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Operational Report about drilling in the Moodies Group of the Barberton Greenstone Belt

(BASE – Barberton Archean Surface Environments)

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INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Operational Report about drilling in the Moodies Group of the Barberton Greenstone Belt (BASE – Barberton Archean Surface Environments)

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ICDP INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Abstract

The BASE (Barberton Archean Surface Environments) scientific drilling project focused on recovering unweathered continuous core through strata of the Paleoarchean Moodies Group (ca. 3.2 Ga), central Barberton Greenstone Belt (BGB), South Africa. They comprise some of the oldest well-preserved sedimentary strata on Earth, deposited within only a few million years in alluvial, fluvial, coastal-deltaic, tidal, and prodeltaic settings and represent a very-high-resolution record of Paleoarchean surface conditions and processes. Moodies Group strata consist of polymict conglomerates, widespread quartzose, lithic and arkosic sandstones, siltstones, shales, and rare BIFs and jaspilites, interbedded with tuffs and several thin lavas. This report describes operations from preparations to the sampling workshop and complements the related scientific report.

Eight inclined boreholes between 280 and 495 m length, drilled during November 2021 through July 2022, obtained a total of 2903 m of curated core of variable quality through steeply to subvertically dipping, in part overturned stratigraphic sections. All drilling objectives were reached. Boreholes encountered a variety of conglomerates, diverse and abundant, mostly tuffaceous sandstones, rhythmically laminated shale-siltstone and banded-iron formations, and several horizons of early-diagenetic sulfate concretions. Oxidative weathering reached far deeper than expected; fracturing was more intense, and BIFs and jaspilites were thicker than anticipated. Two km-long mine adits and a water tunnel, traversing four thick stratigraphic sections within the upper Moodies Group in the central BGB, were also sampled. All boreholes were logged by geophysical instruments. Core was processed (oriented, slabbed, photographed, described, and archived) in a large, publicly accessible hall in downtown Barberton. An exhibition provided background explanations for visitors and related the drilling objectives to the recently established Barberton-Makhonjwa Mountains World Heritage Site. A substantial education, outreach and publicity program addressed the information needs of the local population and of local and regional stakeholders.

Referencing articles

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ICDP INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

1. Organization and Funding

1.1. Management

The DSI-NRF Centre of Excellence for Integrated Mineral and Energy Resource Analysis (CI-MERA), with offices at the University of Johannesburg Geology Department, administered the project. There, Nic Beukes († Jan. 9, 2023), retired professor at UJ and former head of CIMERA, acted as BASE administrative manager, handling its financial planning, contracts, staffing, and a multitude of logistical aspects. He was assisted by the CIMERA manager Sego Mashego and administrative assistant Viwe Kosi. Nic Beukes and Christoph Heubeck jointly defined the roles of the onsite geoscience team, beginning in September 2021. Contracts were negotiated by Nic Beukes and contracted through UJ, represented by CIMERA. Christoph Heubeck acted as principal scientific and onsite geoscience coordinator of BASE and led the scientific processing of core on site September 2021 through March 2022 and again in July and August 2022. During drilling operations (November 2021 to July 2022), Nic Beukes travelled to Barberton about once a month. Without his direction, guidance and engagement, this project could not have been conducted.

The BASE Science Management Team (Table 1), composed of nine senior scientists from as many countries who had jointly co-authored the ICDP drilling proposal, met online about every second month to receive reports and advise on future directions.

Table 1: BASE Science Management Team

Title	First Name	Last name	Affiliation	Country
Prof. Dr.	Nic	Beukes	Univ. of Johannesburg	South Africa
Prof. Dr.	Michiel	de Kock	Univ. of Johannesburg	South Africa
Prof. Dr.	Christoph	Heubeck	University of Jena	Germany
Dr.	Martin	Homann	Univ. College London	UK
Prof. Dr.	Emmanuelle	Javaux	Université of Liege	Belgium
Prof. Dr.	Takeshi	Kakegawa	Tohoku University	Japan
Prof. Dr.	Stefan	Lalonde	CNRS, Brest	France
Prof. Dr.	Paul	Mason	Utrecht University	Netherlands
Dr.	Mike	Tice	Texas A&M University	US
Prof. Dr.	Martin	van Kranendonk	Univ. of NSW, Sydney	Australia

1.2. Onsite Geoscience Team; Local Support

Principal tasks of the onsite geoscience team included the processing of the core, monitoring the drilling crews, performing outreach and education tasks, and maintaining contact to local stakeholders and government relations.

Most onsite geoscience staff members were also trained in and worked at least temporarily in other functions. During Christoph Heubeck's absence, his tasks were split among the other team members.

Local support in Barberton (accommodation, hospitality, community relations, diverse day-to-day needs) was provided by the Barberton Community Tourism manager Astrid Christianson and her office staff, Fikile Mayisela. For core transport, daily travel to and from drill sites, and other transport needs, a Toyota Fortuner was contracted through UJ; for many other tasks, C. Heubeck's pick-up truck was used.

Figure 1: BASE Onsite Geoscience team.

Full-time staff (Fig. 1, Table 2) included:

Table 2: BASE Onsite Geoscience Staff

Christoph Heubeck	Geologist (chief scientist; coordinator; speaker. Lithological descriptions; interpretations; photography). On sabbatical leave from Friedrich-Schiller University Jena
Nic Beukes	Geologist (chief admin officer; in Johannesburg). Financials, payments, staffing, logistics, drilling and services; government relations
Rod Tucker	Geologist (geology drillsite management; daily contact to drilling teams; core pickup)
Chris Rippon	Geologist (core manager; core orientation and slabbing; core saw supervision; core palletising, core transport to CGS, container loading)
Dora Paprika	Geologist (data management; core description)
Phumelele Mashele	Geologist (education, outreach, publicity; stakeholder relations)
Ryan Tucker	Helper (driver, core handling, data entry etc.)
Victor Ndazamo	Geologist (photography, outreach, education)
Thikho Mufamadi	Geologist (photography, core curation)
Derick Dludlu	Helper (core handling, saw operations)
Musa Mavimbela	Helper (core handling, saw operations)
Tony Ferrar	Outreach, community and museum relations
Astrid Christianson	Hospitality, community and government relations, accommodation.

1.3. Drilling Contractor; Roles

From five bids responding to a CIMERA tender, the winning company was selected by the Rating Committee due to its mix of reasonable costs, detailed proposal, and prior experience with research drilling. A contract was signed November 3rd and 8th, 2021. This contract clarified objectives and responsibilities (contract duration, location, access, water, core recovery, environmental protection, drilling shifts, security, HSE, records and reports, special conditions and additional information) and included a number of Appendices (Security, Environmental

Management Plan, HSE Management plan, Drilling Fluids, Cost Schedule etc.). The contract also identified technical and administrative staff of both parties and their contact information. The drilling contractor's staff worked seamlessly with local stakeholders (SAPPI forestry, water, electricity, accommodation etc.), rig transport companies, government oversight, the Environmental Control Officer, and the Onsite Geoscience Team. The Onsite Geoscience Team was in contact with the drillers at least daily for the core handover, so that the initially scheduled monthly drilling reviews could be cancelled. Towards early evening, the contractor's Drill Site Manager broadcast photos of the handwritten daily drilling report of each drilling rig through a WhatsApp group. These were retyped and included into the monthly reports. Monthly billing was received, checked, and approved by Rod Tucker; Viwe Koti and Segopotso Mashego at CIMERA, who, working with Nic Beukes, handled the payments.

The drilling contractor initially assigned two track-mounted drill rigs to the project. Each rig had a crew of five and both rigs were managed by an onsite drilling engineer (the Drill Site Manager). At the Johannesburg Office, the contractor's administrative staff kept records, provided the billing, and dispatched supplies and spare parts from the yard.

1.4. Financing and Contracting

BASE operations were financed through the standard ICDP model in which ICDP provided, after thorough reviews, substantial seed funds, approximately covering 58% of the BASE drilling costs. This initial "quality seal" of ICDP approval strengthened subsequent research proposals by PIs to their national research agencies or employers. The budgets of such proposals then usually included a request for a contribution to the estimated drilling costs.

Segopotso Mashego, administrative manager of CIMERA at UJ, oversaw the finances; all expenditures were authorized by Nic Beukes or Prof. Nikki Wagner, Director of CIMERA. Starting in November 2020, ICDP prepared a Grant Agreement between UJ, the FSU Jena, and ICDP which clarified responsibilities, authorizations, and timing and mode of fund transfers. This document was, after approval by involved legal departments, signed in May 2021. It provided the legal base for the CIMERA Moodies cost center, number 05.05.278783.15, into which all incoming funds were transferred, in part following invoices sent out by CIMERA. Because this was a purely scientific project, no value-added tax was included. ICDP funds were transferred to CIMERA in two instalments, beginning July 7, 2021; national contributions (Table 3) followed shortly thereafter, just in time to make down payments on drilling mobilization costs.

Participants decided at the end of the field workshop in Sept. 2017 to submit a full proposal for the upcoming deadline, January 15, 2018. This proposal was critically reviewed and returned to the team of PIs with the request to clarify and modify several points. Our second attempt, submitted January 15, 2019, was successful and funded with 900,000 USD from ICDP by letter of June 5, 2019. This approval "in hand", PIs proceeded to submit proposals with specific core-based research objectives to their national research organizations and their individual employers. This was a protracted process; proposals in several countries (along with their requests for drilling contribution) were turned down very narrowly or repeatedly, despite several persistent resubmissions. Nic Beukes and Christoph Heubeck, who oversaw the gradual growth of the funds, estimated in February 2021 that enough funds had come in (or had a high likelihood to be granted) to cover drilling costs, our principal expense. A drilling tender was prepared by Nic Beukes in June, issued by UJ in July, and evaluated and awarded in August, for drilling to start in September 2021. Nic Beukes scouted and hired onsite geoscience team members; they were employed through CIMERA at UJ. Various delays caused drilling to begin only November 15, 2021.

Table 3: Financial Contributions to BASE

Country	***Funding by …***	***Program Name***	***PI***	***Institution***	***Amount***	***South African Rand (ZAR)***	***Approx. % of total project***
	14-2017 Workshop	ICDP	C. Heubeck and co-PIs		50,000 USD	641,026	2.8%
	03-2019 Transfer 1				269,321 USD	3,920,105	60.1%
	[1]03-2019 Transfer 2				754,100 USD	11,185,422	
USA	NASA	Exobiology Program grant 80NSSC21K0443	M. T. Tice	Dept. of Geology & Geophysics, Texas A&M University	155,546 USD	2,259,812	9.8%
DEU	[2]Deutsche Forschungsgemeinschaft	SPP1006, proposal He2418/25-1, transferred to ICDP	C. Heubeck	Department of Geosciences, Friedrich-Schiller-Universität Jena	150,000 EUR		8.8%
ZAF	National Research Foundation of South Africa		N. Beukes	Dept of Geology, University of Johannesburg	1,750,000 ZAR	1,750,000	7.6%
JPN	Japan Society of the Promotion of Science	KAKENHI Grants 20H00184	T. Ohtake and Co-PIs	Faculty of Engineering, Hokkaido Universty	12,000,000 Yen	1,607,000	7.0%
BEL	Fonds National de la Recherche Scientifique de la Fédération Wallonie-Bruxelles, Belgique	PDR T.0137.20	E. Javaux	Full Professor, UR Astrobiology, Université de Liege	50,000 EUR	850,610	3.7%
NLD	[5]Dutch Research Council (NWO)	Open Competition Domain Science – XS	P. Mason	Geosciences, Utrecht University	part of 42000 EUR	268,395	1.2%
NOR	University of Bergen	SPIRE 2020	D. Roerdink	Dept. of Earth Science, University of Bergen	150,000 NOK	268,395	1.2%
USA	Harvard University	Origins of Life Initiative	R. Fu	Dept. of Earth and Planetary Sciences		238,824	1.0%
CHE	Université de Lausanne	University of Lausanne starting grant	J. Marin-Carbonne	Faculté des géosciences et de l'environnement	6,000 CHF	102,003	0.4%
ZAF	Council for Geoscience				In-kind support (hyperspectral scanning)		
ZAF	University of Johannesburg				Logistic support		
Sum:						**23,091,592**	100.67%

For comparison: Total income into CIMERA-ICDP BASE account on Nic Beukes's spreadsheet (plus the 2017 workshop funding) 22,823,196

1 These two transfers include the funds awarded to Heubeck from DFG (He2418/25-1). The percentage reflects only the 900,000 USD ICDP contribution

2 Left empty because these funds are already accounted for by the ICDP contribution. Percentage is calculated based on the 150000 € awarded to Heubeck and lumped with the ICDP contribution; not fully transferred to CIMERA

3 A large part of the remainder was used for generating a community XRF data set

In-kind contributions aided significantly to keep costs down. For example, UJ provided vehicles, the rock saw, and a plethora of minor equipment. Mpumalanga Provincial Government provided free use of the BIAS Hall, described below.

2. Geologic Setting

2.1. The Barberton Greenstone Belt

The Barberton Greenstone Belt (BGB, Viljoen and Viljoen, 1969a, b, c; Anhaeusser, 1984; de Wit et al., 1992; Lowe et al., 1999; Lowe and Byerly, 2007; Anhaeusser, 2014) (Fig. 2) of South Africa and Eswatini represents one of the two best preserved records of the early Earth's surface environments (the other being the greenstone belts of Western Australia's East Pilbara Terrane). Its strata, ca. 3.57 to ca. 3.21 Ga in age, offer excellent conditions to reconstruct Paleoarchean (>3.2 Ga) tectonic processes and surface environments.

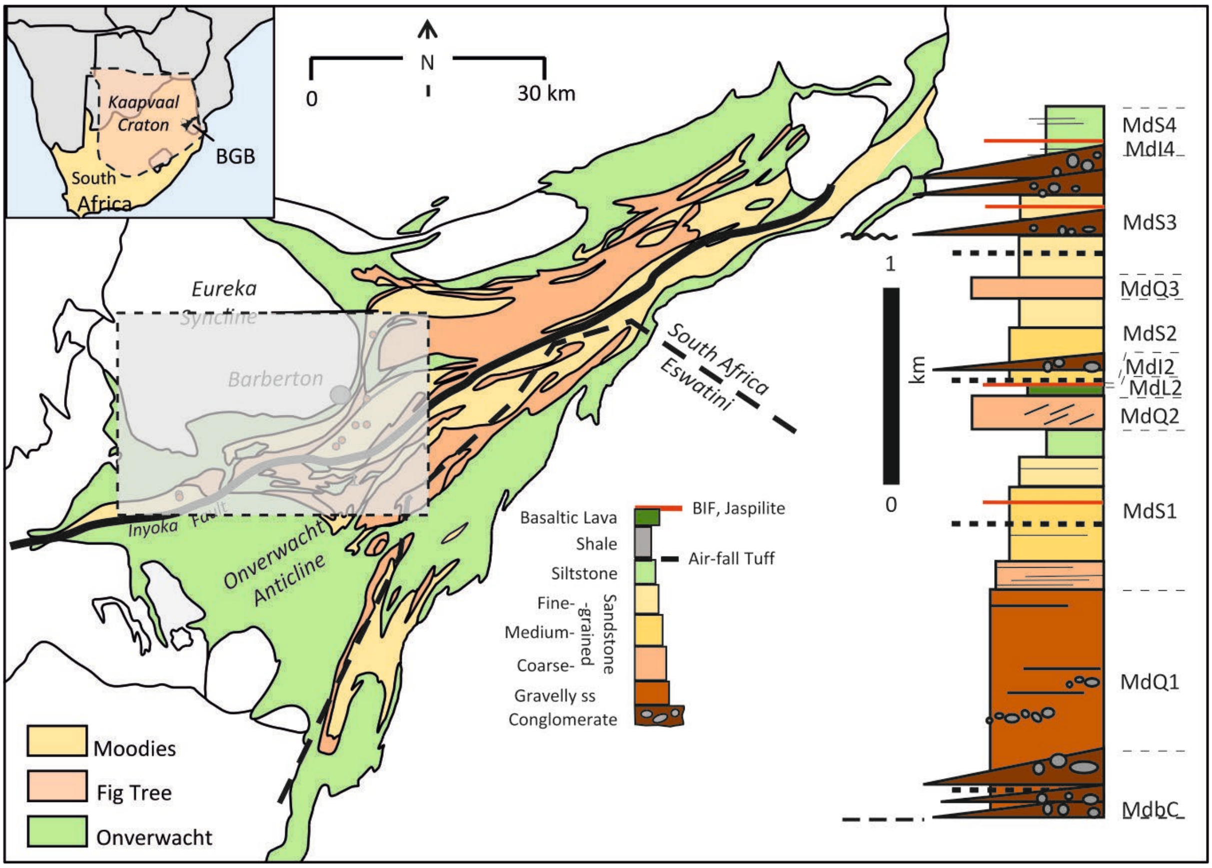


Figure 2: Generalized geologic map of the Barberton Greenstone Belt (BGB). Inset shows location in southern Africa. Stratigraphic column to the right measures ca. 3.7 km in thickness and represents first-order lithology of the Moodies Group strata north of the Inyoka Fault. Area shown in Fig. 3 is outlined by grey dashed rectangle.

Because the BGB exposes stratigraphically coherent, mappable strata in good to excellent outcrops, it permits an excellent understanding of local and regional stratigraphy. This, in turn, allows insights into Archean surface dynamics, e.g., weathering and erosion, tides, atmospheric composition and climate, the record of meteorite impacts, the early biosphere, and its tectonic drivers.

