- *Site Investigations*
- *Slope Stability*
- *Rock Mechanics*
- *Soil Mechanics*
- *Foundations*
- *Borrow Pits and Materials*
- *Roads*
- *Groundwater*
- *NHBRC*
- *Geotechnical Instrumentation*

Geotechnical And Geophysical Survey Description for MPR Siting at Necsa Pelindaba

Client: Manyabe Consultancy and Necsa
GCS Report Reference: 23-0071R02
Client Reference: MPR-EXT-DES-00001

Geotechnical And Geophysical Survey Description for MPR Siting at Necsa Pelindaba

Reference: 23-0071R02 **Date: 17 April 2023**

EXECUTIVE SUMMARY

This report is a desk-top review, from published and unpublished data by the authors, of the regional setting and local geological and geotechnical conditions for 2 small sites that may be selected for an isotope producing, small multipurpose nuclear reactor at Necsa's Pelindaba site.

Both the sites lie in proximity to the regional scale, but inactive Hartbeespoort Fault, part of the Brits graben system. ***The best choice area is S1 as it is likely the least affected by the otherwise ubiquitous minor structural disturbances, faults, folds, joints and fissures present at the Necsa site****. The major structural geological disturbances are very old, having formed in a regional event after the intrusion of the Bushveld complex, ~2.04 Ga years ago. Some overprinting of younger events may influence the rock mass conditions and should be evaluated as part of the geotechnical investigations for the foundation designs.*

In summary, these faults and their related smaller elements should be mitigated by judicious civil engineering practices.

It is recommended that a practicing seismologist should conduct an updated Probabilistic Seismic Hazard Analyses (PSHA) for the Pelindaba Precinct.

Geotechnical And Geophysical Survey Description for MPR Siting at Necsa Pelindaba

Reference: 23-0071R02 **Date: 17 April 2023**

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LEGAL NOTICE

Definitions and Abbreviations

Commercial:

GCS Geotechnical	GCS Geotechnical (Pty.) Ltd.

Technical:

CH	Chainage (metres)
mbgl	metres below ground level
masl	metres above sea level
NGL	Natural Ground Level
FL	Foundation Level
BH	Borehole
SPT	Standard Penetration Test
N	SPT N value (blows per 300 mm)
TLB	Tractor-mounted Loader Backhoe
TP	Test Pit
DCP	Dynamic Cone Penetrometer
EABC	Estimated Allowable Bearing Capacity
G1-G10	Standard classification of natural road building materials (TRH 14)
CBR	California Bearing Ratio
MDD	Maximum Dry Density (kg/m3)
MADD	Modified AASHTO Dry Density
OMC	Optimum moisture Content (%)
PI	Plasticity Index
LL	Liquid Limit
LS	Linear Shrinkage
RMR	Rock Mass Rating
GSI	Geological Strength Index
mi	Hoek-Brown Constant (origin & texture dependent)
RQD	Rock Quality Designation (%)
FF	Fracture frequency
UCS	Unconfined Compressive Strength (MPa)
C (c’)	Cohesion (kPa) – total stress and (effective stress)
Φ (Φ’)	Friction Angle (degrees) – total stress and (effective stress)
Kv	Modulus of Subgrade Reaction (MN/mm or kPa/mm)
CFA	Continuous Flight Auger (pile type)
DCI	Driven Cast In situ (pile type)
Cv	Coefficient of Consolidation (m2/yr)
Mv	Modulus of Compressibility (m2/MN)
MC1	Moisture Content Before Test (%)
MC2	Moisture Content After Test (%)
ρ	Dry Density (kg/m3)
VSR	Very soft rock
SR	Soft rock
MHR	Medium hard rock
HR	Hard rock
VHR	Very hard rock

TABLE OF CONTENTS

EXECUTIVE SUMMARY 2
1.0 PURPOSE 7
2.0 JUSTIFICATION 7
3.0 PROJECT DESCRIPTION 7
4.0 INTRODUCTION 9
5.0 GEOLOGICAL SETTING 9
5.1.1 Background 9
5.1.2 Regional Geology Stratigraphy 9
Fig 1. Geological map of the Pelindaba Precinct Showing the Position of the Two Preferred Sites (S15 (pink circle) &S1 (yellow circle)) (Ref Fig. 1a) 10
Fig. 1a: Stratigraphic Column 10
5.2 Structural Geology 11
5.2.1 Tectonic Setting of the Pelindaba Area 11
5.2.2 Bedding 12
5.2.3 Cleavage. 12
5.2.4 Folding 12
5.2.5 Faulting 12
5.2.6 Normal Faulting 13
5.2.7 Reverse (Extensional) 13
5.2.8 Thrust Faulting 13
5.3 Local Geology at the Target Sites (Site 1 and Site 15) 13
5.3.1 Site 1 13
Fig. 3: Google Earth image of the proposed candidate sites in relation to the northern split of the Hartbeespoort Fault, NE margin of the Brits graben. 14
Fig. 4: Interpretative geological cartoon map of proposed Site 1(regolith, surface scree removed; See Fig 1a for symbols (V-d; Vaalian diabase) 15
5.3.1 Site 15 15
6.0 SEISMIC HAZARD CONSIDERATIONS 16
6.1 General Comment 16
Table 1. A comparison of selected, historic seismic hazard assessment values for the Necsa site 17
6.2 Assessment of Seismic Hazard for Nuclear Facilities 17

7.0 RELEVANCE OF SEISMIC HAZARD CONSIDERATIONS TO THE PROPOSED NEW MPR SITE, PELINDABA....20
8.0 SLOPE STABILITY ASSESSMENT 20
9.0 CONCLUSIONS AND RECOMMENDATIONS....20
10.0 GEOLOGY REFERENCES 21
11.0 PSHA REFERENCES 22
APPENDIX A 24
Fig. A1: Geology of the Valindaba site (Andreoli, 1988). (Ref Legend (Fig. A1/c)....24
Fig. 1A (Detail) 21
Fig. A1/c: Legend 21
Fig. A2: Structures characteristic of the slates and phyllites of the Pelindaba area. 23
Appendix A (Fig. A2): Explanation of the Photographs....23
Fig. A3: Tight, probably faulted and overturned fold in slate (view to west), lower Timeball Hill Formation near Glen Africa Country Lodge (cf. Figure 2); bedding dips: upper limb 57° to SE, lower limb 22° to ENE (Ingram et al., 2000).....24

Geotechnical And Geophysical Survey Description for MPR Siting at Necsa Pelindaba

Reference: 23-0071R02 **Date: 17 April 2023**

1.0 PURPOSE

At the request of Manyabe Consultancy (Pty) Ltd (MC), acting on behalf of Necsa, GCS Geotechnical (Pty) Ltd (hereafter referred to as GCS) was asked to provide a proposal and cost estimate for a two-part study of the geotechnical, geophysical and seismic conditions (Annexure B1: MPR-EXT-DES-00001) as well as a separate geological comparison study (Annexure B2: MPR-EXT-DES-00002) of two candidate sites for the proposed Multi-Purpose nuclear research Reactor (MPR) at the established Pelindaba facility. This report details the findings of the former geotechnical and geophysical survey description and comparison study. Preliminary was undertaken on 14 March 2023 and completed on 15 March 2023 across the two candidate sites, Site Location 15 and Site Location 1.

2.0 JUSTIFICATION

The completion of this investigation and report is reliant upon the results of the geophysical survey that has been allocated in Annexure B1. The report status is therefore considered preliminary.

3.0 PROJECT DESCRIPTION

This study has been carried out in terms of the Development Facilitation Act (DFA), Section 30 of the Government Gazette No. 20775, dated 04 January 2000 as well as the Terms of Reference (ToR) (Annexure B2: MPR-EXT-DES-0001) provided by the Client. This section requires that a geological comparison of the two sites be carried out based on desk top level information as well as fieldwork and indicating the suitability of the sites by reference to a number of factors. These areas of concern and the outcome of the study are outlined below:

PART I: Preliminary assessment of all candidate sites identified in Phase 1 site screening process:

- Assessment of the seismicity and geotechnical/geophysical characteristics of the preferred candidate site locations, slope stability and continuous surface wave (CSW) experiments to be performed (the latter is still outstanding).
- Geotech experiments to be indicative of the site locations response given a design basis earthquake (DBE).
- Slope stability assessments to be indicative of the geotechnical/geophysical characteristics of the site locations.

The output of Part 1 must be a report clearly stating method(s) used, results as well as recommendations the preferred site to locate the MPR.

PART II: Detailed assessment of the preferred site from PART I:

- A full-scale geotechnical and geophysical characterization of the site.

A detailed final assessment report must be generated at the end of PART II and submitted to Necsa.

