal target for artificial recharge (Murray, 2002). Windhoek is probably one of the few cities in the world fortunate enough to have such an aquifer at its doorstep to provide for its needs in time of drought and low rainfall. But such a water supply will only be available if artificial recharge takes place.

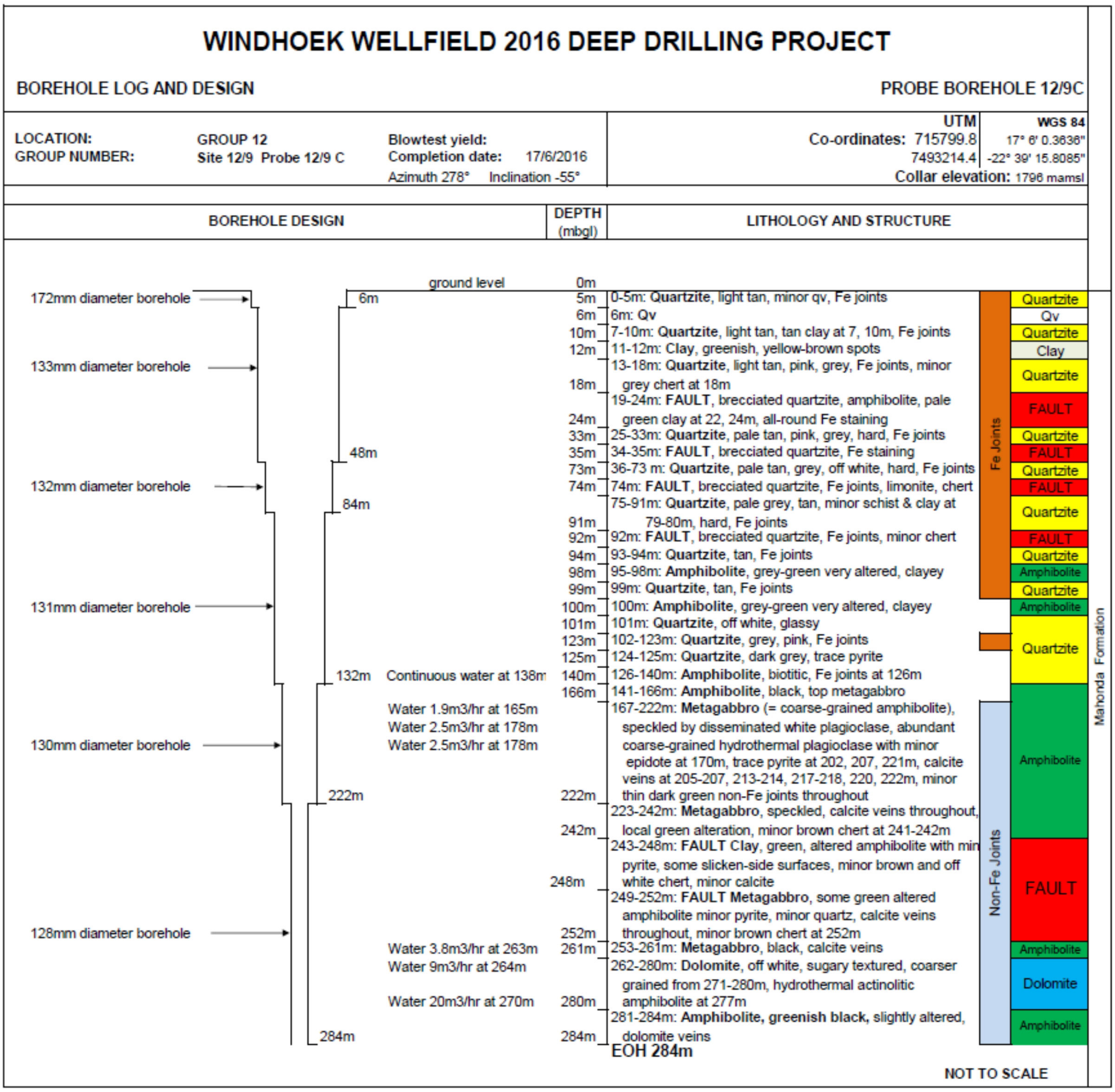
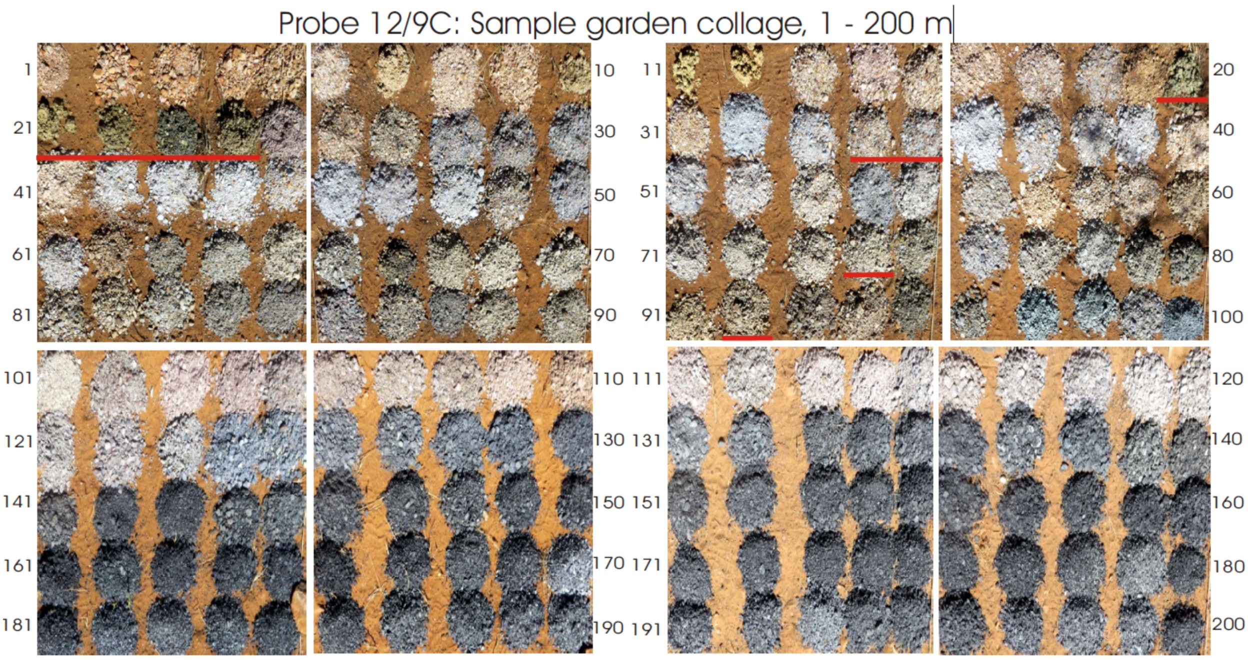