2.2. Composition, Stratigraphy, Structure, Metamorphism of the Moodies Group

The Moodies Group (ca. 3,223±1 to 3,219±9 Ma; Anhaeusser, 1976, 1984, 2014; Eriksson, 1979; Eriksson et al., 2006; Heubeck et al., 2013; Heubeck, 2019; Heubeck et al., 2022b, and many others) is the uppermost major stratigraphic unit of the Barberton Greenstone Belt. It crops out over ca. 110 km length and 40 km width in the Barberton-Makhonjwa Mountain range which reaches up to 1700 m relief. Strata reach up to ~3.7 km in thickness and are dominated by quartzose sandstones, but locally also include thick sequences of siltstones and conglomerates. Shales, banded-iron formation (BIF), and volcanic units are uncommon. Strata were probably deposited within only ~1 to 14 Ma and thus constitute a very-high-resolution, worldwide unique record of Paleoarchean surface processes, perhaps approximately comparable in overall temporal resolution to many Holocene geologic records.

The metamorphic grade is typically lower-greenschist-facies (ca. 320 to 380°C from Raman spectroscopy of organic material) but widespread early-diagenetic silicification preserved micro- and macrotextures in many locations virtually without strain. All strata of the BGB, including those of the underlying Fig Tree and Onverwacht Groups, are tightly folded and cut by major faults. Most Moodies strata are preserved in subvertically dipping or overturned limbs of regional-scale (up to 15 km long, up to 5 km wide) synclines (Fig. 2; Heubeck and Lowe, 1994b; Lowe et al., 2012; Schmitz and Heubeck, 2021). Regional geologic mapping at 1:25,000-scale has covered the central BGB (e.g., Lowe et al. 2012); numerous unpublished detailed geologic maps cover areas of special interest. A detailed Moodies stratigraphy exists only north of the greenstone-belt-axial Inyoka Fault because strata south of that fault mostly experienced a higher degree of hydrothermal alteration (Reimann et al., 2021). All BASE drill sites are located north of the Inyoka Fault.

3. Scientific Objectives and Expected Scientific Results

Most outcrops in the BGB, despite appearing fresh, have been affected by oxidative weathering, the effects of surface- or near-surface biologic activity (e.g., by endolithic bacteria), and/or by near-surface oxic (groundwater) alteration. Even seemingly fresh sample locations, usually limited to steep cliffs and isolated exposures along streambeds, have been subjected to oxidative alteration. Previous drilling showed that weathering extends up to ~20 m depth. Analyzing short (and usually stratigraphically poorly located) underground drill core provided by the mining industry has occasionally been successful (Hessler et al., 2004; Hessler and Lowe, 2006; Javaux et al., 2010; Nwaila et al., 2019) but advanced and high-resolution geochemical research on mine material is commonly compromised by poor geographic and stratigraphic constraints and carries the risk of local hydrothermal alteration or contamination by drilling fluids (Toulkeridis et al., 2015).

Table 4: Drillsite Locations

Name	Location	Setting		Coordinates lat	Coordinates long	along-drillhole length* (m)	direction drilled (deg)	approx. true strat. thickness of Md section (m)	activity visible in Google Earth image of
BASE-1A	Eureka Syncline	Elephant's Kloof		25°44'2.63"S	31° 5'50.65"E	496.85	295	350	ops ongoing July 4, 2022
BASE-2A	Dycedale Syncline	"Tidal Sandstones"		25°47'37.78"	31° 5'1.50"E	367.8	313	290	ops ongoing Feb. 11, 2022
BASE-3A	Saddleback Syncline	Microbial mats		25°49'48.39"	31° 5'26.88"E	280.2	319	218	vacated site July 4, 2022
BASE-4A	Saddleback Syncline	Lomati Delta Complex	distal	25°49'52.60"	31° 4'41.69"E	340.1	322	230	vacated site July 4, 2022
BASE-4B	Saddleback Syncline	Lomati Delta Complex	medial	25°51'11.70"	31° 2'54.70"E	355.5	336	300	vacated site Aug. 9, 2022
BASE-4C	Saddleback Syncline	Lomati Delta Complex	proximal	25°51'39.40"	31° 1.999'E	351.49	336	295	vacated site Aug. 9, 2022
BASE-5A	Stolzburg Syncline	stratigraphic top section		25°54'13.97"	30°50'44.83"E	451.3	27	360	ops ongoing May 31, 2022
BASE-5B	Stolzburg Syncline	stratigraphic base section		25°54'2.80"S	30°50'49.06"E	489.9	13	400	ops ongoing June 11, 2022
						3133		2443	

Tunnel Sections

Lomati	Ben Lomond	entrance	25°48'40.23"	31° 5'58.36"E
Water	(formerly Princeton)	exit	25°48'6.32"S	31° 4'26.43"E
Agnes	tunnel	adit entrance	25°50'3.60"S	30°58'56.70"E
mine	22-level adit	adit entrance	25°49'28.39"	31° 0'7.62"E

Analytical work in Moodies strata in the past 20 years, based on detailed field studies, has identified numerous geologic features related to Archean bio-, geo-, atmo- and hydrosphere processes. These include extensive microbial mats in tidal and fluvial facies, concretions and biogenic reaction products in paleosols, weathering rinds, putative eolian strata, prodeltaic banded-iron formations, exquisitely preserved microfossils, and detailed reconstructions of shoreline and deltaic processes (Heubeck and Lowe 1994a, b; Hessler and Lowe, 2006; Noffke et al., 2006; Javaux et al., 2010; Simpson et al., 2012; Heubeck et al., 2013, 2016, 2022b; Janse van Rensburg et al., 2021; Homann et al., 2015, 2016, 2018; Nabhan et al., 2016a, b; Nakajima et al., 2016; Stutenbecker et al., 2019; Eulenfeld and Heubeck, 2023; Heubeck et al., 2023; see Heubeck, 2019, for a review). Because of the straightforward lithostratigraphic correlation possible north of the Inyoka Fault between terrestrial, transitional and marine Moodies strata, physical, chemical and biologic processes can be traced well beyond the marine record that usually buffers or obscures atmospheric processes.

Drill site selection was based on previous detailed geological mapping by Heubeck and his students. Existing regional geophysical data of the BGB (gravity and magnetics; Burley et al., 1970; Darracott, 1975; De Beer et al., 1988; de Beer and Stettler, 2009; Kuetter et al., 2016) are handicapped by low resolution because the area has a mountainous topography, subvertically dipping strata, strongly varying unit thicknesses and lithologies, and stratigraphically cross-cutting diagenetic alteration fronts. Aerial and ground magnetic surveys had been scheduled for the five drill sites of the BARB ICDP project conducted in 2011 (Arndt et al., 2009) but were never implemented because geological characterization proved sufficient. Geophysical data will nevertheless be crucial for future strategic projects intending to constrain the large-scale (e.g., shallow or deep; symmetric or asymmetric) deep structure of the BGB and to delineate major structural breaks at depth.

The aims of the project were to study Archean surface environments which were crucial to form the foundation of subsequent evolutionary, sedimentary, and tectonic processes. Major targets of investigations were

(1) conformable terrestrial-marine transitions for environmental proxies;
(2) diagnostic lithologies (such as various paleosols, nearshore BIFs, evaporites, basaltic lavas) for their environmental significance;
(3) the compositional, facies and morphological variability of thick and laterally extensive microbial mats; and
(4) sedimentary and mineralogical responses to surface variables, such as tides, climate, potential meteorite impacts, and radiation, in particular in deep-water strata.

Principal questions included:

(1) What was the ecology, 3-D morphology, and metabolism(s) of abundant (oxygenic photosynthetic?) microbial mats preserved in minimally compacted tidal-facies sandstones? Are these properties recorded in their C-isotope microstratigraphy? What were the preservation pathways, origins of early diagenetic chert, and the degrees of thermal overprint? Can we constrain net O2 production rates and the early N cycle?

(2) What is the (cyclo-)stratigraphic and microfossil record of fine-grained marine and prodelta sediments? What is the origin of its clay minerals? How do coastal BIFs and jaspilites relate to

nearby tidal microbial mats? What does the magnetostratigraphic record imply about the strength of the Paleoarchean magnetic field?

(3) What global surface conditions can be inferred? What was the redox state (sulfate, redox-sensitive metal isotopes), temperature and composition of ocean water, of early diagenetic fluids, and of the atmosphere?

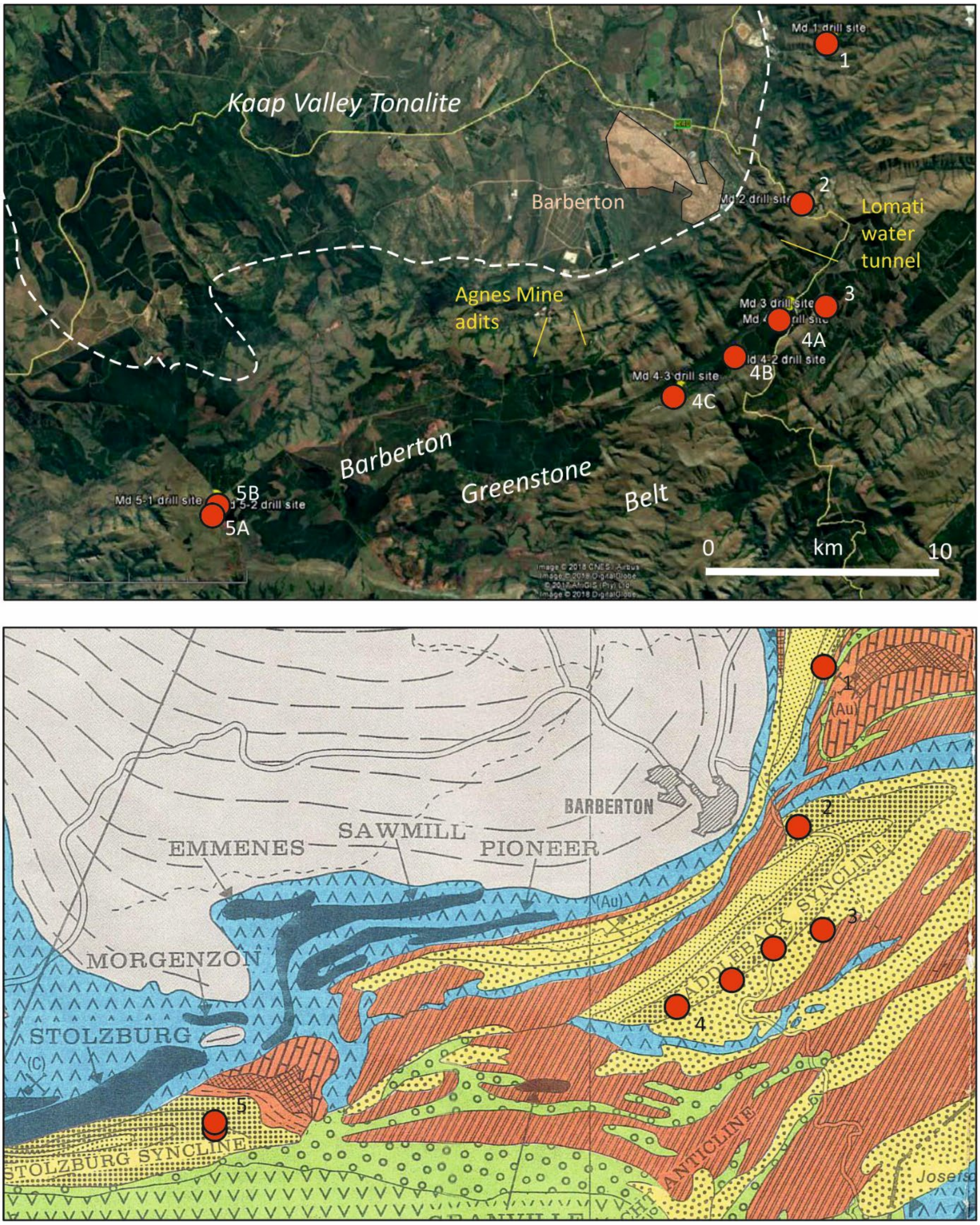


Figure 3: Topographic (Google Earth) and geologic map (Anhaeusser et al., 1981) of the north-central Barberton Greenstone Belt, showing site locations. All sites except Site 5 lie within about 12 km from Barberton. Sites 1 and 2 are next to paved roads: Site 1 within a mine property, Site 2 near a public road. Site 3 and Sites 4A, -B, and -C are on forestry plantation property in low-growth or freshly planted pine and eucalyptus forest. Sites 5A and B are on open grassland in a more remote location, ca. 25 km on forest roads from Barberton.

(4) What can we infer about the role and significance of terrestrial weathering from proxies of physical and geochemical weathering, the composition of variable paleosols, the architecture of aeolian strata and the traces of evaporites and microbial metabolism(s) in terrestrial sediment?

4. Strategy

4.1. Site Selection

An ICDP-funded field workshop October 5 - 10, 2017 outside Barberton was attended by 48 scientists from eleven countries and ten local stakeholders. It brought together a diverse group of sedimentary geologists, stratigraphers, (bio-)geochemists, volcanologists, geochronologists, mineralogists, paleobiologists and paleomagneticists. The mix of experienced scientists and those new to the topic ensured familiarity with geology, operational aspects and rock quality but also the contribution of new expertise and perspectives. Participants walked candidate stratigraphic sections, presented by Christoph Heubeck, formed interest groups (Early life, Paleoenvironment, Metamorphism/magmatism/tectonics, Management), and prioritized the proposed borehole sections. Sites had to (1) provide information that could not be obtained from surface outcrops (contacts, fresh material); (2) address specific scientific questions related to surface conditions of the Archaean Earth; (3) be chosen on the base of significant prior field studies and laboratory work; and (4) allow technically feasible drilling at economically reasonable costs.

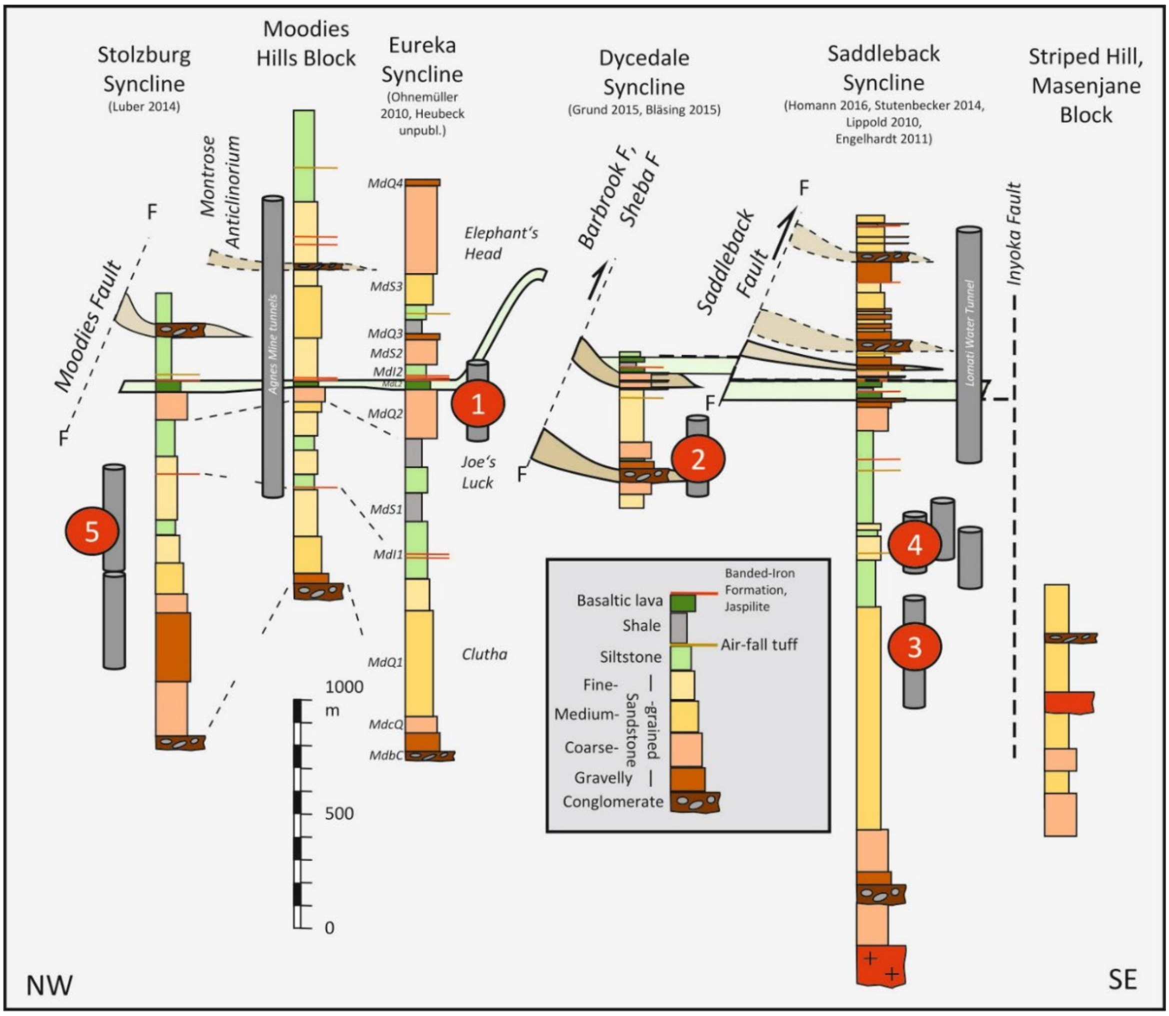


Figure 4: Schematic stratigraphic columns of the Moodies Group, showing architecture of the Moodies Group and correlation of sections (modified after Heubeck et al., 2016). Note position of the Lomati water tunnel in the Saddleback Syncline.

The full ICDP proposal included detailed site characterization which spelled out borehole-specific scientific issues, specific targets and logistical aspects, along with geologic strip maps and predicted geologic profiles along the wellpaths. All boreholes were oriented perpendicular to strike of bedding, drilled at an inclination of 45° from the horizontal and against the (70-90°) dip of bedding in order to maximize stratigraphic thickness in core. Thus, drilling in overturned sections was stratigraphically base-up, progressing from older into younger strata. Because the central objective of the drilling program was to obtain continuous and unweathered core (rather than the identification of facies from diagnostic sedimentary structures, better done on outcrop strata), drilling the bulk of the sections was done at a comparatively thin core diameter (PQ3 = 83mm diameter core, resulting in a 122.3 mm diameter hole).