4.0 INTRODUCTION

The South African Nuclear Energy Corporation Limited (Necsa), a state-owned public company (SOC), proposes to build a new 20 to (max) 30 MW (thermal) Multi-Purpose nuclear research Reactor (MPR) to replace the ageing SAFARI-1 at its Pelindaba site just outside Pretoria in the North-West Province.

The key objective of this project is to ensure that the benefits derived from SAFARI-1, and more advanced technologies, are continued in the MPR in a sustainable and ever growing way going forward. The proposed MPR will be a modern nuclear, fuel and material testing research facility (estimated footprint of 215m x 176m [3.8ha]) with an associated 100m x 100m proposed construction laydown areas adjacent to the development site during the construction phase. The MPR facility is proposed to safely operate for over >300 days per annum at full power for the operational life of the Facility, which is expected to be more than 60 years. The MPR facility will consist of the following:

- The Reactor Building incorporating a Reactor Beam Hall (RBH) experimental area,
- Neutron Guide Hall (NGH) (with provision for the latter expansion to a second NGH) and with NGH viewing gallery. The NGH includes a large instrument area, instrument control rooms, meeting rooms, laboratories, workshops, and restrooms.
- The reactor core which functions as a source of neutrons for producing medical radioisotopes (in-core irradiation of target materials), beam line applications and fuel and material testing; and,
- Fuel and Material Testing (FMT) facility.

5.0 GEOLOGICAL SETTING

5.1.1 Background

The tectonic setting of the area where the Necsa property is nested has been mapped and investigated in considerable detail over a number of years by staff of the Council for Geoscience, Necsa and its predecessors companies, as well as by academics and their students from several Universities (see Figure 1; Courtnage, 1995; Ingram et al., 2010; Andreoli, 1988; Alexandre et al., 2006, 2007, A. Bumby, unpublished data; Basson, 2019; Ormond and Lehmann, 2022; Steenekamp et al., 2018).

These publications have been considered for the preparation of this report and may be consulted by the interested reader. As a general outline, the Necsa property extends across the N-dipping (at 20^{o} to 30^{o}) contact between the dolomite-dominated Chuniespoort Group (blue stratigraphy in Figure 1) and the slate-quartzite-lava dominated Pretoria Group (brown, pink and green in Figure 1). These are major units within the Paleoproterozoic (≥2.3 Ga) Transvaal Supergroup. Necsa, since their inception have been aware of the problem of sink holes in the dolomites, and as such all facilities have always been built on the Pretoria group and no sinkhole has ever developed in the built-up area.

5.1.2 Regional Geology Stratigraphy

The target sites (S1 and S15) are underlain by slate dominated beds of the Timeball Hill Formation (Fig. 1) which is divided into an upper and lower section by a band of predominantly quartzite beds of the so called Klapperkop member (Vkp). Of these, the most prominent is a bed of black, magnetic, and weakly radioactive quartzite best exposed east of the areas under consideration (Appendix 1 {Figs 1 and A2(e to g)}).

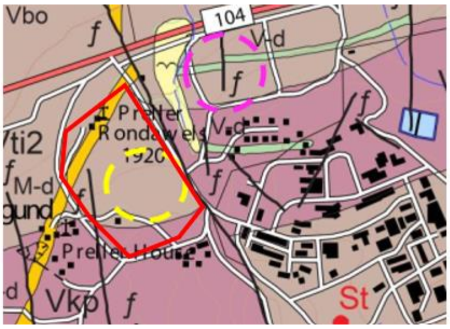

Fig 1. Geological map of the Pelindaba Precinct Showing the Position of the Two Preferred Sites {S15 (pink/purple circle) &S1 (red polygon) (Ref Fig. 1a)}

The lithologies of the Timeball Hill Formation, previously described to comprise of shale, siltstone, and mudstone (cf. Ingram et al., 2010) are better described as slate and phyllite (figs 2; A2, A3); (Andreoli, 1988; Alexandre et al., 2006; see Appendix Table A, F). This is not due to thermal metamorphism, which is absent in the Pelindaba area, but which is commonly seen to the north in the Magaliesberg Formation (Fig. 1a), and is related to the Rustenburg Layered Suite (RLS), e.g. hornfels-type rocks. It is due to low grade dynamo-metamorphic metamorphism which is evident at the 'picnic site' to the south of the investigated sites (see PEL-PIK, Figures 2 and A2, A3 and Table A1). The slate and phyllites have yielded Ar-Ar ages of ~2043 Ma. This (age) postdates the crystallization of the RLS (Alexandre et al., 2006a, b).

Super group	Group	Sub-Group	Formation	Member	Map Symbol
			Quaternary		Q
			Mesoproterozoic syenite dyke		M-s
			Mesoproterozoic diabase dyke		M-d
TRANSVAAL SUPERGROUP	Pretoria Group	Lower Pretoria Group	Magaliesberg		Vmg
			Silverton		Vsi
			Daspoort		Vdp
			Strubenkop		Vst
			Hekpoort Volcanic		Vh
			Boshoek (Vbo)		Vbo
			Timeball Hill	Upper Slate	(Vti2)
				Klapperkop Quartzite and Slate	(Vkp)
				Lower Slate, phyllite	(Vti1)
			Rooihoogte	Bevet Conglomerate	(Vbe)
	Chuniespoort	Malmani Subgroup	Frisco		(Vfr)
			Eccles (Ve)	Leeuwenkloof Member	(Vlk)

Fig. 1: Simplified **s**tratigraphic column in the Pelindaba-Hartbeespoort area (after the 2527 DD Broederstoom sheet Council for Geoscience, Pretoria).

5.2 Structural Geology

5.2.1 Tectonic Setting of the Pelindaba Area

The structural geology of the Pelindaba site is dominated by the regional Hartbeespoort fault (Fig. 2) and by local and very widespread folds and faults (reverse, and thrusts) (Figures 1 to 5, and A1, 2, 3). These local structures and the associated phyllites, have been related to the more regional scale post-Bushveld, pre-Vredefort ±2.043 Ga "Transvaalide fold and thrust belt" (Andreoli, 1988; Alexandre et al., 2006, 2007; Basson, 2018; Ormond and Lehman, 2022). The normal, younger SSW-dipping faults could be related to the collapse of the multi-ring sector of the ~2.0 Ga Vredefort Impact structure (cf. Galdeano et al., 2008). The tectonic setting of the Brits graben as a regional, intracratonic SW-NE extensional event is poorly defined (cf. Basson, 2018) but it is younger that the previous tectonic episodes because it displaces a Mesoproterozoic syenite dyke marked as M-S (Fig. 1).