Figure 8. A: Log and Design of Probe Borehole 12/9C, production holes included the casing design.



0-5m: **Quartzite**, light tan , minor qv, Fe joints; 6m: **Qv;** 7-10m: **Quartzite**, light tan, tan clay at 7, 10m, Fe joints; 11-12m: **Clay**, greenish, yellow-brown spots; 13-18m: **Quartzite**, light tan, pink, grey, Fe joints, minor grey chert at 18 m; 19-24m: **FAULT**, brecciated quartzite, amphibolite, pale green clay at 22, 24m, all-round Fe staining; 25-33m: **Quartzite**, pale tan, pink, grey, hard, Fe joints; 34-35m: **FAULT**, brecciated quartzite, all-round Fe staining; 36-73m: **Quartzite**, pale tan, grey, off white, hard, Fe joints; 74m: **FAULT**, brecciated quartzite, Fe joints, limonite, chert; 75-91m: **Quartzite**, pale grey, tan, minor schist & clay at 79-80m, hard, Fe joints; 92m: **FAULT**, brecciated quartzite, Fe joints, minor chert; 93-94m: **Quartzite**, tan, Fe joints; 95-98m: **Amphibolite**, grey-green very altered, clayey; 99m: **Quartzite**, tan, Fe joints; 100m: **Amphibolite**, grey-green very altered, clayey; 101m: **Quartzite**, off white, glassy; 102-123m: **Quartzite**, grey, pink, Fe joints; 124-125m: **Quartzite**, dark grey, trace pyrite; 126-140m: **Amphibolite**, biotitic, Fe joints at 126m; 141-166m: **Amphibolite**, black, top meta-gabbro; 167-200m: **Meta-gabbro** (= coarse-grained amphibolite), speckled by disseminated white plagioclase, abundant coarse-grained hydrothermal plagioclase with minor epidote at 170m, trace pyrite at 202, 207, 221m, calcite veins at 205-207, 213-214, 217-218, 220, 222m, minor thin dark green non-Fe joints throughout.

Figure 9. Photo collage of the upper 200 m of Probe Borehole 12/9C

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