The five stratigraphic sections selected for drilling are all located within a ca. 30 by 20 km area close to Barberton (Fig. 3; Tables 4, 5). Sites emphasized facies transitions in order to track key sedimentary and geochemical proxies recording environmental and geochemical processes. Sites were specifically chosen to minimize structural complexity and to avoid known zones of hydrothermal alteration. Borehole stratigraphy is correlatable (Fig. 4).

5. Technical Operations

5.1. Permitting and Stakeholder Buy-in

Drilling was originally planned to begin in Winter 2020 to take advantage of the climate but obtaining landowner approval for drilling proved to be more time-consuming than anticipated for Sites 1, 2, and 5 whereas drilling on property of forestry company SAPPI was granted quickly. In addition, the transfer of ICDP funds to South Africa proved to be more complex than anticipated because the granting contract needed approval from legal departments (GFZ, Jena University, UJ) and was signed by UJ on May 25, 2021. The MTPA permit was delayed due to the need to have the non-commercial nature of the project confirmed. All permits except from the South African Heritage Resources Agency, SAHRA (which was concerned that some drill sites were too close to sites of geologic interest) had been completed by July 2021; SAHRA's permit was issued October 11, 2021.

Table 5: Borehole Orientations and Depths

Borehole Number	Final borehole position from the origin (m)		Direction from true North (degrees)	Distance from the origin (m)	Borehole tilt from the horizontal (beginning / end) (degrees)
	N	W			
1A	165.03	346.79	295	384.06	44.7 / 57.1
2A	180.50	190.90	313	262.72	44.8 / 49.2
3A	151.74	132.87	319	201.54	44.7 / 49.9
4A	188.49	149.00	322	240.27	45.8 / 54.1
4B	245.49	108.76	336	268.50	45.4 / 53.0
4C	236.84	107.75	336	260.20	44.4 / 52.7
5A	308.16	155.84	27	345.32	45.7 / 58.7
5B	366.29	87.06	13	376.49	45.0 / 56.0

Through Nic Beukes's efforts at CIMERA in Johannesburg, a drilling tender ("Scope of Drilling Services Required") was published in June 2021, bids received in July, and a selection made by a committee in August 2021. Between April and October 2021, we also applied to the Mpumalanga Province Department of Arts, Sports, and Culture to secure part of the BIAS

(Barberton Iron and Steel) Hall in Barberton to process the core. Nic Beukes sent out a detailed progress report to all involved parties on September 23, 2021.

Figure 5: Onsite stakeholders meeting in April 2021, attended by landowners, government representatives, drillers and environmentalists.

Christoph Heubeck started contacting and briefing local stakeholders (World Heritage Site administration, mining companies, local and regional government, local associations) in 2015 and 2016, so that they were aware first-hand and early about the scientific and non-commercial objectives of the proposed drilling program. Stakeholders were invited to and attended the Barberton workshop in 2017. While funding was organized 2018 through 2021, the coordinator obtained formal letters of approval from property holders and letters of support from professional societies and government agencies.

Astrid Christianson at Barberton Community Tourism led a “grassroots” movement in Barberton by keeping municipality and district officials informed. Christoph Heubeck held (usually while conducting yearly field work) public presentations to the Barberton Mountain Land branch of the Geological Society of South Africa, chaired by Chris Rippon.

Nic Beukes, being an Afrikaans-speaking South African and former CIMERA chair, obtained documents certifying the non-commercial, tax-free status of the project from federal government, set up the accounting infrastructure at the CIMERA office at the Dept. of Geology, University of Johannesburg, and lobbied in Pretoria to have South Africa rejoin ICDP.

On April 7 and 8, 2021, approximately half a year prior to scheduled start-up, Nic Beukes and Christoph Heubeck briefed all stakeholders on the objectives and structure of the drilling program, followed by an inspection of all eight proposed drill sites (Fig. 5, Table 4). This also served to clarify practical questions of access, security, clearing of trees, fencing, water supply, location of the field office, crisis protocols etc.

5.2. Site Inspections, Role of the Ecological Control Officer

Figure 6: Location of Drill Sites (numbered photographs). Sites 3, 4A, 4B, and 4C are located within commercial plantations, Sites 5A and 5B on open grassland, Site 1 in the hairpin turn of a mining road. Site 2 next to a parking lot of the paved R40 road.

The retired ecologist, park planner, and Barberton resident Tony Ferrar was contracted as an Ecological Control Officer (ECO) and conducted baseline surveys of all sites. Tony Ferrar had accompanied the paving of the R40 across the Barberton-Makhonjwa Mountains in the same role about a decade earlier and was intimately familiar with the region and the stakeholders.

Site selection criteria included unproblematic access and infrastructure (Table 4; Figs. 5, 6): Site 1 was located in an active mine with more than a hundred years of continuous operations involving heavy moving equipment; Site 2 was in a sandy flood retention depression immediately next to a parking lot adjacent to the paved R40 road; Sites 3, 4A, 4B, and 4C were on or next to forest roads in mature or recently harvested commercial pine plantations. Only sites 5A and 5B were located in grassland; however, both of these sites were near an abandoned homestead (foundation walls only) overgrown with wattle trees, an invasive tree species. The ECO conducted a baseline environmental survey for each site, inspected sites using a previously agreed-upon checklist, inducted drilling staff in do's and don'ts, visited the sites during drilling operations to conduct audits, conducted final site visits to clear any remaining issues after notification by the contractor that the rehabilitation program had been completed, and wrote final reports on all sites except that located on Fairview Mine property (Site 1, located in a hairpin of a mountain dirt road), and wrote a final protocol. Finally, each site was handed back following a final joint inspection by a drilling contractor's representative, the ECO and the stakeholder / landowner's representative.

5.3. Preparation of Core Processing, Local Infrastructure

Nic Beukes, Christoph Heubeck and Astrid Christianson started to actively look for a site to pro-cess the core in or near Barberton during the site inspection workshop in March 2021. A large former industrial hall in downtown Barberton, the so-called BIAS (Barberton Iron And Steel) building, caught our attention (Fig. 7). BIAS Hall is owned by the Department of Arts, Sports and Culture of Mpumalanga Province; its northern and southern ends house the Barberton Museum and an array of small shops, respectively. The large central section was somewhat underused and served as museum overflow storage and parking area. Through the local Friends of the Barberton Museum Association headed by Chris Rippon and Astrid Christianson, and with the aid of the museum's head, Janie Grobler, BASE, represented by CIMERA, was granted use (free of charge) of about a third of the central hall for core processing, initially for a duration of nine months. The hall turned out to be an excellent location for core processing and outreach due to its large size, flat concrete floor, large windows, high ceilings with a grid of accessible steel rafters, security, in-house access to the adjacent museum infrastructure, oversize steel sliding doors, ample parking, and location in the central business district with numerous facilities within short walking distance.

Figure 7: BIAS Hall where core was processed and public tours were held. A, B: Outside views. C: Inside view prior to occupation by BASE. D: Northern segment of BIAS Hall, now separated from the remainder of the hall by shading cloth. Display material in the foreground; core processing took place in the rear of the hall.

Christoph Heubeck arrived in late September, about a month prior to the start of drilling, to set up accommodation and the processing center and to speak personally with landowners. Water, electricity, internet and site security were quickly installed in September and October 2021 at comparatively low cost; contracts and billing ran through CIMERA. Nic Beukes arranged for a core rock saw and associated equipment (tables, a steel cabinet, field chairs etc.) to be delivered from UJ stores in September 2021. We separated our space from the remaining hall using semi-transparent shading, hung maps and posters, and set up a collection of sawed and polished representative rocks from the Barberton Greenstone Belt in the space facing the entrance (Fig. 7). Astrid Christianson and her staff from Barberton Community Tourism identified two comfortable flats in Barberton for the accommodation of the onsite geoscience staff of six plus occasional visitors and equipped these apartments with appliances, furniture, beds, and household items.

5.4. Initial Mobilization

The drilling contractor had notified us that drilling would start early October 2021, but rig preparation was delayed because the rig returned late from a previous assignment. Rig MDX315 arrived in Barberton November 15, 2021 (coinciding with the beginning of the rainy season) and the first borehole spudded at Site 4A two days later.

Figure 8: Drilling operations, showing offloading of the rig at drill sites, „trammelling" between sites, and transport between sites by flatbed truck on forest dirt roads.

The drilling contractor initially assigned two track-mounted drill rigs (MDX 315 from Nov. 15, 2021; MDX 318 from Nov. 26, 2021) to the task. They were delivered by flatbed truck to a spacious offloading site as close as possible to the drill site, often a timber depot, and then drove to the drill site along forest roads, up to a few km distance (Fig. 8). That drill site had been set up a few days before (clearing and stump removal, grading, flagging, limits, safe area, parking, toilets, staffing board identifying responsibilities and contact information; tent). Upon arrival of the rig at the site, the geologists marked the precise orientation of the drilling direction.

A compact, trailer-mounted Solid Removal Unit (SRU) which was towed to the site processed the drilling mud (Fig. 9B). The SRU worked like a centrifuge and produced sludge-like cuttings which could be bagged and loaded as solids. They were never studied and are considered of no use to the project. The forestry company SAPPI had unspecified use for this material. The drilling contractor supplied stackable black plastic core trays (with lids) in various sizes.

5.5. Water, Accommodation, Site Preparation

The drilling contractor assumed all responsibilities related to day-to-day operations. The contractor supplied a water truck capable of carrying five tons of water. Each borehole had its assigned water extraction point which had been agreed upon with SAPPI; water was extracted from the tank or a drainage using a portable diesel-powered pump and trucked to the drill site, typically a 15- to 30-minute drive away. Water consumption was far higher than anticipated due to numerous encountered fractures, making more water runs necessary than anticipated, so that rigs sat idle occasionally, "waiting on water". The roads, softened by the unusually long and intense rainy season 2021/2022, were occasionally too soft and slippery to safely drive, causing additional delays.

Figure 9: Drilling setup at Site 3. A. Overview; from left: bagged sludge, trailer-mounted SRU, drill rig MDX317, tressels / workbench for drill pipes, tented work area, and storage trailer. The entire site is fenced; B: Solid Removal Unit (SRU); C: „Top Drive"; D: Track-mounted drill rig; E: Site 2 overview; F: Rotary crown with piece of core.

The onsite lead drilling site manager, together with the rig supervisors, actively searched for crew accommodation close to the drill sites. This was generally unproblematic because SAPPI made available brick houses from their forestry compounds. At these sites, the contractor also parked one or two short containers to store tools, trays, electrical equipment, and occasionally cores (Fig. 10). Having accommodation at the forestry compounds was fortunate not only due to their close proximity to the drill sites but also because drilling crew and forestry staff had similar work schedules and both operated heavy equipment. To work at Site 1, on the property of Fairview Mine, drill crew and all onsite geoscience staff had to undergo and pass an on-site briefing ("induction"), a medical examination, and a criminal background check.

Once a site had been cleared of stumps, flammable vegetation removed and the site levelled, it was delimited with flagging tape; parking, safe area, smoking area, and work areas were marked, the equipment placed and connected. Signs were installed, a sump was dug, and the toilet installed. Fifty-five-gallon drums with secure, clamped lids and oil-absorbent pads were put ready for oil/solvent spill clean-up. All drums and barrels were placed in a tray. The SRU was installed and hooked up to the generator.

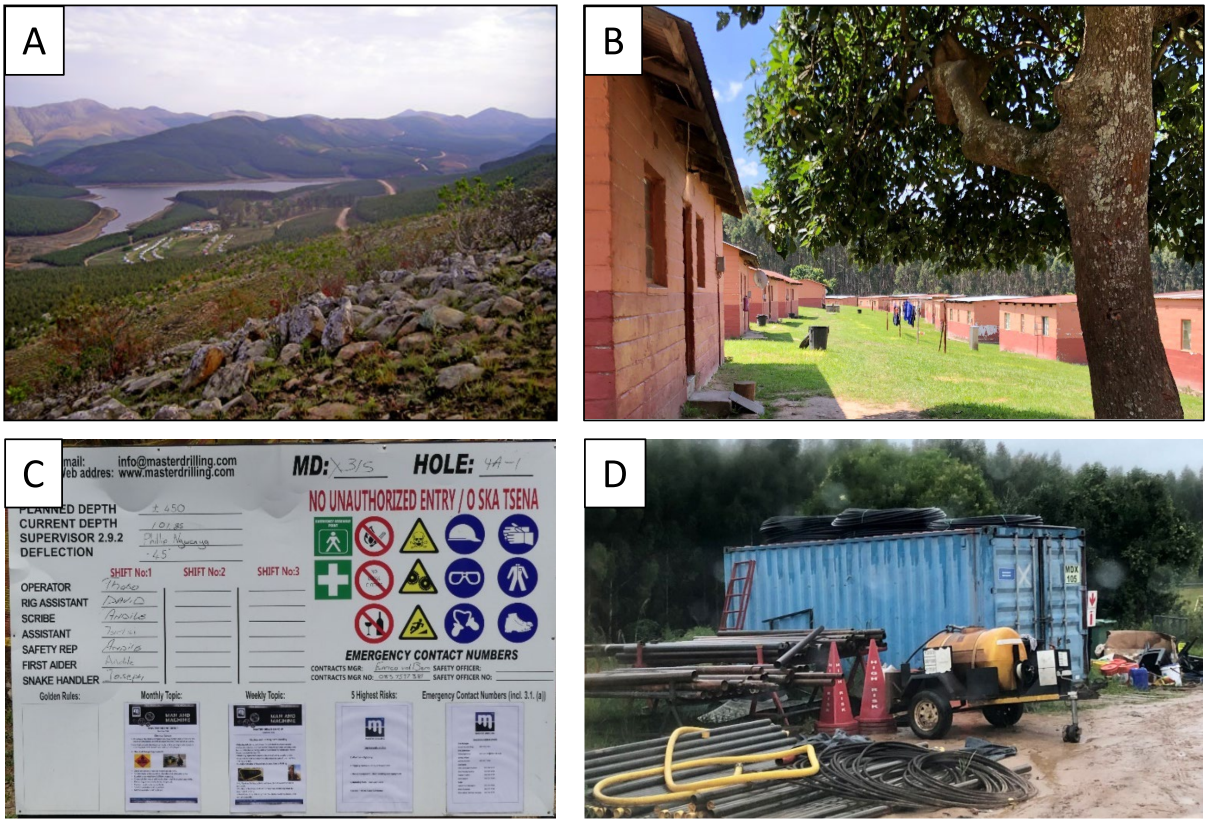


Figure 10: A, B: Highlands Forestry compound; C: Drillsite information board; D: Temporary storage area and container at Highlands Forestry for drilling gear.

Operations, particularly core handling on site, were done exclusively by the drilling crew; visitors stayed outside the fenced perimeter. The very public Site 2, next to the paved R40 and only a few km from Barberton, was fenced with construction-site-quality fence by a local contractor and guarded overnight by SAPPI security (Fig. 9A).

Drillers worked Monday through Friday 7:00 to 15:30 and always started with a safety talk. Every fourth weekend, a long weekend (that is, drilling ending Thursday at noon and starting again Tuesday morning) allowed the mostly Gauteng-based drillers to travel home.

5.6. Drilling

5.6.1. Framework: Rock Quality, Fracturing, Groundwater

The quality of drilled core varied more than anticipated for several reasons: (1) The weathering zone was thicker than predicted, causing the rock to be clayey and friable; (2) the degree of natural fracturing was higher than predicted; (3) deep oxidation along fractures and faults reduced rock strengths even at depth; (4) the drill crews were inexperienced with this type of rock; initially, the optimal coordination between weight-on-bit, rotation rate, and bit type was not perfect; and (5) the first cores, already affected by faults or hairline fractures, were transported on the potholed dirt roads not fully secured, causing some additional breakage. As a result, a substantial number of drill cores arrived broken for processing. This required that some core had to be time-consumingly rearranged, taped, and marked. The rock quality index entered in the database describes this aspect of rock quality.

5.6.2. Drilling Crew

Each rig had a crew of five who shared specific functions (operator, rig assistant, scribe, assistant, safety representative, first aider, snake handler), headed by a site supervisor (Fig. 10).

5.6.3. Coring Plan

Drilling at each site started with PQ3 drill pipe (83 mm core diameter) to allow installation of surface casing for groundwater protection. Once the weathered zone had been drilled through, casing was set, typically between 60 and 100 m depth. Drilling continued from there for some depth on HQ3 (61.1 mm) and switched to NQ3 (47.6 mm) diameter as soon as practical to improve drilling rates. The contractor's drilling operations manager decided the depth at which drill pipe diameter was changed (Table 6).

Table 6: Drilling and Casing Plan

Borehole and rig	Casing down to (m)	PQ3 down to (m)	HQ3 down to (m)	NQ2 / NQ3 down to total depth (m)
BASE 1A (MDX900)	108.44	31.65	108.44	496.85
BASE 2A (MDX901)	138.2	40.9	138.2	367.8
BASE 3A (MDX 317)	less than 11 m	16.65	73.63	280.2
BASE 4A (MDX315)		at least 24.15	101.85	340.1
BASE 4B (MDX315)	66.6	28.50	65.9	355.5
BASE 4C (MDX317)	90.84	37.12	92.99	351.49
BASE 5A (MDX901)	107.79	34.46	106.76	451.30
BASE 5B (MDX901)	96.00	17.90	94.71	489.9

The variable core diameters PQ3, HQ3, and NQ3 corresponded to core trays with four, five, and six grooves, respectively, each 1 m long. While trays with four PQ-diameter cores had to be carried by two persons, the large majority of core trays handled during processing could be readily handled by a single person because they contained only six half NQ-diameter cores. This significantly eased the workflow.