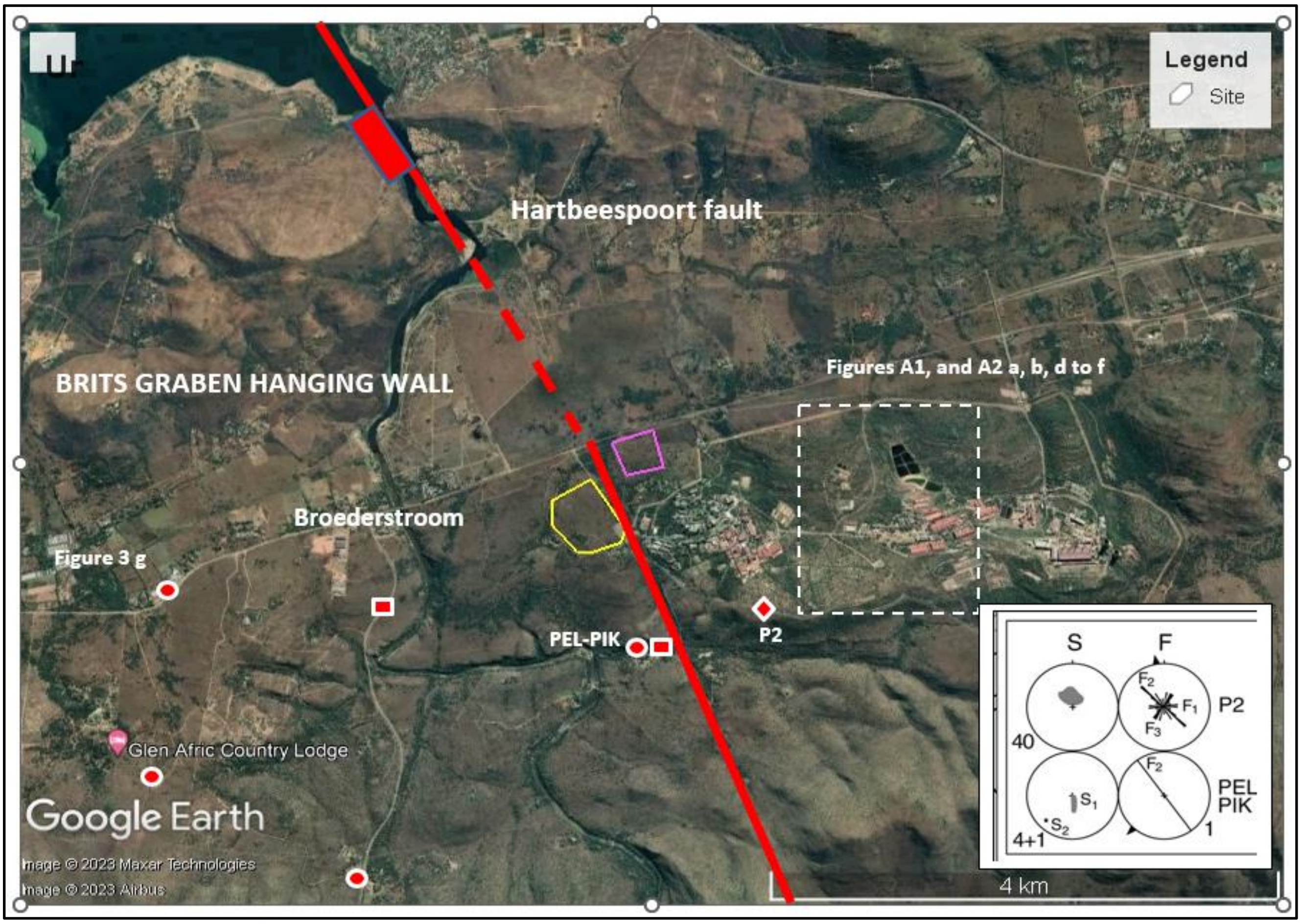

Fig. 2: Google Earth Image of the Pelindaba area showing Proposed Sites 1 and 15 & Points referred in the text. Dashed rectangle, area of Appendix Fig. A1; red box: SW-dipping normal faults cutting N-dipping slates, red dots: thrust faults (cf. Figures A2, A3); red diamond/box: slate/phyllite- samples P2 and PEL-PIK respectively (Table A1, Figure A2c; Alexandre et al., 2006). Inset: Stereonet (equal area, lower hemisphere) showing poles to (S) cleavages, π girdle of poles to bedding, and rose diagram of (F) fold hinges at the PEL-PIK, P2 and sites in the red dashed rectangle; dagger: vergence of thrusts and asymmetric folds (after Alexandre et al., 2006a, 2007; Ingram et al., 2010; MAG Andreoli, unpublished. data).

An ad-hoc investigation of the most recent reactivation of the Hartbeespoort fault by Rizzo et al. (2009) gave inconclusive results. This report provided ages by the Optically Stimulated Luminescence (OSL) technique of an undisturbed Quaternary material overlying diabase (not fault gauge). A problem with this report is that it does not provide coordinates for the dated material, other than stating it came from a poorly located trench within/marginal to the fault (Fig. 3). There was also uncertainty in the interpretation of the ages obtained with a range between ~40 ky – 90 ky (thousand years).

Despite these uncertainties and limitations, Rizzo et al., (2009) concluded that the Brits graben (e.g., the Hartbeespoort fault) "is not a **capable** feature and should not considered as a seismogenic source in a PSHA or (that) is it capable of causing surface rupture at the site. Consequently, the PSHA (PBMR, 2009) remains valid as published."

Definition of a Capable Fault:

A capable fault is a fault which has exhibited one or more of the following characteristics: (1) Movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years.

5.2.2 Bedding

The original sedimentary layering of the slate and quartzite of Timeball Hill (defined as S_0) generally dips between 25^o and 30^o to the north, apart from certain localities where folding causes S0 to be very steep {Figs. A1, A2 (a, b, d)}, or even overturned to the north {Figs. A1, A2 (e, f, g)}.

5.2.3 Cleavage.

An incipient metamorphic foliation {Fig. A2 (c, h, i, and j)} is commonly superimposed on the bedding, and generally dips S at ≤25^o in the more than 40 sites where it was measured at the P-2 sites and in the general Valindaba area (see: top left Stereonet of inset {Fig. 2 & Fig A2 (i). In some places, however, N dipping cleavages are overprinted on the N dipping slates {Fig. A2 (j)}. The bedding (S_o) is completely overprinted (i.e.: unrecognizable) along the thrust structures {Figs. A2 (c, h)}. Two different cleavage orientations were measured in the phyllites at the PEL-PIK sampling site (Figure 2 and inset) with the oldest (S_1) dipping at low angle to N {thrust zone footwall: top and bottom (Fig. 2c). The younger cleavage (S_2) was measured within the thrust zone and dips at steeper angles (~80^o) toward the NE (Fig. A2), bottom left Stereonet inset (Fig. 2).

5.2.4 Folding

Most measurements and observations were made in the road cuts on the southern and western sides of the Valindaba area (Fig. A1), where three principal sets of folds axes were recognized (see top right rose diagram, inset {(Fig 2 and Fig. A1); Alexandre et al. (2006)}. As shown by the rose diagram, the majority of folds have axes oriented NW-SE (F_2) and those oriented E-W (F_1) and NE-SW (F_3) being less common. F_1, F_2, and F_3 denote the chronological sequence, the F_1 faults being oldest and those defined as F_3 being the youngest. The geometry of the folds ranges from gentle and open and monoclinal, as observed on the main road S of Gate 3 (Fig. 2) to very tight {Fig. A2 (d)} and at least in one case rapidly grading from open, monoclinal and ductile to brittle and overturned, all over a distance of few m (Figure A2e, f, and g).

5.2.5 Faulting

Faulting recognised in the area relates to the long dynamic history of the region as discussed above. These reflect the response of the rock mass to stresses imposed due to regional events such as the intrusion of the RLS, the polyepisodic Transvaalide thrust and fold belt , the Vredefort Dome impact and possibly younger events in the early Quaternary (>100 000y (BP):

1. reverse (steeply dipping, compressive but with limited horizontal displacement),
2. normal (steeply dipping, extensional) and

3. compressive ones of the thrust-type.

5.2.6 Normal Faulting

The most important normal fault adjacent to the areas under consideration is the Hartbeespoort fault {Figs. 2 to 5 (Rizzo et al., 2009)}. A well-developed set of normal faults with a SSW dip is found in areas open to the public, along the road south Broederstroom and at the Pelindaba picnic site (PEL-PIK, Fig. 2). The vertical displacements of these faults may be minor, as no major stratigraphic displacement was noted.

5.2.7 Reverse (Extensional)

A good example of a reverse fault with a limited vertical displacement (<2 m) is located along a road cut on the western side of the Valindaba site, ~150 m S of the locality of Fig. A2 (e to g) (cf., Fig. A1). A rather characteristic style of faults, undetermined but probably of a compressive nature is well displayed on the road cut to the south of the Valindaba industrial area (Fig. A1). These faults are steeply dipping and define the ruptured axial plane of cuspate, asymmetric folds with relatively short wavelength and higher amplitude {Figs. A1, A2 (a)}. In a number of cases the folding on the north side of the fault tends to be open with little internal deformation of the slate layers, whereas the south side of the faulted axial plane is defined by significantly steeper, strained and thinned bedding {Fig. A2 (b)}.

5.2.8 Thrust Faulting

Faults of this type are characterized by shallower dips (<45^{o}) but significant, hard to quantify horizontal displacements. They were observed throughout the stratigraphy of the Necsa area, from the Malmani/Chuniespoort Group dolomites south of Broederstroom (Fig. 2) to the phyllites of the lower Timeball Hill Formation at the picnic site, and to the slates of the Upper Timeball Formation (Figs. 1, 2, A1, A2 (c, d, h)}.

The example shown {Fig. A2 (d)} is of particular interest as it was only recognized in a fresh road cut wall, where typical, shallow dipping slate layers (S_0) sit on top of the hinge of a tight, small-scale anticline. The presence of sheared Bevet Conglomerate at the base of the Pretoria Group (Fig. 1; MAG Andreoli, unpublished data) suggests that the contact between dolomites and slates is para-autochthonous and defined by a thrust fault orientated parallel to the bedding.

5.3 Local Geology at the Target Sites (Site 1 and Site 15)

5.3.1 Site 1

Based on the local geology (figs 1 and 4), these two sites are located in the upper part of the Timeball hill formation do not appear affected by mapped faults. Site 1 is very close to the Hartbeespoort Fault (HF) zone, and it is quite possible that the normal ± right lateral movement of the crust along such feature locally reactivated pre-existing, ~2.043 Ga, Transvaalide belt faults and fractures. Site 1 is further away from the HF zone and for this reason it is the less likely to display unwelcomed structural complexities during the construction phase (instability in excavations).

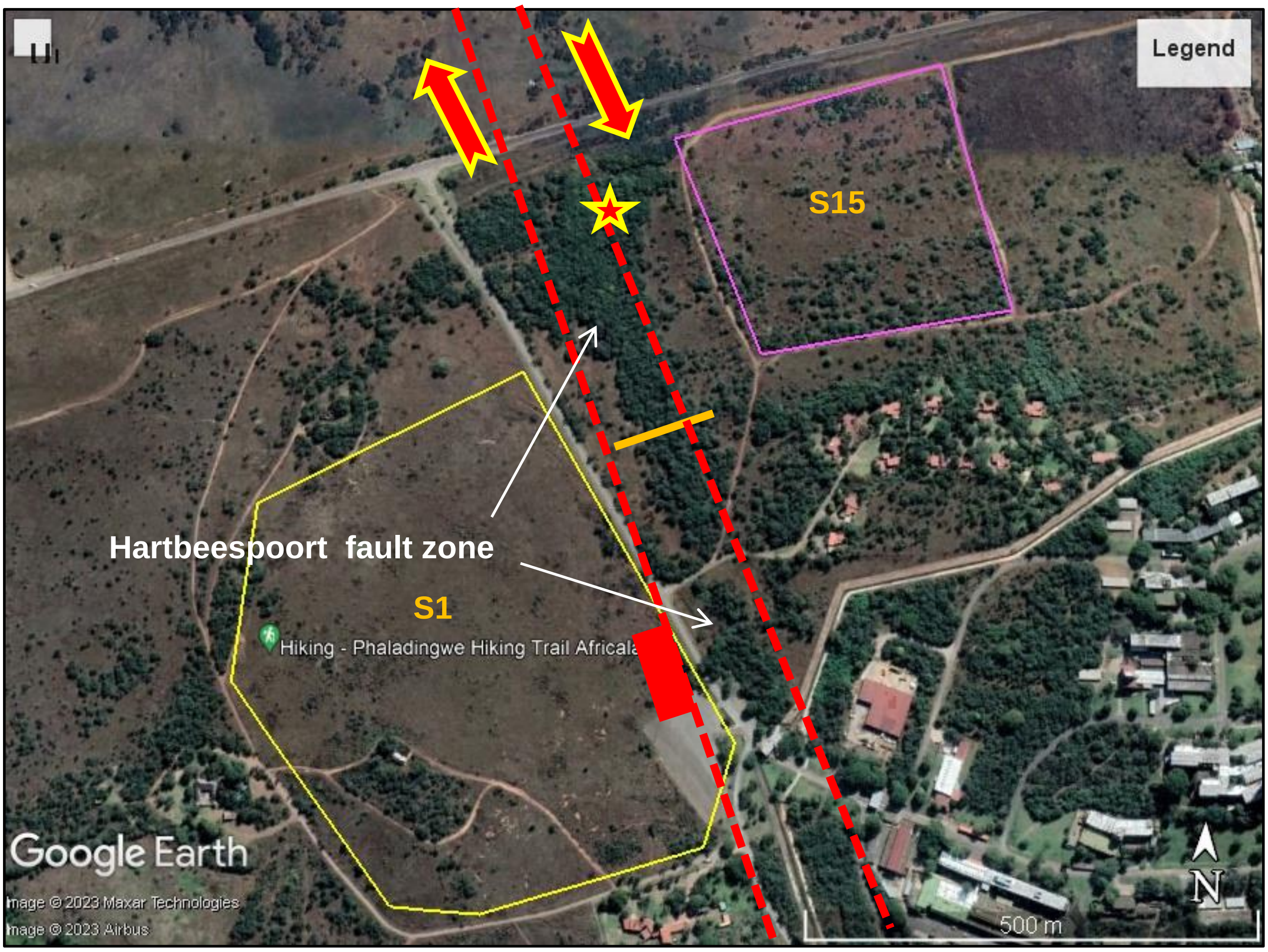

Fig. 3: Google Earth image of the proposed candidate sites in relation to the northern split of the Hartbeespoort Fault, NE margin of the Brits graben.

Explanation:

Yellow Star and orange bar are two different positions of the trench cut to sample the fault overburden (cf., Figs. 5.1 and 2.2; Rizzo et al., 2009). Block on down faulted side (hanging wall) and arrows indicate possible, regional 'right-lateral' strike slip component (Basson, 2019).

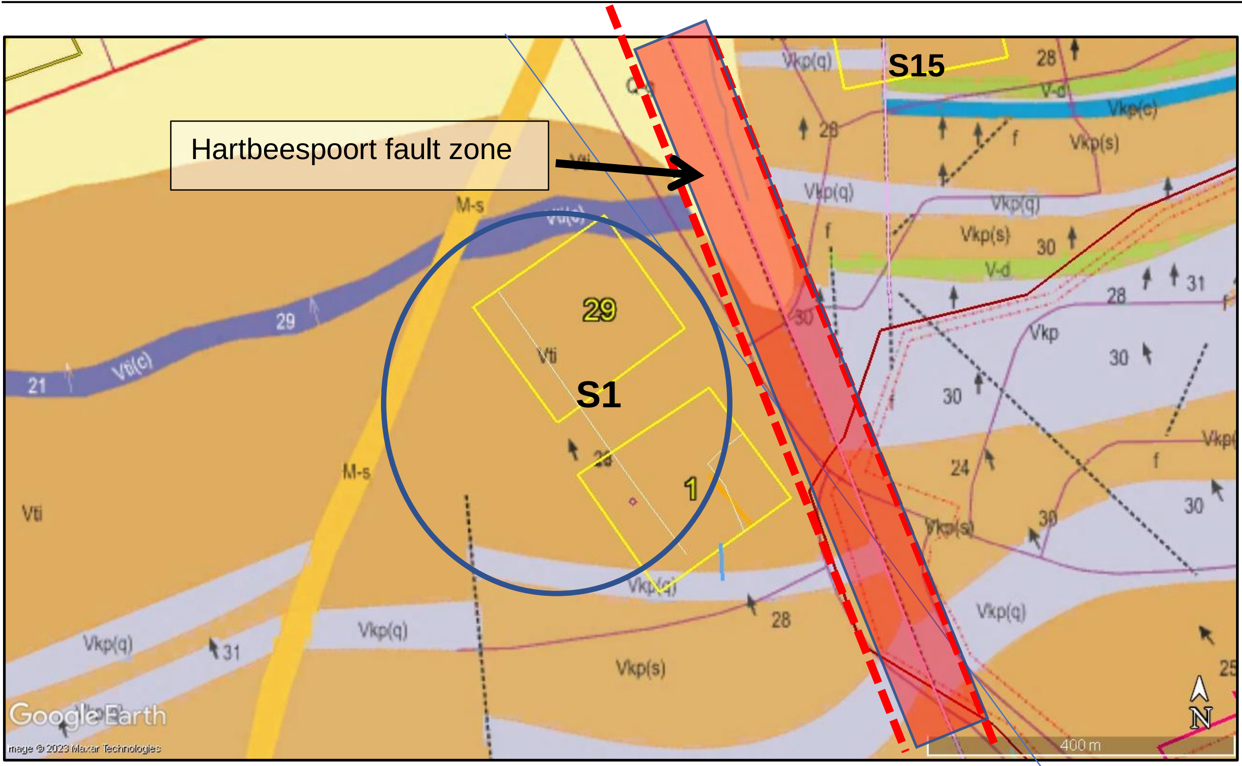

Fig. 4: Interpretative geological cartoon map of proposed Site 1{regolith, surface scree removed; See Fig. 1~~a~~ for symbols (V-d; Vaalian diabase)}.

5.3.1 Site 15

This candidate site is also located in the upper Timeball Hill Formation but is the one that is structurally most compromised by small faults (Fig. 5). These faults are correlated to the ~2.043 age Transvaalide age structures of the Valindaba site (Figs. A1 and A2). The stratigraphic and structural relationship of the weathered diabase mentioned by Rizzo et al. (2009) from the bottom of their trench is contentious.

According to the afore mentioned report, this diabase was presumed to be a dyke of Bushveld age (Andersen et al., 2001), meaning it is a steep intrusion much older than the post-Palaeoproterozoic Hartbeespoort fault (see above). However, the exposed rocks (Fig. 5) show strata-bound sill –like intrusions of Palaeoproterozoic (Bushveld-age or older) diabase closest to the probable position of the trench. This weathered diabase is most likely the on-strike extension of that weathered diabase intersected in TP03 of trench 1 in Site 15 (Fig. 5). Accordingly, it is concluded that the trench, wherever it was, stopped short of intersecting the Hartbeespoort fault zone and that the rock described by Rizzo et al. (2009) was a bedding-parallel sill in the unfaulted upper part of the Timeball Hill Formation.