BASE boreholes were drilled using water-based hydrocarbon-free drilling mud and using wireline diamond coring in which the core barrel travels up- and downhole within the drill string on a steel cable connected to a winch. This avoids the laborious and time-consuming need to retrieve the bottom-hole assembly by frequent "round trips", including breaking the drill string, recovering the core, and making up the drill string again. To recover the inner barrel assembly after having drilled for the length of the core barrel (3 m), the drill head containing engine and gearbox was detached from the top of the drill string and slid sideways; then, the recovery tool (a spear-shaped "overshot" adaptor, part of the catching assembly) was lowered down inside the drill string and latched onto the swivel head assembly at the top of the core barrel. This disengaged the latches of the inner barrel assembly from the outer barrel and the drill pipe. A winch then hoisted the barrel and its core within the drill string to the surface. The only time the drill string had to be tripped was when the core bit needed to be replaced and on completion of the borehole. However, the drilling conditions required frequent reaming.

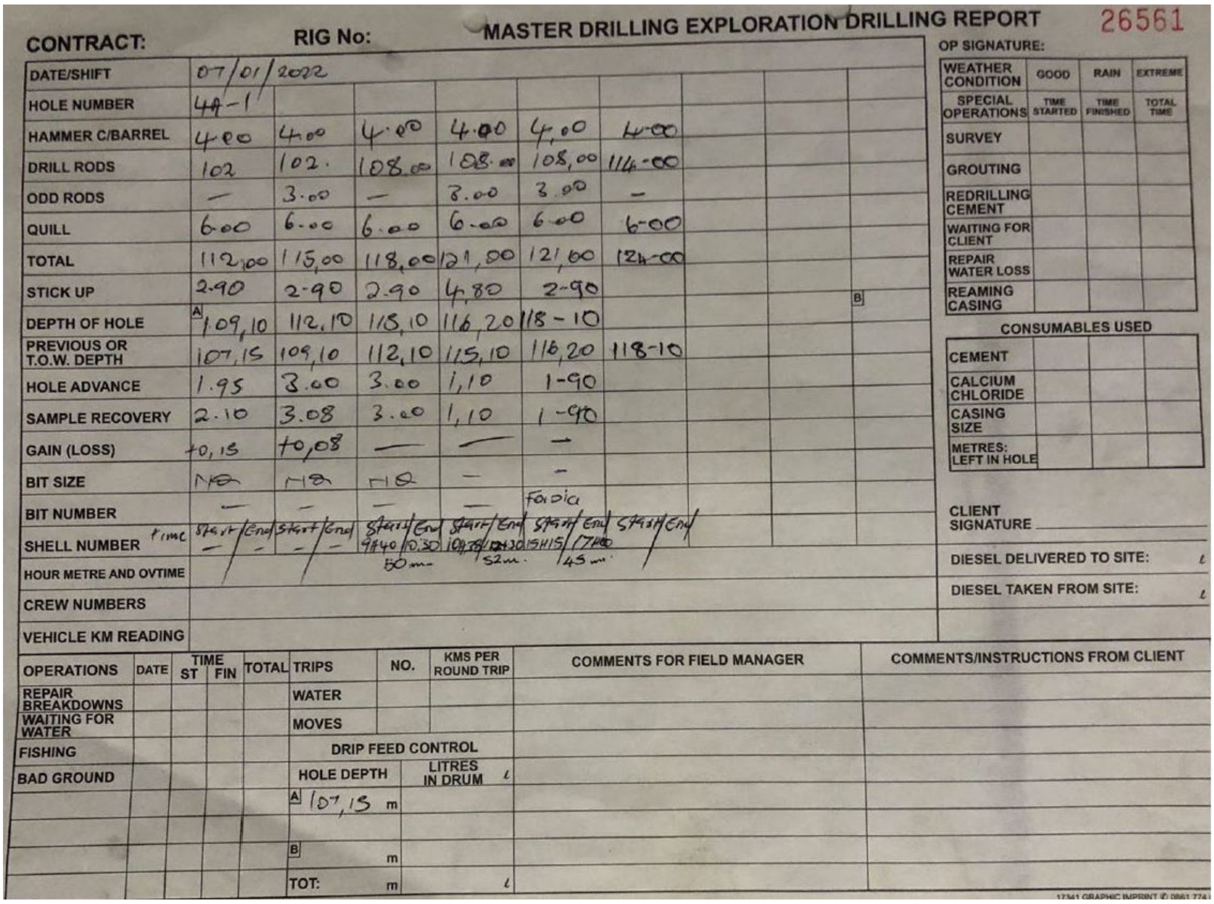
5.6.4. On-site Core Handling

The 3 m-long core barrel was laid on tressels and opened at its lower end. Its upper end was hooked to a cable and slowly raised using the winch, causing the core to slide out of the core barrel under its own weight (Fig. 11). The core, usually in several pieces and guided by two helpers, slid into a 3 m-long V-shaped angle iron on a grooved tressel. Once the barrel had been emptied, the angle iron with the core was transferred to the core trays where a driller washed the pieces and used a hammer to break the core so that its pieces would fill one of the slots of a (previously labelled) plastic core tray. Operators then marked driller's depths using yellow (rarely green) plastic tags (Fig. 11). The length of the core run was measured and marked in a handwritten Driller's Daily Report (Fig. 12) which was transcribed at the drilling contractor's office. The ends of each 3 m core run were marked in the trays by labelled plastic markers showing driller's depth. Core recovery was calculated on a "rod-by-rod' basis. Accurate depth measurements were recorded by the rig supervisor in the Daily Report sheet by adding the lengths of all rods, couplings, core barrels, shell and crown in the hole and subtracting the portion of the rod string protruding from the hole (Fig. 12). This system worked well.

Figure 11: Core retrieval at Site 3.

Filled core trays were stacked on site during the day and either taken down to the BIAS Hall in Barberton by drillers at the end of shift or the next morning, or picked up by Rod and Ryan Tucker at the drill site or the nearby camp after the end of shift. A drilling rig produced ca. three to six core trays (12 to 36 m of core) per day.

We found out that particularly the friable cores were susceptible to breaking by vibration during transport, and learned that the trays had to be stacked such that they fit neatly into and onto each other, that the topmost tray had to be covered by a lid, that the stack had to be firmly strapped to a particle board base plate, and that the ubiquitous potholes had to be avoided to the degree possible.



CONTRACT: RIG No: MASTER DRILLING EXPLORATION DRILLING REPORT 26561

DATE/SHIFT	07/01/2022					
HOLE NUMBER	4A-1					
HAMMER C/BARREL	4.00	4.00	4.00	4.00	4,00	4-00
DRILL RODS	102	102.	108.00	108.00	108,00	114-00
ODD RODS	–	3.00	–	3.00	3.00	–
QUILL	6.00	6.00	6.00	6.00	6.00	6-00
TOTAL	112,00	115,00	118,00	121,00	121,00	124-00
STICK UP	2.90	2-90	2.90	4,80	2-90	
DEPTH OF HOLE	A 109,10	112,10	115,10	116,20	118-10	
PREVIOUS OR T.O.W. DEPTH	107,15	109,10	112,10	115,10	116,20	118-10
HOLE ADVANCE	1.95	3.00	3.00	1,10	1-90	
SAMPLE RECOVERY	2.10	3.08	3.00	1,10	1-90	
GAIN (LOSS)	+0,15	+0,08	–	–	–	
BIT SIZE	HQ	HQ	HQ	–	–	
BIT NUMBER	–	–	–	–	Fabia	
SHELL NUMBER time	Start/End –/–	Start/End –/–	Start/End 9H40/10.30 50m	Start/End 10H35/12H30 52m	Start/End 15H15/17H00 45m	Start/End
HOUR METRE AND OVTIME						
CREW NUMBERS						
VEHICLE KM READING						

OP SIGNATURE:

WEATHER CONDITION	GOOD	RAIN	EXTREME
SPECIAL OPERATIONS	TIME STARTED	TIME FINISHED	TOTAL TIME
SURVEY			
GROUTING			
REDRILLING CEMENT			
WAITING FOR CLIENT			
REPAIR WATER LOSS			
REAMING CASING			

CONSUMABLES USED

CEMENT			
CALCIUM CHLORIDE			
CASING SIZE			
METRES: LEFT IN HOLE			

CLIENT SIGNATURE

DIESEL DELIVERED TO SITE: ℓ

DIESEL TAKEN FROM SITE: ℓ

OPERATIONS	DATE	TIME ST	TIME FIN	TOTAL	TRIPS	NO.	KMS PER ROUND TRIP	COMMENTS FOR FIELD MANAGER	COMMENTS/INSTRUCTIONS FROM CLIENT
REPAIR BREAKDOWNS					WATER				
WAITING FOR WATER					MOVES				
FISHING					DRIP FEED CONTROL				
BAD GROUND					HOLE DEPTH	LITRES IN DRUM ℓ			
					A 107,15 m				
					B m				
					TOT: m	ℓ			

17341 GRAPHIC IMPRINT

Figure 12: Driller's „Stick-up" Sheet.

5.6.5. Drilling Schedule and Progress

The first rig arrived in Barberton on November 15, 2021 and the first borehole spudded at Site 4A two days later. Initial drilling progress of ca. 5 to 8 m per day was far slower than the contractor had predicted, so that the contractor assigned a third, new drill rig (MDX 317) on February 3, 2022, to the project. These measures and continuous optimization in the drilling parameters significantly improved core recovery and drilled meters per day. However, logistical problems with moving the rigs between locations due to the lack of available flatbed trucks, soft and washed-out roads, and lack of adequate water supply, together with the very rainy summer of early 2022, caused additional delays. Drilling ended on July 26, 2022, after a total of 3135 m drilled and 2903 m of core recovered. All scientific objectives of the project had been reached; all boreholes had reached their planned total depths.

Moving rigs between sites (Fig. 8) from end of drilling to spudding took approximately ten days, including weekends. This included pulling the drilling assembly, flushing the hole to strip the borehole wall from drilling residue, filling the hole with clean water, geophysical logging (one to two days), pulling the surface casing, driving ("trammeling") the rig on its own tracks to a location where a flatbed truck could load the rig; transferring it to an offloading point, trammeling to the new site, setting up there and properly orienting the rig.

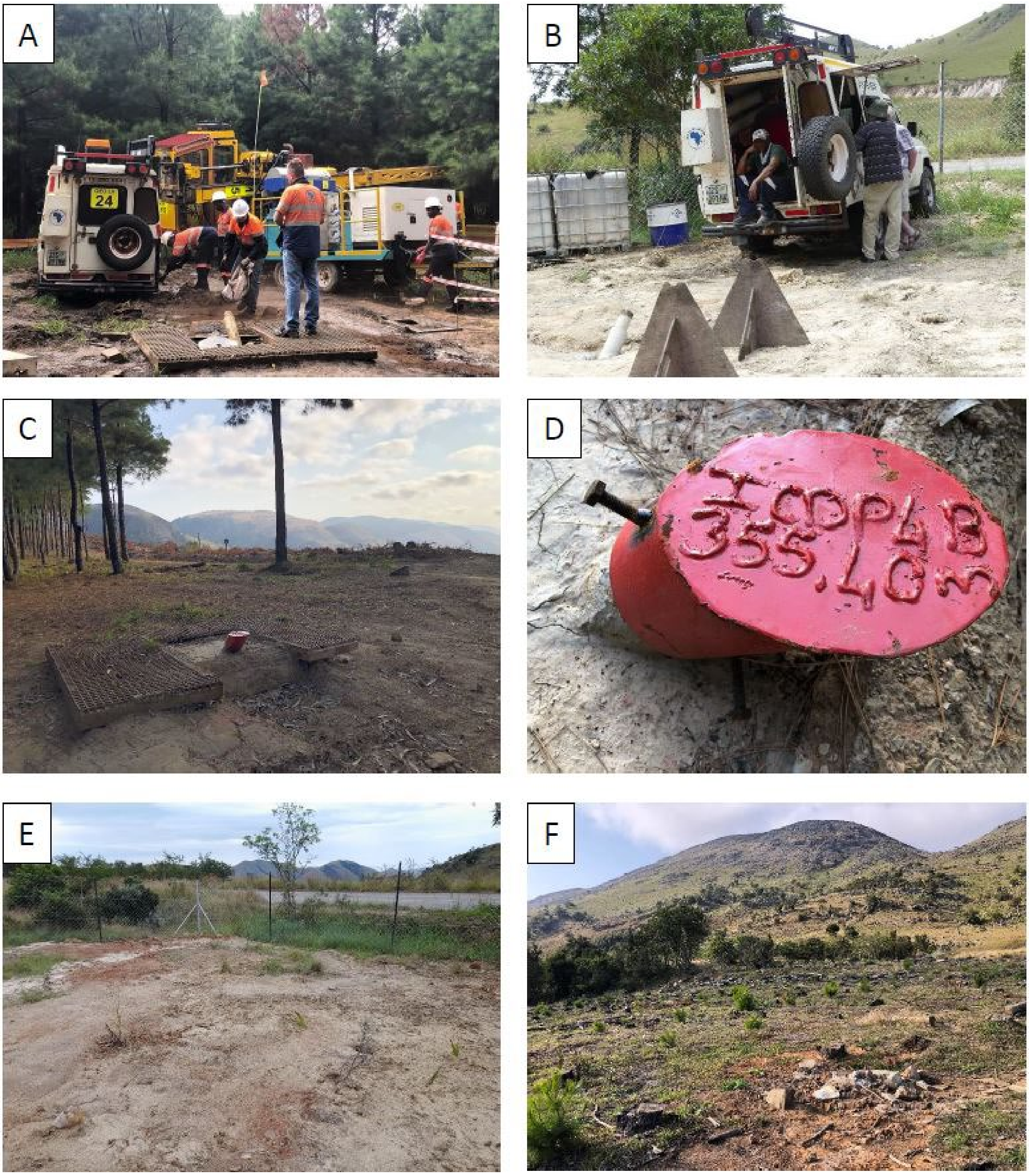


Figure 13: Post-drilling site operations. A, B: Logging; C, D: Site 4 B with cap welded on; steel grating is yet to be removed; E: Site 2 with equipment removed; site still needs to be raked and fence removed; F: Site 4C rehabilitated.

5.6.6. Logging and Well Abandonment Operations

After reaching total depth, the rig crew pulled the final core barrel, pulled the drill string, and flushed the hole. Logging services were provided by Wireline Africa Inc. A wireline unit logged each cleaned and fluid-filled borehole, usually the day after the rig had pulled the drill string (Fig. 13A, B). Logging usually took two days. Logging data are described in Section 10.4. Following geophysical logging, surface casing was pulled except for the final few m which were left in the hole. The annulus was sealed (grouted) using a viscous bentonite clay mixed with cement. The borehole was then plugged and covered by a steel cap (Fig. 13C, D) which was welded on in June and July 2022. None of these caps were visible in March 2023 anymore. After departure of the drilling rig and the loading the remaining site equipment, the ground was cleaned and raked (Fig. 13 E, F). Minor spills were taken care of by absorption material. Section 5.2 describes the rehabilitation protocol.

6. Scientific Operations

6.1. Core Handling Workflow

In the BIAS Hall, we had set up a core processing workflow by stations, arranged clockwise. Each station had at least one principal attendant, a working area and a waiting area (Fig. 14).

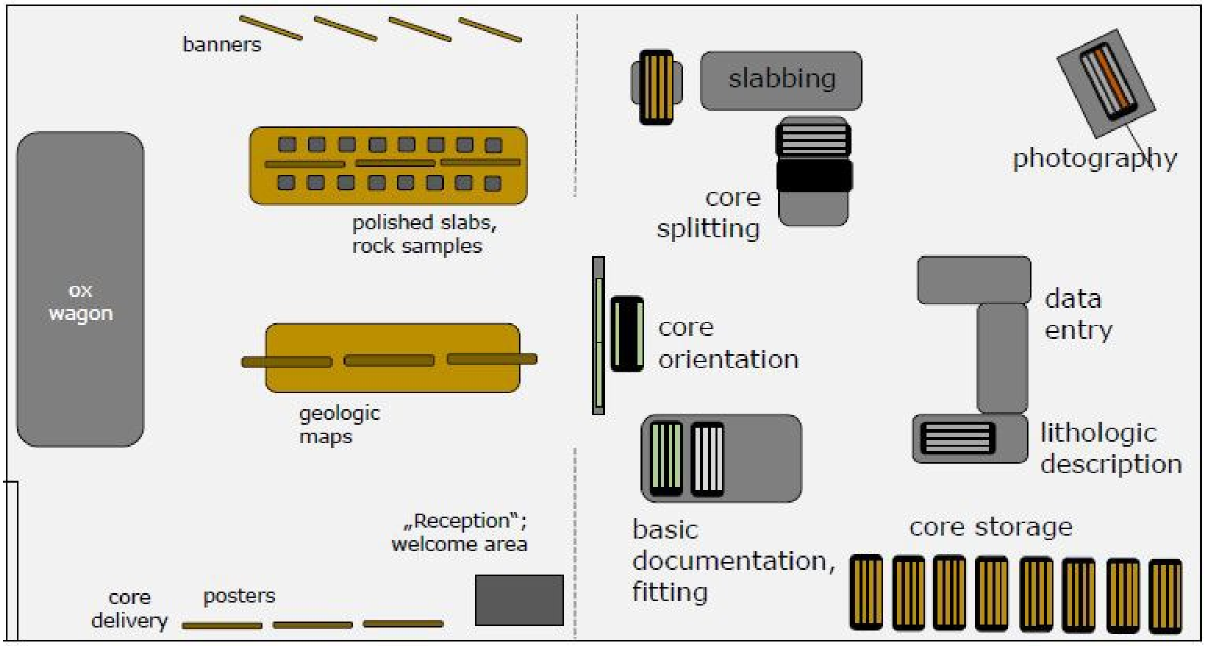


Figure 14: Work flow of core processing in BIAS Hall. „Reception" desk left, staffed by Phumelele Mashele. Exhibition area and the museum's ox wagon are visible in the background. Chris Rippon, with back to camera, working at core orientation, Rod Tucker at basic documentation and fitting. Derick Dludlu and Musa Mavimbela (far right) tend to the yellow core saw; Dora Paprika in front of them is shown splitting and labelling the core. The photography stand is out of view to the right. Ryan Tucker is busy at data entry; the lithology description table in the center foreground is unoccupied.