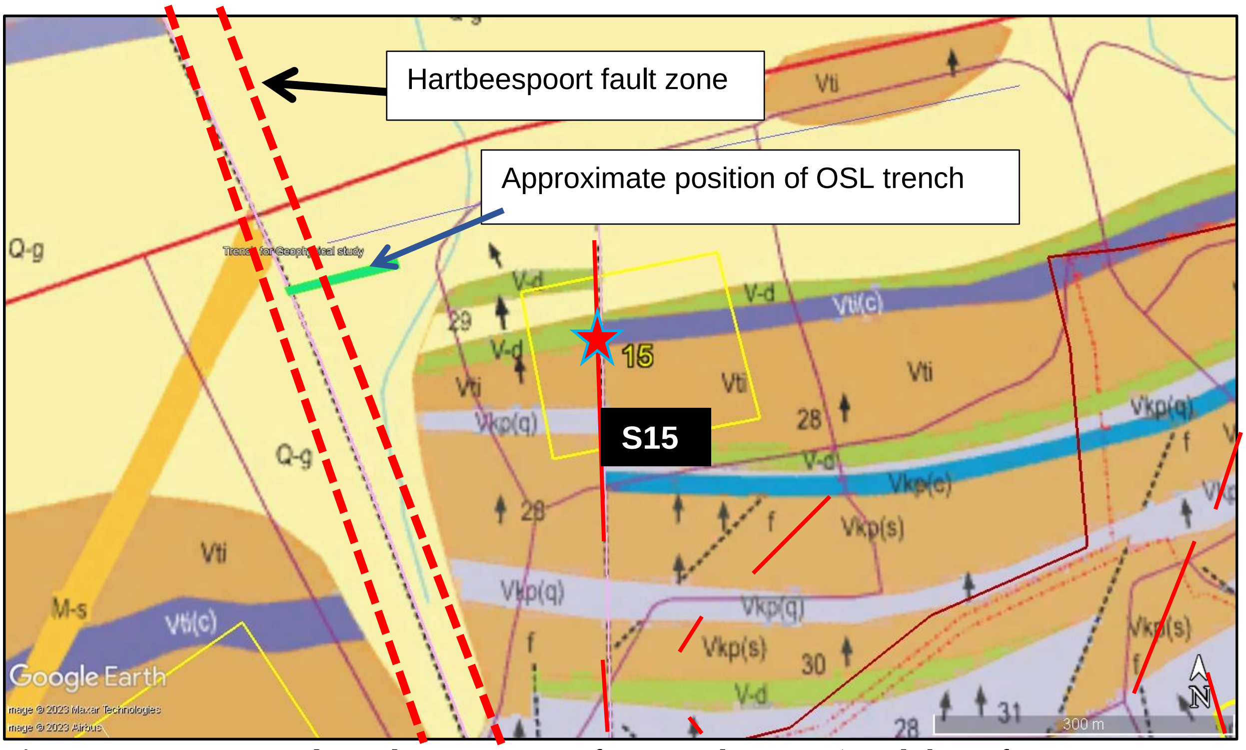

Fig 5: Interpretative geological cartoon map of proposed Site 15 (regolith, surface scree removed; modified after Andersen et al., 2001). (Fig. 1a for symbols; V-d; Vaalian age, Palaeoproterozoic diabase). Green bar: approximate position of ±60 m trench for OSL dating (Rizzo et al., 2009; (M.A.G. Andreoli, unpublished data). Blue-red star: approximate position of pit TP03 of trench 1, Site 15 (GCS Report 23-0071 Necsa MPR Site 15).

6.0 SEISMIC HAZARD CONSIDERATIONS

6.1 General Comment

For the sake of completeness, an overview of the seismic hazard work relevant to Pelindaba and the need for regular updates to this work is provided below (A Kikjo). In addition, Table 1 summarizes previous seismic hazard data for the Pelindaba area: some were obtained from country wide events catalogues (Brandt, 2011; Midzi et al., 2020), whereas those by Kijko et al. (2001) and PBMR (2009) were site specific probabilistic seismic hazard analyses (PSHA) generated using all structural, tectonic data available at the time. The data in Table 1 do demonstrate that, even considering possible seismic sources from the platinum mines near Brits, the hazard posed by tremors and earthquakes might be mitigated by the judicious application of sound engineering principles. However, the values reported in Table 1 are expected to change somehow, should a new PSHA be conducted for sites 1, 15, and 29 using the more recently published tectonic data for the region within 30 km from the Necsa industrial site (References: see 1. Introduction; PBMR, 2009; Rizzo et al., 2009).

Table 1. A comparison of selected, historic seismic hazard assessment values for the Necsa site

References	**Brandt, 2011**	**PBMR, 2009b***	**Kijko et al., 2011**	**Midzi et al., 2020**
PGA** (g)	~0.05-0.1	±0.2 (mean)	0.178	±0.039 (mean)
Probability of non-exceedance over 50 years	90%		84%	90%
Largest credible earthq.ke m_{max}			5.05±0.5	5.28±0.9
Worst case scenario (WCS)	MMS < VI		5.55[#]	
Probability of WCS recurrence (y)		±1.0 x 10^{-4}	±1.8 x 10^{-5}	±0.5 x 10^{-3}

* **Figure 4-11**: **Peak Ground Acceleration; [#]: 0-25 km from site, 10 km depth hypocentre.

6.2 Assessment of Seismic Hazard for Nuclear Facilities

Assessing seismic hazards for critical structures (especially nuclear facilities) is highly regulated. In Europe, the key organization responsible for establishing and implementing safety standards for nuclear facilities is International Atomic Energy Agency (IAEA), headquartered in Vienna, Austria. In the United States of America, similar role plays organizations, e.g., the U.S. Nuclear Regulatory Commission and the U.S. Department of Energy.

The safety guidance's and recommendations provided by the above organizations address **<u>all types of nuclear facilities</u>** as defined by the IAEA Safety Glossary (IAEA, 2004)

(a) Nuclear power plants.
(b) Research reactors (including subcritical and critical assemblies) and any adjoining radioisotope production facilities.
(c) Storage facilities for spent fuel.
(d) Facilities for the enrichment of uranium.
(e) Nuclear fuel fabrication facilities.
(f) Conversion facilities.
(g) Facilities for the reprocessing of spent fuel.
(h) Facilities for the predisposal management of radioactive waste arising from nuclear fuel cycle facilities.
(i) Nuclear fuel cycle-related research and development facilities.

In general, the hazardous effects of seismic events, which include induced-, triggered seismic events and tectonic-origin earthquakes, can be divided into three categories:

1. Effects resulting directly from a certain level of ground shaking.
2. Effects at the site of the event resulting from physical surface faulting or deformations and
3. Effects triggered or activated by a certain level of ground shakings.

As a result, in the broad sense, seismic hazard analysis includes geological and geotechnical hazards, such as permanent ground displacement, soil liquefaction, slope instability, tectonic and non-tectonic subsidence, and events like tsunamis or landslides.

However, this note provides only information on how the effects resulting directly from ground shaking should be investigated. The geotechnical aspect of seismic hazards and the meteorological and hydrological hazards in the nuclear facility site is provided by the IAEA document NS-G-3.6 (2004) and the IATA No. SSG-18 (2011), respectively.

Seismic hazard analysis can be performed in two different ways, probabilistic and deterministic.

The essence of the probabilistic seismic hazard analysis (PSHA) is a calculation of the probability of exceedance of a specified ground motion level at a specified site (Cornell, 1968; Reiter, 1990).

The ultimate result of a PSHA is a *seismic hazard curve*: the annual probability of exceeding a specified ground motion parameter at least once. (For details, see Appendix A). The seismic hazard curve quantifies the hazard at the site from all possible seismic events of all possible magnitudes and distances from the site of interest by considering their frequency of occurrences. An alternative definition of the hazard curve is the frequency of exceedance vs ground motion amplitude (Budnitz et al., 1997; McGuire, 2004).

The PSHA procedure is based on two types of information: (1) observed seismicity, recapitulated by earthquake catalogue, and (2) area-specific geological and seismo-tectonic data. After combining a selected model of earthquake occurrence with the information on the regional seismic wave attenuation (known as the ground motion model, GMM), a regional seismotectonic model of the area is formulated. Besides, the PSHA takes into account site-specific soil properties.