To define the workflow among ourselves, we initially used a handout which spelled out all processing steps in detail. The paragraphs below describe these steps (Fig. 15).

6.2. Reception, Repacking, Labelling, mDIS Entry

After offloading from the vehicle, core trays were briefly inspected for completeness and order, and stacked by drill site. Individual cores were then moved to the last (usually partially empty) core tray of the previous day if at least two sections of that tray would otherwise have remained empty ("repacking"). The black plastic core trays were neatly labelled using a white marker (box numbers, core run numbers, "START", arrows).

The lengths of each core section and its number of pieces were entered into mDIS (Fig. 15A). The software mDIS (Mobile Drilling Information System) is an open-source, web-based, platform-independent software application for the management of geological samples and drilling engineering data and is under continued and advanced development by ICDP. mDIS is operated through a browser and consists of hierarchically structured forms (parent-child relationships; e.g., Project, Curation, Contact, Core, Drilling, Geology, etc.) that can be generated repeatedly and filled with data. Noticeably, the system is based not on absolute depth values (which can change during a project lifetime due to adjustments) but on core number – section number of the core in the core tray – number and length of piece of core within a section. Only those pieces are measured and labelled with lengths; the system automatically adds all piece lengths to arrive at dynamic depth values. Several report forms allow to show data in tabular, graphic, or digital formats, and to print QR code labels for sampling.

Immediately after repacking, the full core trays were photographed dry and wet to record presence, core continuity, and rock quality. The existence of these "book-in" photos proved helpful later when core segments disintegrated, were occasionally mishandled, or misplaced during processing.

6.3. Photography

The photography station was located on a trolley next to a lifting frame which had been fabricated from a tripod and a horizontal outlier, the end of which held a smartphone at a fixed location and height (Fig. 15D). The trolley could be easily reoriented; that is, the short side of the tray pointing exactly towards, but just slightly outside, the sunlight coming through the large windows of the BIAS Hall. Core and tray were wiped clean, and a data bar placed at the lower long end.

Tray photos were taken between November 2021 to the end of March 2022 and in the last two weeks of July using an iPhone 8 smartphone (72 dpi, 3956 * 1902 pixel; ca. 2.3 MB); photos taken April through June 2022, with only a few exceptions, used a lower-resolution HUAWEI VOG-L09 smartphone (96 dpi; 3428 * 1613 pixel; ca. 1.7 MB).

6.4. Orientation

After returning from "book-in" photography, core pieces were taken from their tray, placed on a 4-m-long angle iron which had been set on nudged bricks on two tables, and rotated for a common and correct orientation (Fig. 15B). We had initially planned to use the downhole instrument TrueCore by Boart Longyear to obtain sample orientation, but the drilling crew had problems with its operations. We thus oriented core by hand based on the angle at which bedding (inclination known from surface outcrops) intersected the 45°-degree inclined borehole. Chris Rippon oriented all core segments on a horizontal angle iron such that the bedding lowpoint faced downhole. This marking technique worked well; where bedding was poorly visible, estimates were made or proper fits with the end pieces of previous core sections were sought. Where core was badly broken, pieces were taped. Once oriented, the yellow cut line was drawn on top of the horizontal core with a long steel ruler, thus defining left and right halves of the core. Yellow arrow marks (<<<<<) were drawn on the yellow cutline to indicate the direction to the drill rig. Red-and-blue parallel lines were drawn on left and right halves to indicate the same. Full meters were marked on the outside of the core in black. The marked core was returned to its tray and transferred to the core saw waiting area.

Figure 15: Stations of core processing in BIAS Hall. A: Packing; B: Orientation; C: Slabbing and splitting; D: Photography; E and F: Data entry and lithological description.

6.5. Slabbing

The core saw operators took a marked core segment from its tray, shortened it with a hammer if necessary to fit in the 30 cm-long slotted cradle, and placed it such that the yellow cut line faced upward. The tray was automatically and slowly drawn into the (housed) saw blade by a toothed pulley (Fig. 15C). An operator retrieved the slabbed core in its cradle on the other end of the housing. The saw operator returned both the right and left halves, still placed next to each other, into the core tray. We installed various contraptions on the saw to reduce dust, noise, and mist; the saw operators used ear protection and protective masks. The saw operated flawlessly for nine months and rarely required a change of the saw blade, supplied at short notice by a geosupply store. A self-made sump with a pool pump bought from a local hardware store circulated water. Core saw operators also cleaned and maintained the core saw.

6.6. Tray Labelling, Separation of Archive and Working Halves

Once core from a tray had been completely slabbed, it was placed on a large table next to an empty core tray. A helper carefully duplicated all markers from the original core tray to the other tray using a white permanent marker and added a “W” (Working) and an “A” (Archive), respectively, to the core tray number. Usually, the lower half of the split core and any core pieces too broken to be moved remained in the original tray (now labelled "A" = Archive). The upper half of the split core was transferred to the new core tray (labelled "W") which became the working half. At this point, both trays also received handwritten labels on the front and depth information on the side (Fig. 15F). Finally, and prior to photography, the black full-meter markings from the outside were extended to the slabbed core faces.

6.7. Repeat Photography

Both archive and working halves and their trays with the data bar were cleaned and photographed again wet and dry (Fig. 15D). Then, the working half moved to the storage section, the archive half into the lithology waiting area.

6.8. Geological Core Description

For its initial geological description, a core tray was placed on a table, illuminated by two high-powered LED desktop lamps (700 lumen); the core was sprayed wet. A 90° seating arrangement between the describing geologist and the data entry operator turned out to be best to transmit the information while the saw was running noisily (Fig. 15E). Investment in a large computer screen quickly paid off because it greatly reduced scrolling.

Core description used ICDP’s mDIS system and all information was entered in two categories: Lithofacies and Special Features. The lithofacies terminology included lithologic units (e.g., sandstones, interbedded sandstone-shale couplets, conglomerate etc.) combined with specific subsets of sedimentary structures (laminated, cross-bedded, with microbial mats, mud-chip-bearing, granuly etc.). We attempted to transfer these terms between boreholes but found that differences in primary depositional facies, degree of weathering and fracturing, cementation and hydrothermal alteration were large enough to change lithofacies appearances significantly, making new definitions a common necessity. This approach reduced comparability between borehole lithologies but allowed the detailed recording of subtle lithologic and textural changes. If workload and core variability allowed, we identified lithofacies units >2 cm in thickness, distinguished by lithofacies, contact type, grain size, sorting, and a code from the Munsell rock color chart. Typical units, however, were 7 to 12 cm thick; unusually thick units reached up to 40 cm.

The category “Special Features” included non-pervasive primary sedimentary features of a lithofacies such as isolated clasts of various types, sedimentary structures (such as mud cracks, mud clasts, rhythmic bedding, shale coatings, load structures, fluid-escape structures, cross bedding, erosional scours, slump folds, microbial mats, concretions etc.). Post-depositional features in this category recorded slump folds, fractures, faults, veins, and (pyrite) mineralization which were not or insufficiently included in the definition of the lithofacies nomenclature (e.g, lithofacies = cross-bedded medium-grained sandstone; special feature = quartz-veined).

Dora Paprika, our principal data manager, oversaw the database and kept digital order.

6.9. Close-up Photography

Taking advantage of the freshly slabbed and sprayed core, we took ample close-up photographs using a LUMIX SLR with ca. 3000 * 4000-pixel resolution. Each scene also photographed a small handwritten label stating borehole, core, section, piece, arrow pointing into the younging direction, and depth; the stated depth on that label was always the measured depth marked in handwriting on the core and constituted the depth of the label, not of the feature. The text of the label was always oriented such to face stratigraphically upward. These close-up photographs proved to be very useful in subsequent core description. In the evening, Christoph Heubeck adjusted, cropped and rotated the photos.

Figure 16: Labelling, packing and shipping of palletizing core trays in August 2021.

6.10. Archival; Preparation for Shipping

Once cores had completely dried again, trays were stacked about 20 trays high in separate section (working, archive) and checked for completeness of labelling. Towards the end of operations, questions concerning pallet sizes and numbers became relevant because inquiries showed that most pallet sizes which allowed two trays to be placed side by side were too wide to fit in the pallet racks of the BGR Spandau core repository. Appropriate pallets were ordered inexpensively locally. We gradually occupied adjacent parts of the BIAS Hall to arrange pallets. Trays fit snugly into each other such that they immobilized cores, and stacks were secured tightly by steel bands. Only the topmost trays received a lid. A forklift from the hardware store across the street facilitated the loading of the 29 pallets with 503 trays containing the working core on a truck (Fig. 16).

7. Core Shipping and Storage

7.1. Core Shipping and Storage of Archive Core at Donkerhoek

A total of 29 pallets, each with two stacks of about 12 core trays each, were shipped to the CGS's National Core Repository in Donkerhoek in August 2022. This archive is the legislated custodian of all geoscience data in South Africa. It provides an accessible but safe storage for the core, and a resource for future research. A SisuRock Gen2 three-camera hyperspectral scanner at this facility was used to image the complete core in 2023. The RGB camera provides natural color images at high spatial resolution while the spectral cameras provide mineralogical information in the Visible-Near Infrared (VNIR), Short Wave Infrared (SWIR), and Long Wave Infrared (LWIR) electromagnetic spectrum.

7.2. Core Shipping and Storage of Working Core at BGR Berlin-Spandau

Nic Beukes at UJ arranged with Chris Rippon in Barberton for DHL Shipping to transport the working core to the ICDP core repository at the BGR German federal core storage center in Berlin-Spandau. 28 pallets were loaded with core trays plus one pallet with boxed samples from the tunnels. This required two shipping containers because pallets available in Barberton proved to be too wide to place them two high, two side-by-side in a container, as we had originally planned. Instead, they had to be placed three-high, one-row-only in the middle of each container.

The packed and palleted working core had to first wait for the availability of containers, then of a suitable cargo vessel. The core left Barberton September 30 and arrived at a Federal Core Repository in Berlin November 30, 2022. Upon arrival, we found that one pallet at the top of a stack had toppled during transport and was wedged vertically between pallet stack and container wall; fortunately, the tight steel band strapping and the sturdy lid covering the topmost core tray had prevented core to fall out.

> The working core is currently stored at
> Nationales Bohrkernlager für kontinentale Forschungsbohrungen
> Wilhelmstr. 25-30
> 13593 Berlin (Spandau)

The samples from the probed tunnel sections were shipped to Jena and processed there. Chips and thin sections are archived in the departmental archive, c/o Prof. Christoph Heubeck.

8. BASE Drill Core Geology; Preliminary Scientific Assessment

8.1. General Remarks

The drilling campaign drilled a total of 3135 m, recovering 2903 m of core, yielding a recovery rate of 94 % (Appendix A). Lost core material consisted of sections in the weathering zone which were not cored (5 - 70 m thick), broken core due to oxidative weathering or due to extensive fracturing at depth.

All objectives of the drilling program were accomplished. The coring program encountered several surprises:

(1) Unexposed strata over- and underling the weathering-resistant "Lomati Delta Complex" (Stutenbecker et al., 2019) of Saddleback Syncline in BASE-4A, -4B, and -4C did not consist of (deep-water) shale but of friable, cross-bedded tuffaceous sandstones. This will require a reassessment of facies.
(2) Virtually all boreholes encountered a high degree of fractured rock, resulting in excessive water consumption and lost circulation; oxidation along these fractures was encountered even at 250 m depth.
(3) The jaspilite unit MdI1 in Stolzburg Syncline was encountered significantly thicker at depth than mapped at the surface (Luber, 2014) because finely interbedded shale-BIF was found to over- and underlay the silica-rich central section.
(4) BASE-2A encountered a thick association of cobble conglomerates interbedded with and reworking of carbonaceous microbial mats, confirming the interpretations from weathered roadside outcrops (Heubeck et al., 2016) and supporting previous claims of terrigenous, not entirely marine sedimentation.
(5) BASE-3A, drilling a sandy-tidal-flat facies (Homann et al., 2015), encountered repetitively stacked, ca. 20-90 cm thick, fining-upward genetic units. They consisted of microbial-chip conglomerate at the erosive base, overlain by massive sandstone, overlain by horizontally stratified, faintly microbially laminated sandstone, and capped by fully developed "crinkly" microbially laminated sandstone.
(6) Virtually all boreholes encountered some felsic volcanic tuff (Heubeck et al., 2013, 2022b) but most are very thin and consisted of off-white fine-grained ash (not accretionary lapilli); most were slightly to fully reworked.

Core quality was variable because of deep weathering, core fracturing, and drillers initial problems to properly adjust the rate of penetration and weight on bit to the special conditions of variably hard rock and the inclined borehole.

The preliminary stratigraphic columns of Appendix A provide orientation for subsequent lithologic and stratigraphic research. Thus, fault zones, tuffs or tuffaceous horizons, segments of abundant microbial mats, or of well-developed laminations etc. were marked. The locations of symbols representing sedimentary structures are approximate. On each log, a thin stratigraphic column qualitatively illustrates rock quality, thus indicating the depth of weathering at the surface and along fracture/fault zone networks.

8.2. Brief Description of Each Borehole

Drill site **BASE-1** was located in Elephant's Kloof valley on the grounds of Fairview Mine, ca. 10 km northeast of Barberton (25°44'2.63"S 31° 5'50.65"E). The borehole probed the overturned (inner) limb of the arcuate Eureka Syncline of the north-central BGB. The drill site had to be moved from its originally planned location along a mine road due to space constraints into a stratigraphically lower position in a wide turnout of a hairpin turn; it therefore spudded in altered schistose ultramafic rocks of the Weltevreden Formation of the Onverwacht Group in an anticlinal shear zone (locally known as the Zwartkoppie horizon of the Sheba Fault Zone). BASE-1 drilled, after having reached the faulted base of the Moodies Group at ca. 126 m depth, stratigraphically upsection. Drilling started May 19 and ended July 27, 2022, at a total depth of 496.85 m (Heubeck et al., 2022b). True stratigraphic thickness of cored Moodies strata is approximately 350 m.

This section targeted thick fine-grained siliciclastic strata of MdS1 and MdS2 in deep-water facies (delta slope turbidites of MdS1 and MdS2; offshore jaspilites and BIF of MdI1 and MdI2). These units are also intermittently exposed in the Clutha Creek drainage ca. 4 km to the north (Heubeck, unpublished field notes) and along the slopes and ridges paralleling Elephant's Kloof valley. A second target was the progradational coarsening-upward / shallowing-upward sandstone complex of MdQ2, abruptly overlain by the regional Moodies basaltic lava (MdL2), in turn overlain by jaspilites of unit MdI2 and fine-grained deep-water strata of MdS2. All targets were reached. The mine geologists examined all cores before they left Fairview mine.

BASE-2 (25°47'37.78"S 31° 5'1.50"E) was located ca. 5 km from Barberton next to a parking lot of a geoscience stop ("Tidal Sandstones") along the paved R40 route (The Geotrail) which winds its way across the central BGB from Barberton to the Josefsdal/Bulembu border post with Eswatini. The borehole targeted a retrogradational (deepening- and fining-upward) fluvial-coastal-estuarine section partially exposed on the northern, south-dipping limb of the Dycedale Syncline, described by Heubeck et al. (2016) and Homann et al. (2018). This site has spectacular outcrops in deeply eroded (badlands-type) friable tuffaceous sandstones on grasslands slopes adjacent of the drill site, and in good but weathered roadside outcrops north of the drillsite; neither of those allow geochemical sampling. The borehole spudded February 3 and reached TD on March 15, 2022. It was drilled using a tracked rig on its first deployment and drilled for 367.80 m top-down. True stratigraphic thickness of cored Moodies strata is approximately 290 m. This section was of high interest to the paleoenvironment, sedimentary and life groups: From base to top, the units included fluvial sandstones with several intervals of microbial mats in channelized conglomerates ("*life on land*"; *weathering rinds on clasts*), coastal (lagoonal, sabkha) sandstones with abundant, in part rock-forming *vadose-zone* sulfate concretions (now largely silicified), interrupted by at least one aridisol (*terrestrial weathering*) with teepee structures and a single andesitic lava flow (*weathering intensity*). These units are overlain by thick estuary sandstones (*tidal dynamics*) with significant tuffaceous contribution. Because key marker units known from outcrop (the top of the thick cobble conglomerate and the 1 m-thick andesitic lava) were encountered ca. 40 m earlier than anticipated from the extrapolation of surface dip angle, the post-drill cross-section shows numerous out-of-syncline, accommodation-type thrust faults. At least one such low-angle thrust fault is prominently visible in roadside outcrop. BASE-2 was also the most public site of the drilling campaign; these aspects are described below.

BASE-3 (25°49'48.39"S 31°5'26.88"E) was located on the north-facing rocky slope in the central Saddleback Syncline, stratigraphically near the top of unit MdQ1. The borehole had originally been intended to spud ca. 200 m further uphill (stratigraphically further downsection), approximately on top of the ridge, but had to move downslope (stratigraphically upsection) to the wide dead end of a forest road on a steep rocky slope in order to occupy a suitable drilling location. From this "platform", the rig drilled a 45° inclined borehole in young pine growth in the downslope direction. It was spudded in November 25, 2021, and reached total depth on January 26, 2022, after having drilled for 280.2 m base-to-top (upsection) through a thick low-relief tidal platform with abundant signs of microbial life. The true stratigraphic thickness of cored Moodies strata is approximately 218 m. The primary objective was to investigate stratigraphic patterns (rhythmicity, stacking) of microbial mats and their sandy host rock, to obtain continuous sections of microbial-mat-bearing sandstones, and to investigate a thick tidal channel and a ca. 30 m thick unit of abundant calcareous "minimounds" resembling small stromatolites within the kerogenous-laminae-laced tidal sandstones (Heubeck et al., 2023).