All the information required by a complete PSHA is subjective and often highly uncertain. According to the convention established in the fundamental document by Budnitz *et al*. (1997), two types of uncertainties are associated with PSHA: aleatory and epistemic. By default, any complete PSHA supposes to account for these two uncertainties. Any PSHA without the incorporation of the above uncertainties is considered to be incomplete.

The deterministic seismic hazard analysis (DSHA) is used as an alternative to the probabilistic approach. It provides information on the conservative (the worst case) scenario of the expected ground motion vibration. For details, see Appendix B and, e.g., IATA SSG-9 (2022).

Assessment of Deterministic and Probabilistic Seismic Hazards for a nuclear facility in South Africa requires the following:

1. Compilation of seismic events catalogue. Selection of earthquakes within a radius of at least 450 km from the site.

2. Analyse seismicity data for the area and evaluate the catalogue's completeness and accuracy.

3. Literature review of published seismotectonic sources and zones. The study and selection of the relevant ground-motion models (GMM) suitable for the identified area. The typical output of the PSHA should be expressed in terms of PGA for rock (V_{S30} = 760 m/s).

4. Assessment of the area-characteristic maximum possible earthquake magnitude(s) for the identified seismotectonic sources.

5. Assessment of the earthquake recurrence parameters, viz., mean annual seismic activity rate, the Gutenberg-Richter b-value for the identified seismotectonic sources.

6. Probabilistic seismic hazard analysis, i.e., assessment of the annual probability, that a specified level of ground motion will be exceeded at least once at the site. This assessment should include the construction of earthquake recurrence curves for the selected areas for the

return period and the probability of exceedance for the mean, median, 5%, 15%, 85%, and 95% percentiles of the horizontal component of the peak ground acceleration (PGA).

7. Following relevant regulations, several earthquake-designed levels (EDL) must be considered. One of them is, e.g., Maximum Credible Earthquake (MCE). These design levels indicate seismic hazards and risks for the investigated site based on different return periods.

8. For investigated infrastructure, several EDL's should be computed, associated with different return periods as, e.g., of 2,475, and 10,000 years.

9. Application of Logic-Tree formalism. The logic tree formalism will capture epistemic uncertainty associated with selecting the appropriate GMMs, earthquake recurrence parameters and area-characteristic maximum possible earthquake magnitude m_{max}.

10. Horizontal and vertical components (plots and tables) of mean, uniform hazard response spectra (UHRS) for specified return periods. In addition, the analysis should provide plots of 5% damped UHRS for various fractals (e.g., mean, median, 5^{th}, 15^{th}, 50^{th}, 85^{th} and 95^{th}).

11. The plot of elastic response spectra (ERS) for damping 5% anchored at the specified earthquake design level, as, e.g., MCE.

12. PSHA in terms of earthquake magnitude. The analysis should include area characteristic PSHA, assessment of the area characteristic, maximum possible earthquake magnitude m_{max} and the annual probability of exceedance and return periods of specified value of earthquake magnitude.

13. Deterministic Seismic Hazard Analysis (DSHA). Deterministic seismic hazard analysis (DSHA) involves the development of a particular seismic scenario, according to which expected damages (losses) can be estimated. It provides a framework for the evaluation of the worst-case damages. (For more information, see Appendix and document, e.g., IATA SSG-9, 2022).

14. Hazard de-aggregation. By definition, the PSHA aggregates ground motion contributions from earthquake magnitudes and distances of significance to a site of engineering interest. The procedure of de-aggregation should be performed for the specified return period for spectral accelerations 1.0, 2.5, 5.0 and 10.0 Hz and PGA.

15. An account of site effect. Any ground motion model (GMM) is specific to a soil or rock type on which the PSHA is to be made. These ground types are known as the site classes (International *Building Code*, 2000; *NEHRP Provisions*, 2001; *Eurocode 8*, EN 1998-1, 2004) and are classified as rock, soft rock, firm soil and soft soil. The site classes are defended by their shear velocities, V_{S30}, most often averaged over the upper 30 m. The applied ground-motion models provide values of *PGA* for the reference $V_{S30} = 760\ m/s$. The account for V_{S30}, different from the reference $760\ m/s$ can be done by multiplication of the reference *PGA*($V_{S30} = 760\ m/s$) by a correction factor C_f.

16. Selection of accelerograms matching UHRS. The information should identify the most significant seismic sources in magnitude and distance. It includes the choice of several horizontal and vertical time histories matching the UHRS spectrum.

7.0 RELEVANCE OF SEISMIC HAZARD CONSIDERATIONS TO THE PROPOSED NEW MPR SITE, PELINDABA

1. Following the safety guidance and recommendations provided by IAEA (2004), requirements of seismic hazard assessment apply to **all types of nuclear facilities,** including research reactors (subcritical and critical assemblies) and any adjoining radioisotope production facilities.

2. Following the safety guidance IAEA NS-R-3, 2016, Rev1. CL 5.1A, p. 21 (attached), site-specific hazards shall be periodically reviewed using updated knowledge, **typically every ten years**, and shall be re-evaluated when necessary. A review after a shorter interval shall be considered in the event of evidence of potentially significant changes in hazards (for example, in the light of the feedback of operating experience, a significant accident or the occurrence of extreme events). The implications of such a review of site-specific hazards for the safe operation of the nuclear installation shall be evaluated.

8.0 SLOPE STABILITY ASSESSMENT

With respect to the existing gentle slope morphology of the two sites (6 to 8%), both are considered stable in terms of slope stability. If significant bulk excavations are envisaged during construction, then a more detailed assessment of the site will be required, especially on the north-facing cut slopes due to the unfavourable orientation of the bedding in the shales.

9.0 LIMITATIONS AND ASSUMPTIONS

The following is a summary of the limitations and assumptions applicable to this preliminary investigation and report:

- **The preliminary test pits that were urgently organised under MPR-EXT-DES-0002 (GCS Geological Comparison report 23-0071R01) are not intended to replace the more formalised trench mapping to identify fault features with the assistance of the geophysical surveys (CSW) that will be completed as part of this report.**

- The extensive literature search has revealed the possible occurrence of inferred faults traversing both sites and these have been marked on the geological maps as accurately as possible.

- A preliminary status has been temporarily applied to this report and will be finalised once the geophysical (CSW or MASW) surveys have been completed to allow the more precise trench mapping to be finalised. The required extent of geophysical surveys and effective trench mapping to confirm and expose any structural disturbances or faults that may affect the selection of one site over the other can only be realised with the appropriate environmental authorisations if considered necessary.

10.0 CONCLUSIONS AND RECOMMENDATIONS

A review of the published and unpublished geological data and available reports on the Necsa sites indicates the two proposed alternative sites both have some geological flaws as they are situated within 400 m from the regional scale Hartbeespoort fault. The latest PSHA report (PBMR, 2009) considered this fault inactive and non-capable.

Site 15 is probably the least desirable due to the presence of an additional, ~2 Ga old fault and a few others within a distance of 0.5 km. Site No. 1 is thus ranked more suitable as it lies further away from the Hartbeespoort fault and from other minor faults.

Whichever site is ultimately selected, they will both be influenced by the proximity to the large Hartbeespoort Fault zone and faults, folds, fissures, and joints buried under the regolith/colluvium that will be exposed during construction of the project. **The preferred selected site will be further investigated in Part II using more detailed test pits, boreholes and geophysical surveys for foundation and civil engineering purposes and using the Necsa layout as the new final site boundaries.**

The seismic hazard on both sites is considered to be low. However, in terms of international guidelines an updated PSHA is due for the entire Pelindaba but this should not influence the current EIA process.