All these objectives were reached. The borehole initially cored slightly gravelly sandstone of a coastal-plain facies (ca. 0 - 50 m), then reached a sandstone unit (ca. 50 – 100 m) of numerous, stacked, ca. 0.2 – 0.7 m thick, fining-upward units consisting of (base-up) erosionally-based microbial-chip conglomerate, massive sandstone, flat microbial mats, and tufted microbial mats. A cross-bedded sandstone unit ca. 50 m thick (100 – 149 m drilled depth) may represent an estuarine channel. The “minimound” unit, also mapped in the eucalyptus plantation at the base of the slope, was encountered at ca 199 – 239 m depth. The borehole surprised by its numerous fractures, many of which lined by oxidative halos.

Of all BASE sites, this core offers the most detailed insight in how early life handled the challenges of exposure, tides, and abrasion. It appears to be unique worldwide. This section is of central interest to the scientists interested in early life and paleoenvironmental conditions.

The three boreholes of BASE-4 (A, B, C) investigated the “Lomati Delta Complex” (LDC), a wedge-shaped coarse-clastic body extending over ca. 8 km strike length in the central Saddleback Syncline by drilling one well each through its distal (BASE-4A), medial (BASE-4B) and proximal (BASE-4C) facies. The proximal part of this wedge, ca. 300 m thick, is well exposed as a prominent ridge in grasslands southwest of SAPPI plantations; the medial (ca. 150 m thick) and distal (ca. 12 m thick) segments are poorly exposed in extensive, mature pine and eucalyptus plantations occupying the wide Lomati Valley. The region is well accessible by the Ameide Road, a major trunk forestry road along the valley axis. The wedge, interpreted as an estuarine delta complex and named “Lomati Delta Complex” (LDC), had been studied stratigraphically, sedimentologically and petrographically (Stutenbecker et al., 2019). Microbial mats had been mapped in the distal and proximal outcrop sections, making this site an ideal candidate to investigate microbial life in a terrestrial-marine transition zone. The microbial mats in the distal location drilled by BASE-4A are probably erroneously identified in outcrop but microbial mats were newly documented in BASE-4B and in overlying outcrop; their occurrence in the proximal outcrops was confirmed by BASE-4C. Approximately stratigraphically midway in the wedge-shaped units, an aqueously reworked thick yellow tuff provides a sound stratigraphic marker. Sedimentary structures (mudcracks, mudchip conglomerates, crossbedding, mud coating on ripples, fluid-escape structures etc.) abound in outcrop. Over- and underlying unexposed and weathering-susceptible strata had been assumed to be shaly and to represent deep-water deposits, analogous to stratigraphically equivalent units in the Stolzburg and Eureka Syncline. Preliminary assessment of the core, however, suggests that these strata represent highly tuffaceous, poorly cemented sandstones in estuarine facies.

All three boreholes drilled stratigraphically upwards (northnorthwestwards) and at an angle of 45° through the overturned, ca. 70-75° southward-dipping, northward-younging strata on the >3 km thick overturned limb of the Saddleback Syncline (Heubeck and Lowe, 1994a). Drilling in the fractured, tuffaceous, medium- to coarse-grained tuffaceous sandstones was accompanied by frequent loss of circulation; thus, water consumption was far higher than anticipated. As a result, drilling parameters were occasionally not optimally adjusted. Long sections of the recovered core, particularly in the friable sandstones, show densely spaced drilling-induced stress fractures.

The three BASE-4 boreholes were expected to provide firm proximal-to-distal and marine-to-terrestrial correlations through a highly dynamic but systematic stratigraphic sequence of units to address the questions of microbial life in the transition zone (exposure to the atmosphere, radiation, resilience, metabolism) and basin dynamics (subsidence, sedimentation rates, tides, currents, paleogeography).

BASE-4A (25°49'52.60"S 31° 4'41.69"E) was the first borehole of the BASE drilling campaign. The rig arrived on site November 15, 2021, the borehole spudded two days later, and reached total depth at 340.1 m depth on January 26, 2022. True stratigraphic thickness of cored Moodies strata is approximately 230 m. The rig had to overcome several difficulties: (1) The rig crew was initially inexperienced with the rock types and the operating parameters required to obtain high-quality core in friable sandstones; (2) the thickness of the fully weathered soil zone, assumed to be minor, was ca. 62 m thick; unweathered core was not reached until 125 m depth (ca. 90 m vertical depth); (3) the summer rainy season was particularly intense. The borehole initially penetrated a seemingly monotonous sequence of medium-grained, tuffaceous, horizontal- and cross-bedded friable tuffaceous sandstones with thin shale coatings, carrying rare angular shale mudchips and common white tuff clasts, and interbedded with numerous cm-thin (largely aqueously reworked) air-fall tuff beds. The distal equivalent of the LDC was encountered between 201.9 and ca. 219 m drilled depth. It is represented by an (in places spectacular) repetitive sequence of very-high-energy coarse-granule sandstone interbedded with shale-clast conglomerates and some (in-place) mudcracked shale beds. In places (e.g., ca. 288 - 305 m), green shale laminae, white tuff clasts, and red jaspilite sand grains result in a colorful sandstone. Rhythmically bedded sandstone – (green) shale couplets on bedding planes and foresets are common.

BASE-4B (25°51'11.70"S 31° 2'54.70"E) was set up at the junction of several secondary forest roads just upslope of (and stratigraphically below) a prominent forested ridge, ca. 1670 m downdip from BASE-4C and ca. 3820 m updip from BASE-4A. Drilling started on February 9, 2022, and ended at 355.5 m depth on March 23, 2022. The true stratigraphic thickness of cored Moodies strata in the borehole is approximately 300 m. Drilling progress was good through evenly firm rock at ca. 10 to 15 m / day. The borehole started coring after leaving the zone of profound weathering at 27 m. It penetrated a lithologically similar sequence as BASE-4A. The high-energy, very-coarse-grained and mudchip-carrying units extended over ca. 150 m thickness (ca. 135 – 284 m), with several indications of (reworked?) microbial laminations. A highly tuffaceous unit, approximately midway in the target unit, occurred between 175 and 219 m depth. Rhythmic, likely tidal, bedding was commonly encountered. The quality of the core was affected by extensive oxidative alteration and fracturing between 188 and 288 and from 315 to 350 m depth. The reasons for this alteration at significant vertical depth is unknown; possibly, these are expressions of a wide alteration zone associated with a brittle shear zone along Lomati Valley, of vertical fractures extending to this depth, or of a hydrothermal halo surrounding a porphyritic mafic dike mapped ca. 50 m beyond the location of the end of the borehole in an unusual, approximately bedding-parallel orientation. Also, the core shows several zones of an unusual, evenly dark grey discoloration (e.g., 151 - 176 m).

Site **BASE-5** cored top-down a ca. 860 m thick section. This required two offset boreholes in which the bottom of borehole 5A correlated with the top of borehole 5B. It targeted a conformable deepening-upward (transgressive) sequence from fluvial-evaporitic floodplain at the stratigraphic base to below-wavebase prodelta facies at the stratigraphic top in the eastern Stolzburg Syncline (Luber, 2014). The site was chosen to be located approximately midway between a major, obliquely crosscutting dolerite dike to the west and the tight curvature encountered in the hinge of the Stolzburg Syncline in the east; it also attempted to avoid mapped faults of minor offset and relied on good but weathered and intermittent surface outcrop for stratigraphic and structural control. The true stratigraphic thickness of cored Moodies strata, combined from both boreholes, is approximately 740 m. The stratigraphic base of BASE-5A overlaps the cored top of BASE-5B by about 20 m (cp. Appendix D).

BASE-5A (25°54'13.97"S 30°50'44.83"E) spudded April 5, 2022, and reached its TD of 451.3 m on May 18. It started coring at 30 m depth. Basal strata probably overlap with those at the top of BASE-5B by about 20 m and represent rhythmically bedded tuffaceous and shaly (green) fine-grained sandstones with common slump, dewatering, and load structures, indicative of high rates of deposition, largely below wave base (451 – 385 m) in a distal delta mouth bar and upper prodelta setting. A minor sandy delta lobe was drilled between ca. 385 m (base) to 320 m (top). Lower-slope prodelta sedimentation dominates the remaining, overlying section (ca. 320 – 30 m core depth), with spectacular intervals of rhythmically bedded (e.g., 180 – 206 m) and slumped, micro-laminated BIF, jaspilite and shale between 230 and 290 m. The ferruginous section, stratigraphically known as MdI1, was significantly thicker than predicted from its surface exposure (10 - 15 m); it correlates lithostratigraphically to a jaspilitic interval mapped as MdI1 near 180 m depth in BASE-1, more than 31 km to the northeast. The interval 175 – 295 m (MdS1) probably represents the finest-grained, deepest-water, most distal facies encountered during the BASE drilling program, alongside a similarly fine-grained section in BASE-1 at 160 - 270 m depth. The true stratigraphic thickness of cored Moodies strata in BASE-5A was approximately 360 m.

BASE-5B (25°54'2.80"S 30°50'49.06"E) started drilling June 3, 2022, and terminated at 489.9 m depth on July 17, 2022. Coring started at 17.9 m depth. The section (base to top) begins in tuffaceous, cross-bedded, slightly gravelly floodplain sandstones with common early-diagenetic silicified sulfate concretions (ca. 500 - 350 m depth), probably representing vadose-zone diagenesis of sulfate-bearing tuffaceous sediments. They contain evidence of microbial sulfate reduction ("*life on land*"; Nabhan et al. 2016b), This zone is overlain by coarse-sandy and gravelly shoreline-facies sandstones, ca. 350 to 300 m, possibly interrupted by lagoonal sediments consisting of reworked tuffaceous (lapilli) siltstones (ca. 315 – 306 m). Overlying thick, green, monotonous medium-grained tuffaceous sandstones with common load structures may represent shoreline and upper delta-mouth bar facies with extensive reworking, slumps, load structures and shale-free foresets (ca. 306 – 100m), gradually grading into finer-grained sandstones with some rhythmically bedded segments (150 – 18 m). Thin shaly jaspilites were encountered at 93 and 108 m depth, the latter reworked as chip clasts. Microbial mat-sandstones were not encountered in either core. The section is generally rich in tuffaceous material. The true stratigraphic thickness of cored Moodies strata in this borehole was approximately 400 m.

9. The Tunnel Sections

9.1. Challenges and Opportunities Provided by Tunnel Sampling; Objectives

Three tunnels traverse Moodies strata in the central BGB approximately at right angles to strike: (1) The Lomati water tunnel below Saddleback Hill in the Saddleback Syncline, ca. 2 km south of Barberton; (2) the Ben Lomond (a.k.a. Princeton) and the 22-level adits of Agnes Mine in the Moodies Hills Block, ca. 8 km west of Barberton. We succeeded in sampling all three of these tunnels during the drilling campaign. The data obtained add significantly to the stratigraphic extent of unweathered Moodies samples and can easily be stratigraphically and lithologically integrated into BASE data. We therefore include a basic description of this data set although this endeavor had not been included in the ICDP proposal and had not been funded by any national research organization either.

We here briefly describe the setting and sampling of all three tunnels; a more detailed description was topic of two B.Sc. theses completed in 2023 at the University of Jena under supervision of C. Heubeck (Seifert, 2023; Bender, 2023). Visual inspection and initial point counting of medium-grained sandstones shows that samples from all three tunnels are fresher than virtually all surface outcrop samples above the tunnels. Samples were relabelled, photographed, packed and shipped to the Department of Geosciences, FSU Jena.

9.2. Lomati Water Tunnel

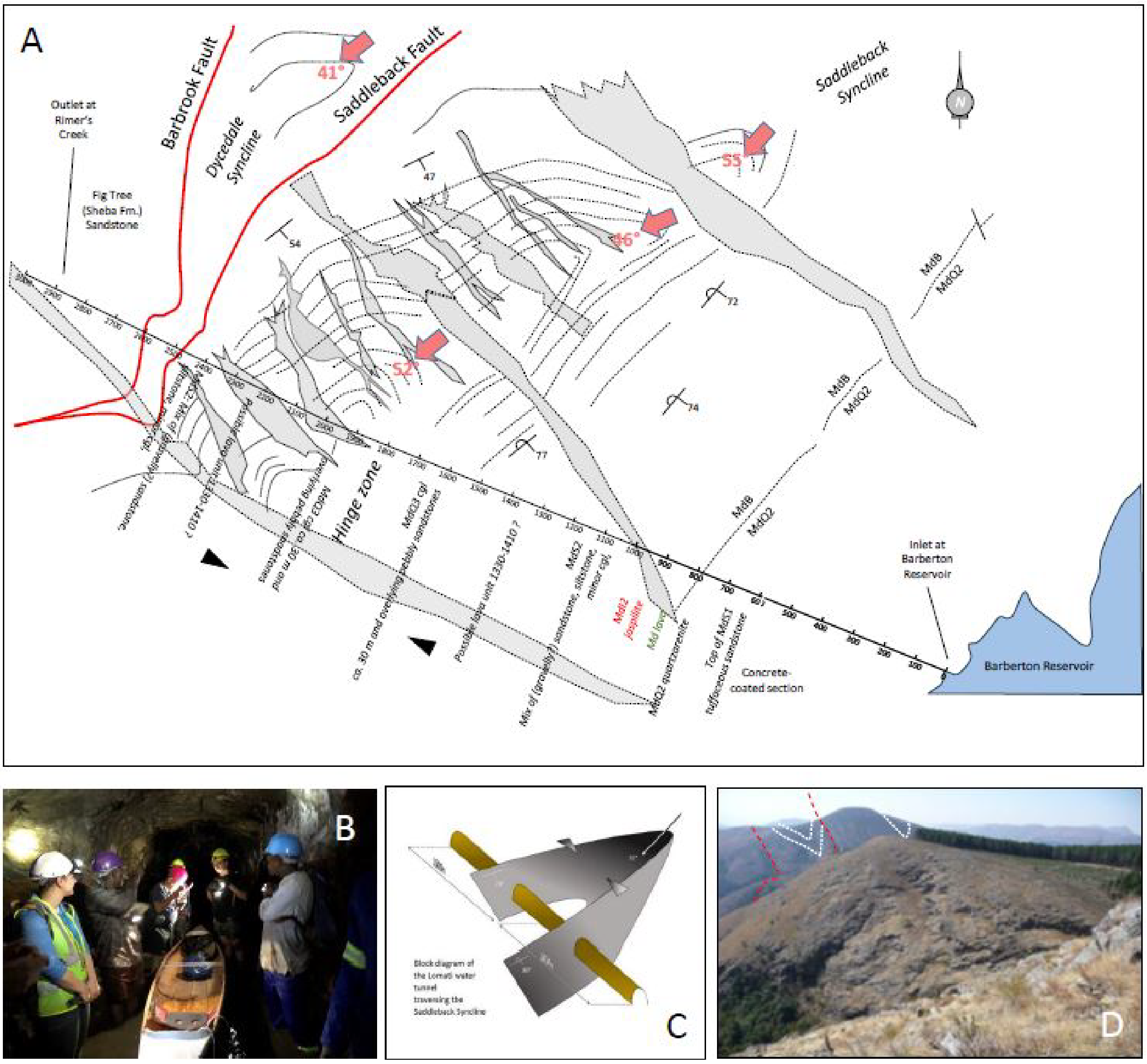


Figure 17: Lomati Water Tunnel. A: Sketch geologic map, showing bedding traces marking the core of the Saddleback Syncline. Red arrows mark plunge direction of fold axis. B: Sampling in the Lomati Water tunnel. Water level had been temporarily lowered. C: Diagrammatic 3-D diagram illustrating the relationship between tunnel and synclinal limbs. D: Saddleback Hill, important structural features highlighted. The Lomati Water tunnel runs ca. 350 m below the ridge crest in the distance.

9.2.1. Setting and Sampling Procedure

The 2870 m long *Lomati Water Tunnel* (Fig. 17, Appendix C) connects the Barberton water reservoir with a water treatment facility in Rimer's Creek Gorge outside Barberton (Fig. 2). The tunnel, blasted and drilled in 1989, is accessible by wading when water level is temporarily lowered during inspections. Uniquely, the tunnel crosses at nearly right angle both limbs and the hinge section of the Saddleback Syncline (Fig. 2) by traversing two inward facing sections of the middle and upper Moodies Group, each about 1000 m thick (Fig. 17). Strata of both synclinal limbs and of the hinge zone are intermittently exposed and mappable on Saddleback Hill (1,598 m) and its continuation along strike, ca. 300 m above the tunnel. Reconnaissance geological mapping by Lippold (2011) and Bender (2023; unpublished) documented a sequence of fluvio-deltaic and tidal sandstones and fluvial conglomerates. Legacy tunnel data include a very basic pre-construction strip map and cross section (van Wyk, 1985), a partial lithologic log near both tunnel mouths (Hose, 1990), and pencil-drawn detailed tunnel wall drawings by the mining geologist Don MacAulay (1987), focusing on faulting, fracturing and veining. No legacy rock samples exist from any of these studies. Both copies of the post-construction report, filed with the City of Barberton and at Grinaker Engineering, have been lost.

Access to the Lomati Water Tunnel was impossible in the past years because Mbombela Municipality engineers and managers were understandably reluctant to interrupt the principal water supply for the ca. 60,000 inhabitants of Barberton and Emjindini. Christoph Heubeck had logged the condition of the tunnel and drawn a cursory lithologic strip log during an inspection 2018. After much lobbying, inspection and sampling was again permitted for March 22, 2022 within scheduled tunnel maintenance, for which engineers shut off the water supply to Barberton and lowered the water level. A team of nine geologists coordinated by Christoph Heubeck sampled a total of 99 samples (80 kg), approx. every 20 m, from the two Moodies limbs and the hinge zone totalling 2120 m long, using short sledge hammers to knock samples from abundant protruding rock faces of the roughly hewn walls in the spacious tunnel. Wall rocks above the water line were moist but free of recognizable microbial coats. Rock types and sedimentary structures were readily recognizable. Three generations of sprayed distance markers (blue, red, yellow) allowed adequate distance calibration. A canoe was used for sample transport. Sandstone petrography was investigated in the BSc thesis of Bender

9.3. Adits of Agnes Mine

9.3.1. Setting and Sampling Procedure

BASE boreholes and the Lomati water tunnel probe three of the four major Moodies synclines north of the greenstone-belt-axial Inyoka Fault, namely the Eureka, Saddleback and Stolzburg

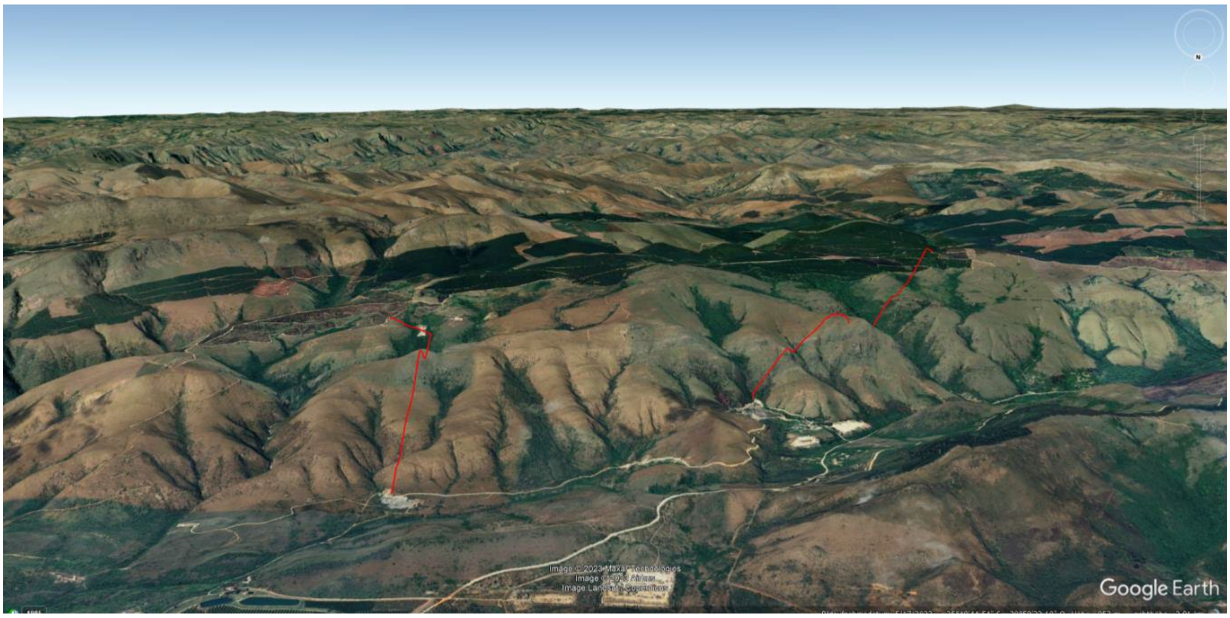


Figure 18: Location map showing surface traces of Agnes Mine tunnels (red) in the Moodies Hills Block. Traces are draped on a Google Earth perspective view. View is towards the south; Agnes Mine in the center foreground. The 22-level adit is seen to the left, the Ben Lomond tunnel to the right.

synclines and one minor syncline, the Dycedale Syncline. Not drilled were strata on the Moodies Hills Block because of a lack of suitable drilling locations. The Moodies Hills Block presumably represents the southern limb of a major syncline of which its northern limb and the hinge have been removed by uplift and erosion by up-to-the-north faulting along the northern margin of the BGB. It is tectonically contiguous with the Eureka Syncline (Anhaeusser et al., 1981; Heubeck and Lowe, 1994b). The Moodies Hills Block is traversed by two mining tunnels (adits; Fig. 28) that crosscut its steeply south-dipping, northward-younging stratigraphic sequence roughly perpendicular to strike. Each tunnel is nearly 2 km long and ends at the Sheba Fault, which limits the Moodies Hills Block to the south.

9.3.2. Ben Lomond Adit of Agnes Mine: Geology, Sampling Campaign

The Ben Lomond (a.k.a. Princeton) adit traverses a ca. 1500 m thick section of the upper Moodies Group. It is about 3 m high and 3 m wide. Mine train tracks run along it (Figs. 18, Appendix C),

Javaux et al. (2010) reported the world's oldest acritarchs from "*… five short drill holes drilled from the underground levels 600 m below the surface in the Agnes gold mine, Moodies Hills Block*" in siltstones. No additional information on these – potentially highly relevant cores – exists. Hose (1990; her Appendix 1f) documents a 2269 m long stratigraphic section through the Princeton Tunnel of Agnes Mine; associated samples have, however, been lost. Seifert (2023, unpublished) provides a stratigraphic cross section through the tunnel and examined the sandstone petrography.

9.3.3. The 22-level Adit of Agnes Mine: Geology, Sampling Campaign

The 22-level adit traverses ca. 1600 m thick strata of upper Moodies strata correlatable with surface outcrops and with the stratigraphic sequence in the Ben Lomong tunnel along strike (Figs. 18, Appendix C). Its dimensions are similar to that of the Ben Lomond adit but it has no train tracks. The adit exit is located on or very near the vertical, E-W-striking Moodies Fault which juxtaposes Onverwacht volcanics and mafic schist to the north against Moodies siltstones and fine-grained sandstones to the south; the vertical displacement is at least several km. Along this fault, the northern limb and the hinge zone of a former major syncline have presumably been eroded by up-to-the-north faulting. The remaining Moodies section (Fig. 18), representing the southern limb of that syncline, faces north. The Zig-Zag trail below the nearby electricity powerline and excellent continuous roadside outcrops of the unused Devil's Staircase Road ca. 1 km to the east provide the bases for outcrop correlation. Hose (1990; her Appendix 1g) documents a stratigraphic section of 1717 m in the 22-level adit; associated samples, however, have been lost.

10. Description of BASE Basic Data Sets

10.1. Data Sets Originating from Drilling Operations

Fig. 19 shows an example of the daily driller's report which BASE members received per *WhatsApp* in the evening. The CIMERA office and the onsite science teams also received weekly an interim accounting report as an Excel spreadsheet from the drilling contractor. This, in turn, formed the base for the more detailed and complex monthly accounting report and invoice. A member of the BASE onsite geoscience team, mostly Rod Tucker, checked these reports and signaled approval for payment by the CIMERA office.

icdp INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

MASTER DRILLING

Master Drilling Exploration

Drillers Shift Report

21527

Drill Rig Number	MDX 317	**Date**	07-01-2022
Hole Number	BASE 3-A	**Drill Operator Name**	[redacted]

Depth of hole at end of shift	A	95-63 MQ
Depth of hole at beginning of shift	B	82-34 HQ
Total meters drilled (A-B) = C	C	13.29-MQ

Time shift started	D	07H00	Time of restart	G	
Time shift ended	E	17H00	Time of b/down	H	
Total shift time	F	10 Hours	**Total down time**	I	

Meters p/h (Total meters divided by Total Shift time – Total down time) = (C/F-I)

Break Down /Standing Time Reason

START	STOP	TOTAL	TASK / DELAY	COMMENT
07H00	07H15	15mins	LOADING CORE BOXES AT STORE.	
07H15	07H45	30mins	DRIVING TO SITE.	
07H45	08H15	30mins	CHANGING RB35 GASKET	SPRAYING WATER OUT.
08H15	09H45	1HOUR 30mins	DRILLING	
09H45	10H30	45mins	PULLING OUT DRILL RODS	BIT IS FINISHED.
10H30	10H45	15mins	CHANGING DRILL BIT	
10H45	11H30	45mins	LOWERING DRILL RODS	
11H30	12H45	1 HOUR 15mins	DRILLING	
12H45	13H00	15mins	WAITING FOR WATER.	NO WATER RETURN
13H00	16H15	3HOURS 15mins	DRILLING	
16H15	16H30	15mins	PULLING OUT INNER TUBE.	
16H30	17H00	30mins	PULLING OUT DRILL RODS	BIT IS FINISHED.

E.O.S CREW: [redacted]

Acknowledgement

Name Geologist		Signature	
Name Supervisor		Signature	
Name Manager	[redacted]	Signature	

Form No: FRM-MDX-ODD-000 8-E

Page 1 of 1

20130 GRAPHIC IMPRINT 0861 774 681

Figure 19: Daily Driller's Report, here of Jan. 7, 2022, for borehole BASE-3.

10.2. Data Sets Based on the Drill Core

10.2.1. Photography

The technical setup of photography was described in chapter 6.3. BASE photographs are organized by borehole, then by core tray. The file structure on the ICDP BASE web site follows ICDP conventions and distinguishes between full core (whole rock; WR) and slabbed core which in turn is denoted as A = archive or W = working. All full core in trays were photographed in wet and dry states unless the core was too crumbly. Similarly, all working halves and archive halves of the slabbed core were photographed wet and dry, with a few exceptions. Each photograph also shows a data bar at its base (Fig. 20).

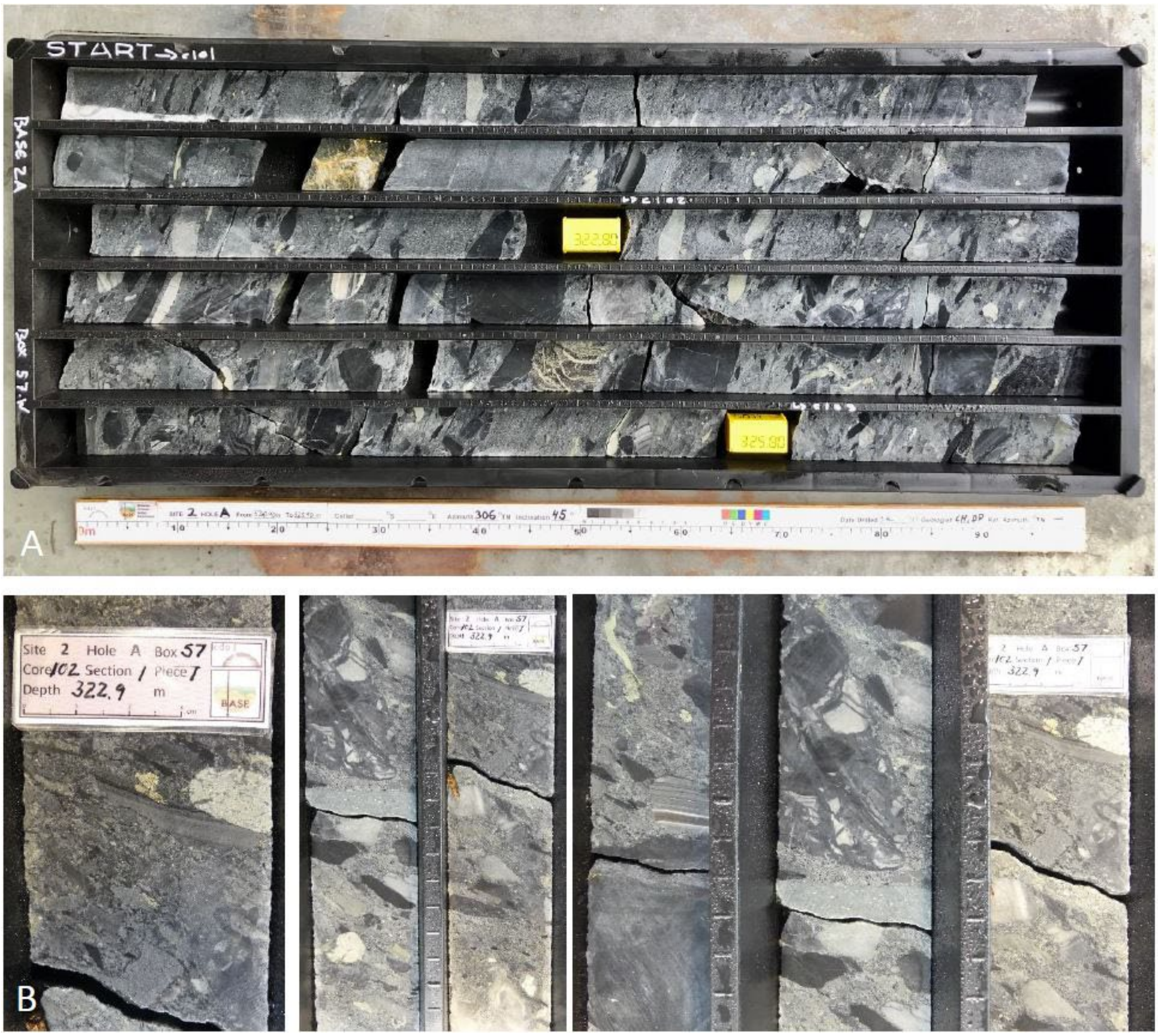


Figure 20: Examples of core photographs. A: Slabbed and wet core of box 57 of borehole BASE 2, showing ca. 2.5 m of core 101, all 3 m of core 102, and ca. 0.4 m of core 103. Stratigraphic top is to the upper left. Data bar provides information about depth, date, and staff. B: Examples of hand-held close-up photographs of the same core tray, showing textures of the cobble conglomerate and composition of individual clasts, mostly latite ("feldspar porphyries") and chert.

At the Spandau core facility, most core trays (containing five core sections of approx. 1 m each) of BASE-5A, BASE-2, and BASE-3 were scanned using a DMT core scanner in order to preserve their sedimentary textures in detail. This generated high-resolution (11000 * 4000 px; ca. 160 MB) images which allows 1:1-scale printouts of the images without pixelation.

Table 7: Logging Tools Deployed

Borehole	Gamma Ray from 3-Arm Caliper	Magnetic susceptibility	Borehole fluid Temperature	Three-Arm Caliper	Borehole Acoustic Televiewer
	GRC	MSUS	GTMP	CC01	ATV
1A	●	●	●	●	●
2A	●	●	●	●	●
3A					
4A					
4B	●	●	●	●	●
4C	●	●	●	●	●
5A	●	●	●	●	●
5B	●	●	●	●	●

10.2.2. Conventions, Depth

Core naming conventions followed ICDP protocol (Expedition – Site – Hole – Core – Section – Split). All depths represent handwritten marked depths (by the Onsite Geoscience Team) on the core, not the driller's depths marked on the yellow or green plastic blocks. These driller's depths usually deviate only by cm to several dm from measured and marked core depth. We used and accepted driller's depth, however, where there was core loss or bad ground. We found that driller's depth and measured depth were balanced within a few dm at the end of each borehole, after 280 to 498 m of drilling. In processing the core, we saw no advantage to introduce a second, potentially confusing depth scale by modifying driller's depth markings to a slightly differing, newly calculated core depth because future depth-dependent information, such as profiles, correlations, and thickness variations would not have been recognizably affected by such corrections. Detailed interpretation of geophysical logging may change that assessment.

10.3. Data Sets Based on Downhole Logging

All boreholes were surveyed (log depth, true depth, hole tilt and azimuth, axial and polar coordinates) to check for agreement with planned azimuth and inclination. On the first borehole (BASE-4A), the Boart Longyear TrueCore instrument was deployed to record core orientation; however, we stopped its use after a few days because we found that the drill crew had difficulties in applying and reading the instrument and because the predictable and constant angle of intersection between bedding and core made it possible to orient the core reliably prior to slabbing.

Table 8: Logging Depths

Borehole	Steel casing to (m)	Top log (m)	Logging to (m)
1A	108.44	9	496.85
2A	138.2	9	367.20
3A			280.20
4A			320.01
4B	66.60	9	355.00
4C	90.84	9	351.49
5A	107.79	9	451.00
5B	96	9	489.92

We initially intended to do basic geophysical logging (total GR, magnetic susceptibility) on the core and thus did not log the first two boreholes BASE 4A and 3 except for surveying. We soon realized, however, that this approach was erroneous because the fractured and broken core in core trays would have made laboratory logging difficult. All subsequent boreholes (BASE-1A, -2A, -4B, -4C, -5A, -5B) were therefore logged with total GR, magnetic susceptibility, temperature, caliper, and borehole acoustic televiewer (ATV) (Fig. 21; Tables 7, 8). ATV logging provided continuous, high-resolution ultrasound images of the borehole wall for detection and characterization of fracture networks. Porosity and resistivity logs were not run because they did not contribute recognizably to the objectives of the drilling campaign. The geophysical contractor, Wireline Africa, provided log data in raw and processed format.