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APPENDIX A

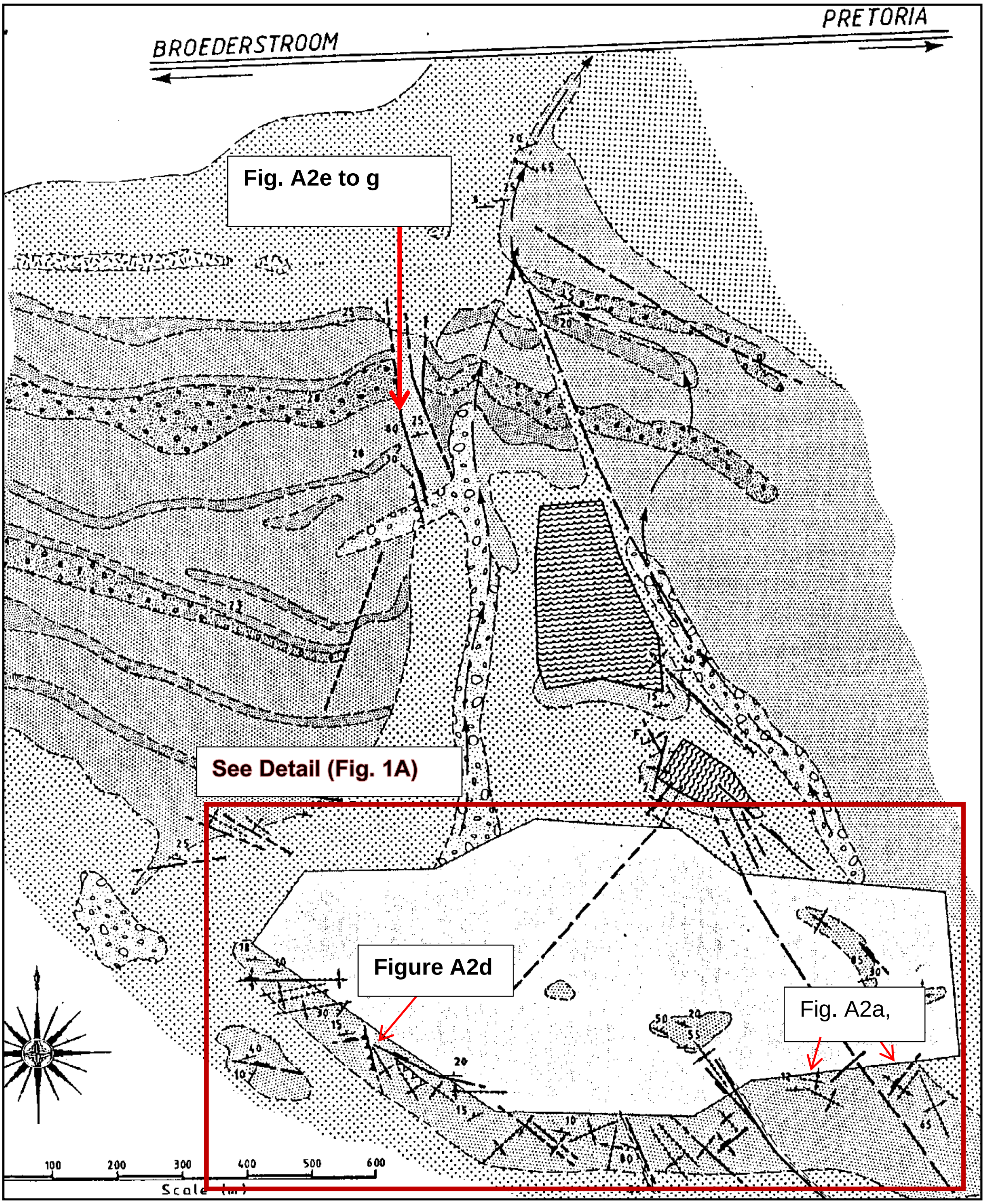


Fig. A1: Geology of the Valindaba site (Andreoli, 1988). (Ref. Legend (Fig. A1/c).

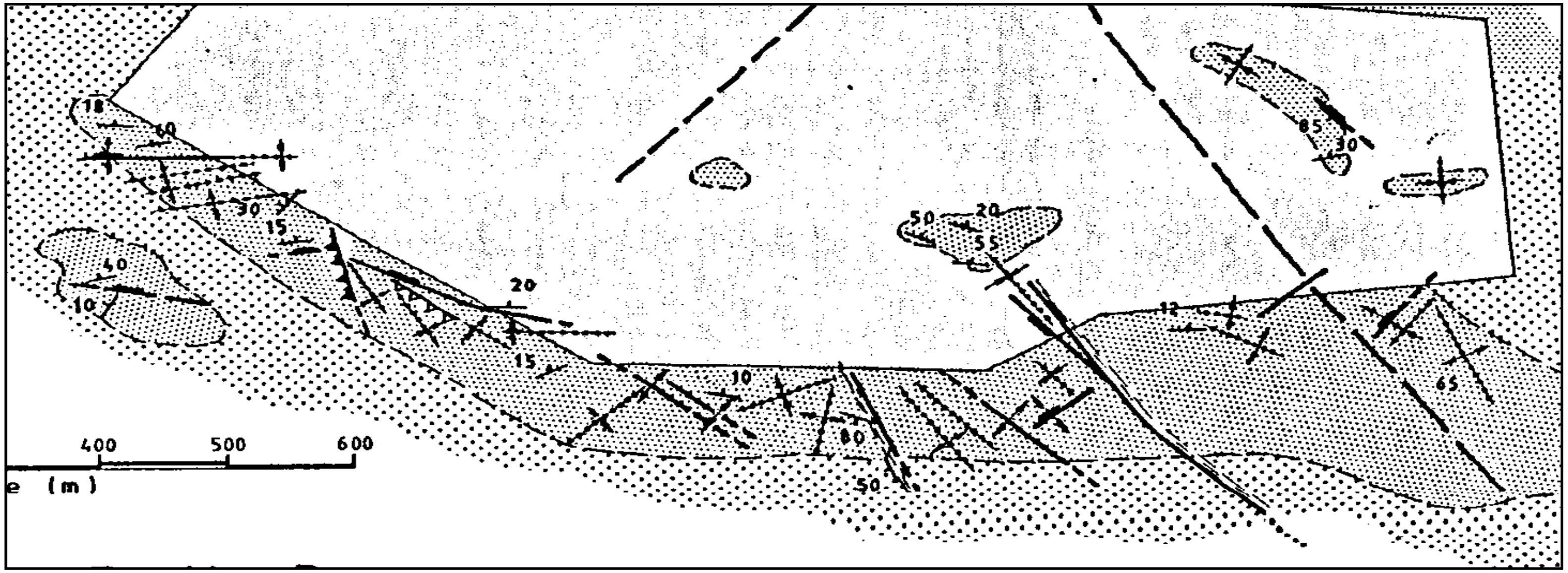


Fig. 1A (Detail)

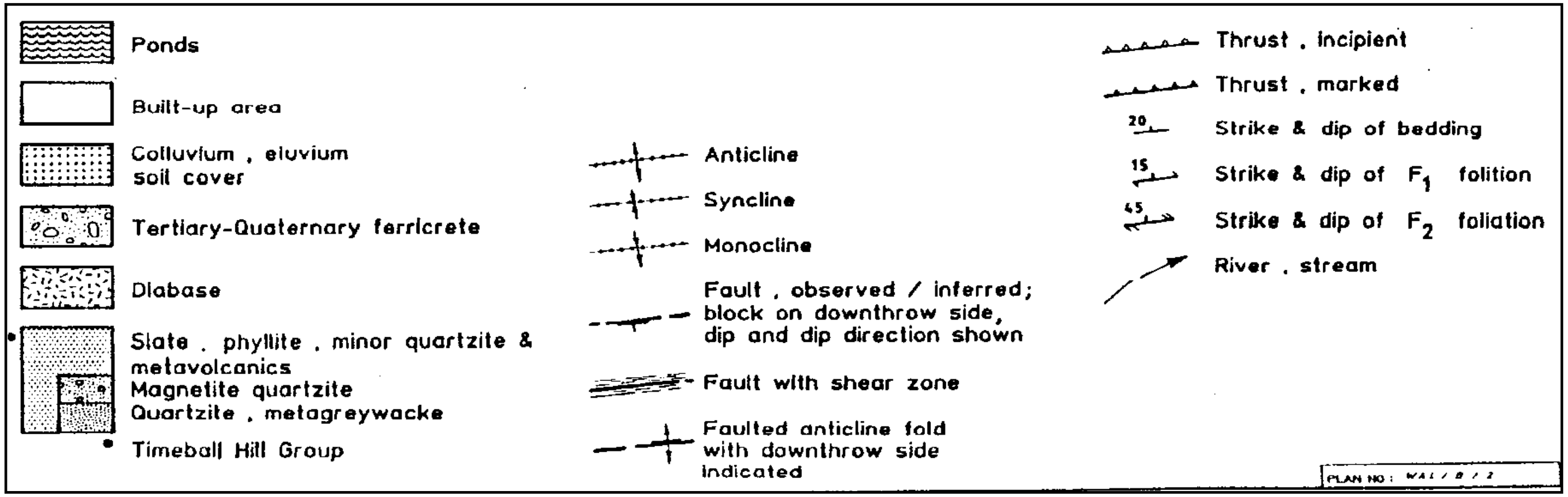
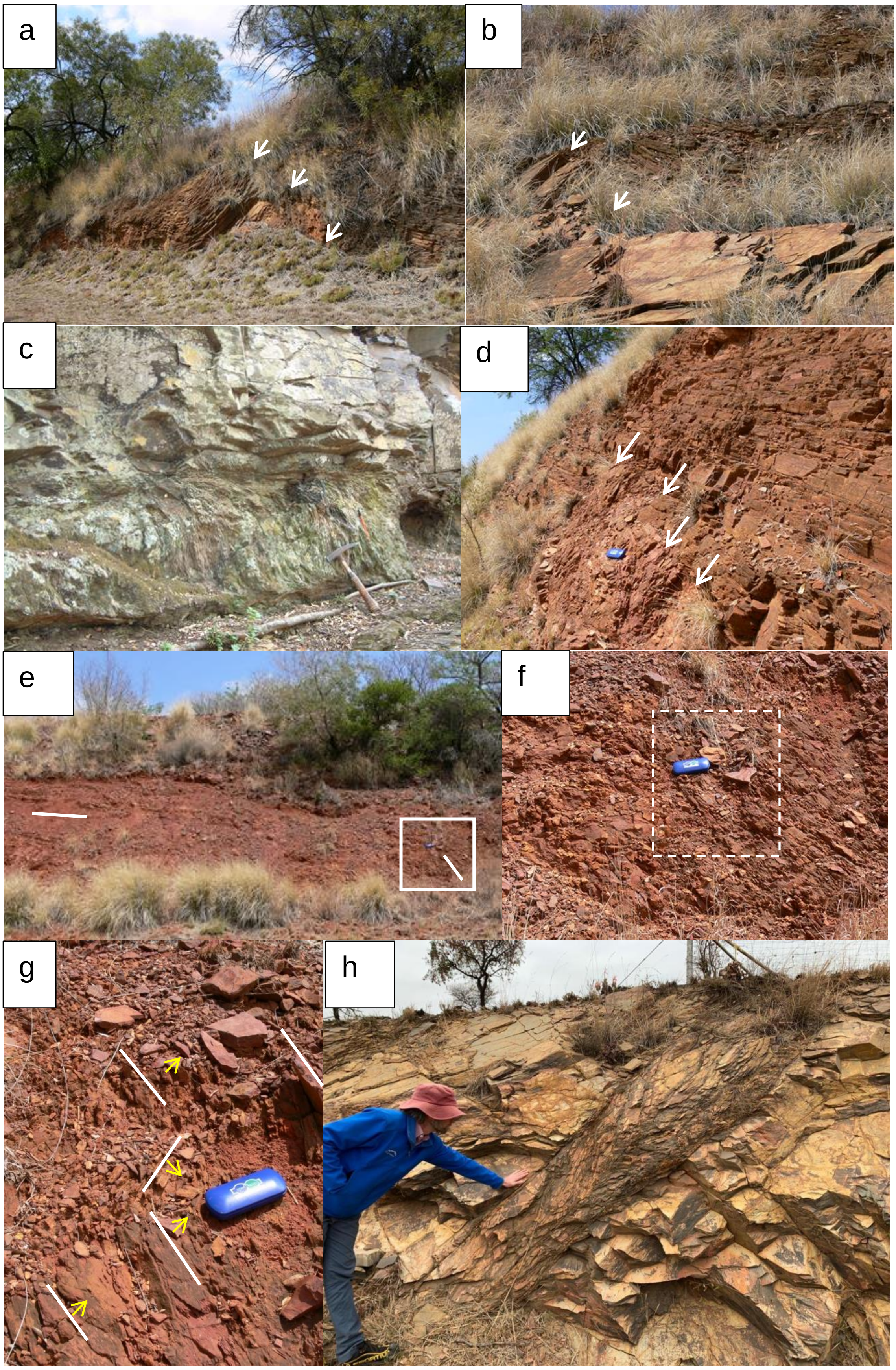


Fig. A1/c: Legend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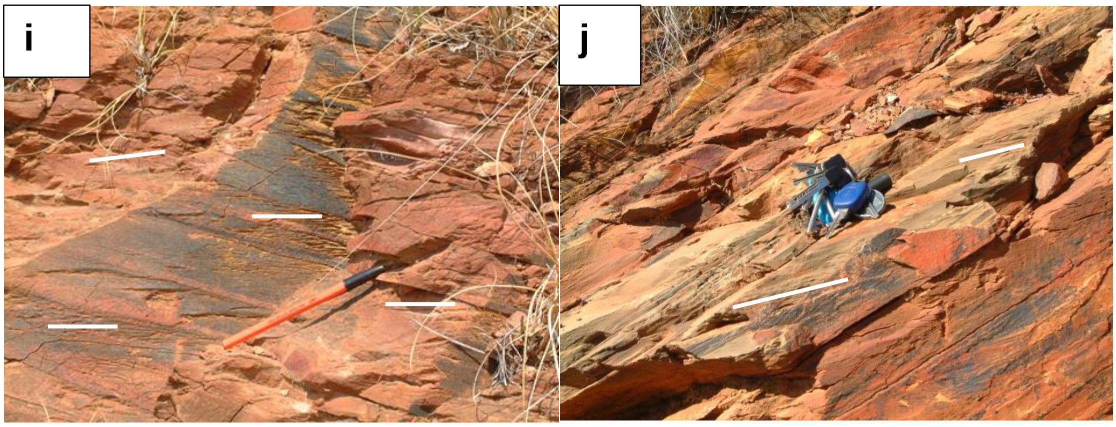

Fig. A2: Structures characteristic of the slates and phyllites of the Pelindaba area.

Appendix A (Fig. A2): Explanation of the Photographs

Explanation of and reference to the figure (Fig. A2)

- **(a) and (b),** asymmetric ductile to brittle folds on a road cut north of the P2 sampling site (Figs. 1 and A1) with arrows indicating hinge;
- **(c)** bedding parallel thrust zone in the Rooihoogte formation near the base of the Pretoria Group (PEL-PIK, Figure 1) The same bedding-parallel cleavage (S_1: dip 17° ± 12° to N348°± 7°) is pervasive both above and below the thrust, and is in many places accompanied by a fanning set of lineations (L_1 plunge: 7° ± 3° to N327° ± 27°).
- **(d)** Cryptic thrust fault (see arrows) separating Timeball Hill slates above (dip 15^o to NNW) from tightly folded (steeply dipping slates below (NNW axial plane) (Fig. A1);
- **(e) to (g):** hinge sector of cryptic, monoclinal fold structure; white bars: bedding, yellow arrows: 'stratigraphic up' direction (Fig. A1); h: thrust fault zone in Timeball Hill slate (credit: Prof. A. Bumby);
- **(i) and (j):** two photographs from the site of (e) above showing different dip/orientation changes between bedding (S_0) and (white lines) cleavage (S_1)

Fig. A3: Tight, probably faulted and overturned fold in slate (view to west), lower Timeball Hill Formation near Glen Africa Country Lodge (cf. Figure 2); bedding dips: upper limb 57^{o} to SE, lower limb 22^{o} to ENE (Ingram et al., 2000).

Table A1: Mineralogical description of samples collected close to the sites (after Alexandre et al., 2006).

Sample	Coordinates	Figure	Mineral Constituents	Comments:
P-2.	25° 48’ 17.16” S 27° 55’ 23” E.	Cf. A1a, b).	quartz – white mica – chlorite ±rare pyrite porphyroblasts up to 1mm across in alternating quartz-rich and quartz-poor layers.	dark grey, finely banded **slate.** Typical size of minerals: 50-100 m; largely fresh, apart from the replacement of pyrite by limonite. The sedimentary layering (S0: dip 13° to N350°) is of compositional nature and marked by chlorite-white mica aggregates. This bedding is transposed by a pervasive cleavage (S1: dip ~ 12° to N170°) defined by incipient crenulations of the chlorite-white mica aggregates (Figure 4A) or by white mica lepidoblasts that are axial planar to small scale, north-verging asymmetric crenulation folds. In places, the intersection of S1 on S0 produces an indistinct lineation L1 plunge: <10° to N80°). Acicular chlorite needles (50-80 _m in length) define a weakly developed, subvertical S2 cleavage not noted in outcrop.
PEL-PIK	25° 48’ 27.66” S 27° 54’ 46.46” E.	4B	white mica, quartz, fine opaque dusting	S1 cleavage coaxial to a recumbent, intrafolial fold (Figure 4B), was sampled in the footwall of a ~70 cm thick, bedding parallel thrust zone in the Rooihoogte formation near the base of the Pretoria Group (Figure 2). The same bedding-parallel cleavage (S1: dip 17° ± 12° to N348° ± 7°) is pervasive both above and below the thrust and is in many places accompanied by a fanning set of lineation’s (L1 plunge: 7° ± 3° to N327° ± 27°). The latter derive from the intersection of S1 and a S2 cleavage (dip:70° to N45°) coaxial to mm-to-dm scale crenulation folds.