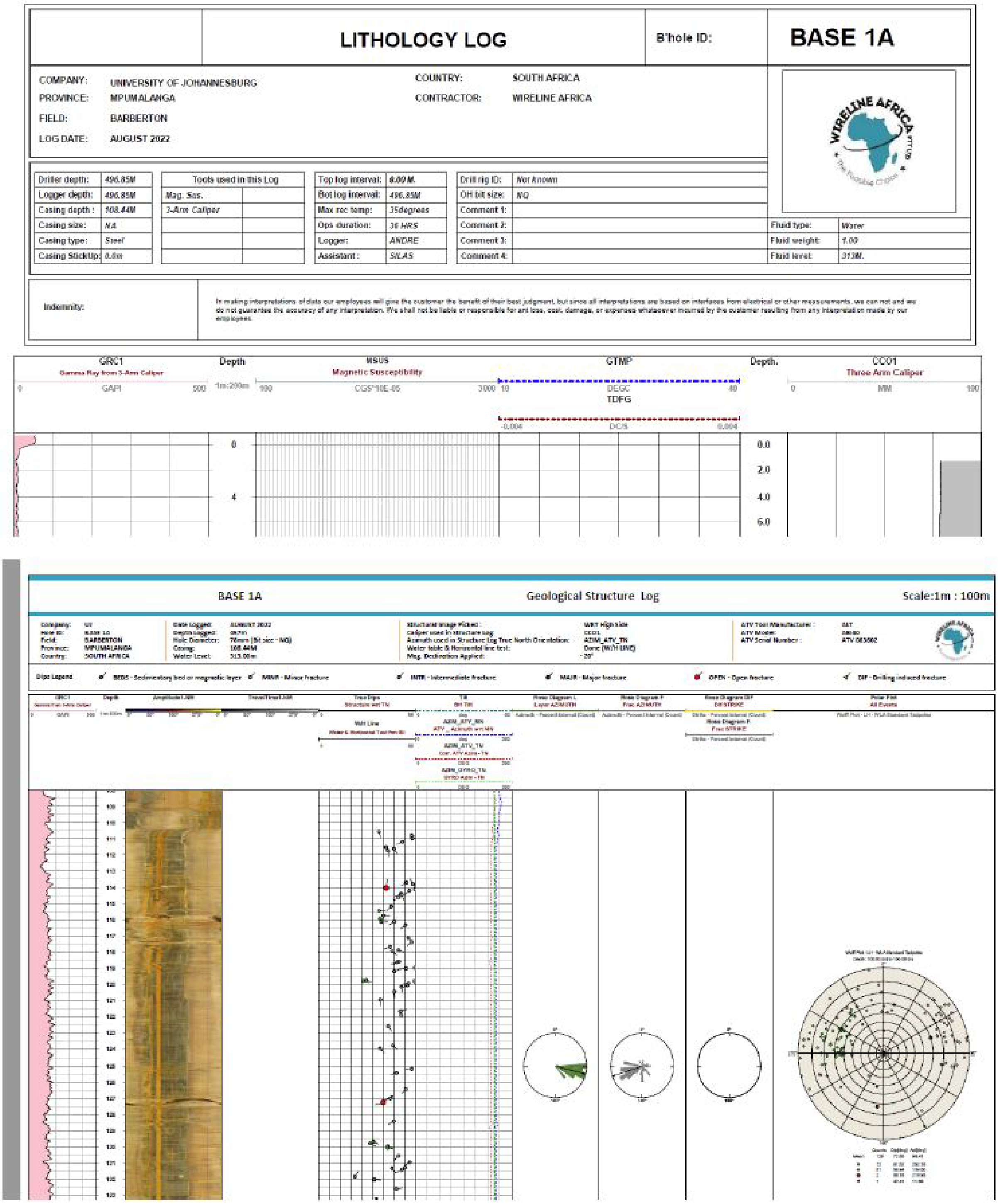


Figure 21: Headers of the lithology (top) and structure logs (bottom).

10.4. Geochemical Reference Data Set

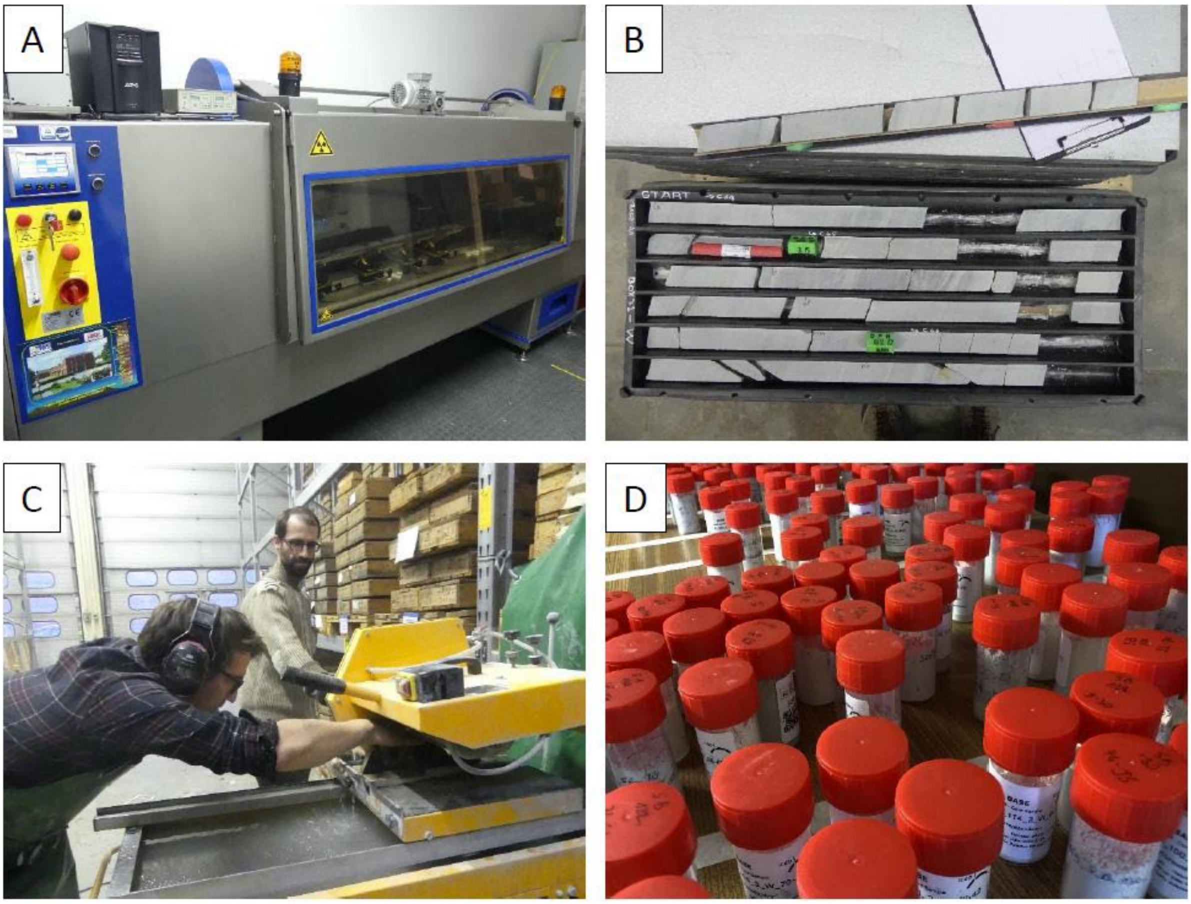


Figure 22: Producing the Geochemical Reference Data Set. A: Avaatach XRF core scanner. B: Representative core tray. From each of the six grooves of this core tray, a piece ca. 10 cm long and ca. 1 m apart was removed and assembled in the portable groove to be x-rayed. Ca. 500 core trays were processed this way; all depths were documented to the mm. Red marker replaces sample taken for powder analysis. C: Cutting core halves into quarters. D: Aliquots of powdered rock samples.

All cores were sampled in January and February 2023 to construct a combined geochemical reference data set composed of major elements, trace elements, and mineralogy using X-ray fluorescence (XRF) scanning (Spandau, Brest), XRF bulk rock fusion disk analysis (Utrecht), and X-ray diffraction (XRD) on pressed powder pellets (Paris), respectively (Tables 9 and 10).

Table 9: Locations of samples and intervals taken for the geochemical reference data set - XRF Scanning

			High-resolution intervals (m) (3 cm steps)		Medium-resolution intervals (8 cm steps)		Low-resolution (50 cm steps)
Bore-hole	**Drilled depth (m)**	**Length analyzed (m)**	**length of sections (m)**	**intervals (m)**	**length of sections (m)**	**intervals (m)**	**length of sections (m)**
1A	497	399	27	175 to 180, 404 to 426	17	387 to 404	355
2A	368	264	21	140 to 161	39	161 to 210	204
3A	280	269			35	215 to 250	234
4A	340	264			8	154 to 162	256
4B	355	150			7	85 to 92	143
4C	350	306			24	208 to 232	282
5A	451	411	117	178 to 295			294
5B	490	460			145	300 to 445	315
Total:		**2523**	**165**		**275**		**2083**

A brief description of each method follows:

(1) All cores were scanned using the Avaatech core scanner at the BGR core repository in Spandau (Fig. 22). This instrument records characteristic X-ray spectra of a ca. 1 cm^2-sized area for elemental composition. Core samples were therefore selected about one m apart (that is, about one sample per core box groove or approx. five samples per tray; Fig. 22) and sequentially arranged in the instrument tray. In regions of medium interest, scanning was done in steps of 5 to 10 cm, and in the zones of highest interest, in steps as low as 3 cm. Measurements took about six weeks of full-time work. Table 9 shows the chosen intervals of high, normal, and low sampling density.

(2) At the same facility, core was (destructively) sampled for powdering and bulk rock geochemical analysis. Core segments ca. 10 cm long were selected approximately every 5 m (i.e., approximately one sample per core box) (Fig. 22) and slabbed in half, cutting parallel to the core long axis using a core saw (Fig. 22). The unused half of the slab (a quarter core) was returned to the core tray. Selected samples were crushed and powdered by two technicians at Brest in April 2023. Because the powders were more voluminous than anticipated, aliquots of the reference set and some remaining rock chips from the saw cut are available upon request from Stefan Lalonde (Brest) and Paul Mason (Utrecht). Amandine Migeon processed the pressed powders for high-precision whole-rock trace element analysis by HR-ICP-MS (Brest).

Table 10: Locations of samples and intervals taken for the geochemical reference data set - Reference Powders

Borehole	Drilled depth (m)	Length analyzed (m)	Total Samples	Intervals of high-resolution sampling (ca. every 2.6 m)	Intervals of medium-resolution sampling (ca. every 6 m)	Intervals of low-resolution sampling (ca. every 14.5 m)
1A	497	399	37	175 to 180, 404 to 426	387 to 404	98 to 175, 180 to 387, 404 to 497
2A	368	264	28	140 to 161	161 to 210	104 to 140, 210 to 368
3A	280	269	22		215 to 250	11 to 215, 250 to 280
4A	340	264	19		154 to 162	76 to 154, 162 to 340
4B	355	150	11		85 to 92	50 to 85, 92 to 200
4C	350	306	23		208 to 232	44 to 208, 232 to 350
5A	451	411	64	178 to 295		40 to 178, 295 to 451
5B	490	460	46		300 to 445	30 to 300, 445 to 490
Total:		**2523**	**250**			

(3) Whole-rock powders were analyzed at Utrecht University (Paul Mason) for major elements by XRF. Wavelength-dispersive XRF measurements for major elements were carried out sequentially using a Thermo Scientific ARL PERFORM'X 4200W. Loss on ignition (LOI) was measured by thermo-gravimetric analysis at 1000°C. Fusion beads were prepared using 0.6 g sample and 6 g of flux, consisting of 66% lithium tetraborate, 34% lithium metaborate and 0.5% lithium iodide.

(4) Stefan Lalonde wrote Matlab code to plot large numbers of core-scan XRF data points, usable for custom plots, e.g., for choosing a core interval to plot geochemical profiles as high-quality Adobe Illustrator-editable PDF files.

(5) Powders were analyzed for quantitative mineralogy by X-ray diffraction at the

Museum d'Histoire Naturelle in Paris (Pierre Sans-Jofre and his PhD-student Laurane Fogret) in May and June 2023.

10.5. Borehole and Wellsite Documentation

10.5.1. Pre- and Post-drill Geologic Cross Sections

Detailed geologic maps of the regions around the drill site had been drawn. Based on those, Christoph Heubeck drew predictive cross sections which were updated and annotated as drilling progressed. Their principal purpose was to check the progress in reaching borehole objectives by correlating the stratigraphic sequence encountered in the borehole with surface geology. Once total depth was reached, final cross sections were prepared (Appendix D).

The final borehole sections generally differ from the predictive boreholes by showing (usually unexpectedly thick) weathering zones and much greater stratigraphic detail. They do not contain major inconsistencies except at BASE-2 where the top of the conglomerate was encountered about 30 m earlier than predicted from outcrop data. This offset was interpreted in the BASE-2 post-drill cross section by postulating a series of out-of-syncline accommodation faults, each with minor offset. At least one such fault is well documented in the roadside outcrop north of the drill site (cp. Heubeck et al., 2016; their Fig. 7).

10.5.2. Stratigraphic Logs

The overview lithostratigraphic logs (Appendix A) are principally based on the evaluation of core tray and close-up photographs. The scale of each log is such that the entire log occupies a single A3-sized printed page; the vertical resolution is thus approximately 2 m. Thinner units are not or only selectively represented. Because five of the eight BASE boreholes were drilled stratigraphically upwards (base to top), depths increase on the scale upwards on these logs, so that the stratigraphic column can be displayed in the correct (youngest unit on top) orientation.

11. Education Outreach Publicity (EOP)

11.1. Philosophy; Objectives, Strategy

The Barberton region has had a long history of exploration for (and mining of) gold from the hydrothermal mineralization in deep-reaching ductile-brittle shear zones, mostly along the northern margin of the greenstone belt. The mines make up the backbone of the town's economy. Residents thus naturally see drilling activities as an element in the exploration for gold. For these reasons, it was apparent that the communication of the scientific, non-commercial objectives of the BASE drilling program had to take a prominent place in the project, considering that seven of the eight BASE boreholes were located within the Barberton-Makhonjwa World Heritage Site (BASE-1, on the grounds of Fairview Mine, is the exception). The ICDP proposal had addressed this challenge by proposing EOP activities in a 3*3 matrix (before – during - after activities vs. small or once – medium-sized or temporary – large or permanent). Over the previous years, Christoph Heubeck with his students had created awareness of the geological features among the Barberton population through regular public talks at the Barberton Mountainland Branch of the Geological Society of South Africa and in numerous articles in the local newsletter "Barberton Times" and the regional newsletter "The Lowvelder". Prior to drilling at the easily accessible Site 2, we informed the Barberton community through displays in shops, schools and other public places.

11.2. Realisation

11.2.1. General

Astrid Christianson, the manager of Barberton Tourism, together with Phumelele Mashele, the BASE education and outreach coordinator, organized all activities related to welcoming, hospitality, accommodating and entertaining individuals and groups of visitors. Phumelele, with the assistance of Victor Ndazamo, Thikho Mufamadi and other members of the geoscience on-site team, oversaw a wide range of outreach activities, assisted with core processing and archiving, guided school classes and drop-in visitors, and created figures for handouts and posters. Christoph Heubeck created a temporary geological exhibition in the forward section of the BIAS Hall, composed of posters and maps suspended from the ceiling rafters, brochures, handouts, and slabbed and polished rock samples. Appropriate representative samples had been collected and stored over many years.

Figure 23: Education / Outreach / Publicity activities. A, B: Phumelele Mashele explaining rock types to a film crew and to learners, respectively. C, D: Field Trips to drill sites BASE-4A and -2. E: The rock saw, explained by Musa Mavimbela; F: Visit by the leadership team of the University of Mpumalanga.

11.2.2. Radio and Schools, TV, Movie Production; the Barberton Community

Radio plays a higher role in information dissemination in Africa than in Europe or the US. Phumelele Mashele thus organized a series of weekly, 30-minute-long radio interviews at a local, Emjindini-based radio station and visits to the Nelspruit-based Radio Laeveld radio station. This gave us the opportunity to spread information about the project in isiSwati and English. Phumelele Mashele, Victor Ndamazo and Thikho Mufamadi proactively contacted schools, encouraging them to visit the BIAS Hall and, in particular, the drilling operations at the highly accessible Site BASE-2. Attendance was initially slow because the school year ended with the exam period in November and December, followed by summer vacation, but a steady stream of elementary and high school learners from Emjindini, Barberton, and Nelspruit visited the BIAS Hall and the drill sites soon after the school year had begun again in February. It occasionally proved to be problematic to disseminate the information from school board supervisors to principals to teachers and to make them aware of the value of a visit. School class visits counted as many as ninety heads, which provided a welcome temporary interruption from the daily routine of core processing (Fig. 23).

Phumelele Mashele was interviewed and featured on July 5, 2022, in a contribution to 50/50, a country-wide TV feature program, in which she reflected on her upbringing in Barberton, her changing perception of the mountains, and her participation in this international drilling program. Nic Beukes described in a Newzroom Afrika (a national news channel) interview on May 14th, 2022 the global significance of the Barberton region and why the BASE project was drilling there. The local population was also kept informed by presentations to the Barberton branch of the Geological Society of South Africa prior to and at the end of the drilling program; both events were well attended.

SANHU, a Nelspruit-based production company, produced on behalf of the timber company SAPPI, the principal landowner, a 22-minute-long movie in which stakeholders, scientists, and drilling contractors were interviewed and portrayed. A planned visit by a crew from the German government's ARD TV studio for southern Africa, based in Johannesburg and scheduled for February 2022, fell victim to the outbreak of the Russia-Ukraine war.

11.2.3. Print and Online Media

The project was featured in German and South African geoscience newsletters (GSSA Newsletter, March 2022; Heubeck et al., 2022a; Heubeck, 2022), three articles in the regional daily *Lowvelder*, an issue of the *Umjindini Guardian*, press releases (August 2022), the journal *Lichtgedanken* (12 March 2023) of the Friedrich-Schiller-University Jena, a press release of the provincial tourism authority KLBCT, the cover of the science journal *Scientific Drilling* (Febr. 2022), and the journal *Science* (Voosen, 2022).

Following the proposal workshop in 2017, Christoph Heubeck informed the BASE Science Team initially irregularly through a Newsletter. During the drilling campaign, its format became one-page biweekly. The newsletter informed about drilling progress, initial results, and activities around the drill site. The Newsletter returned to a monthly schedule after the end of the drilling program. It proved to be effective in keeping the BASE project in the minds of its worldwide readership of about 70. During drilling operations, a daily annotated Picture of the Day appeared on the ICDP BASE webpages.

Phumelele Mashele maintained a Facebook site which informed a community of followers about BASE activities, largely related to visits. It contained a collection of movies and photos of the drilling operations. The project reached 440 followers and is active even at present, recording BASE activities around Barberton and worldwide.

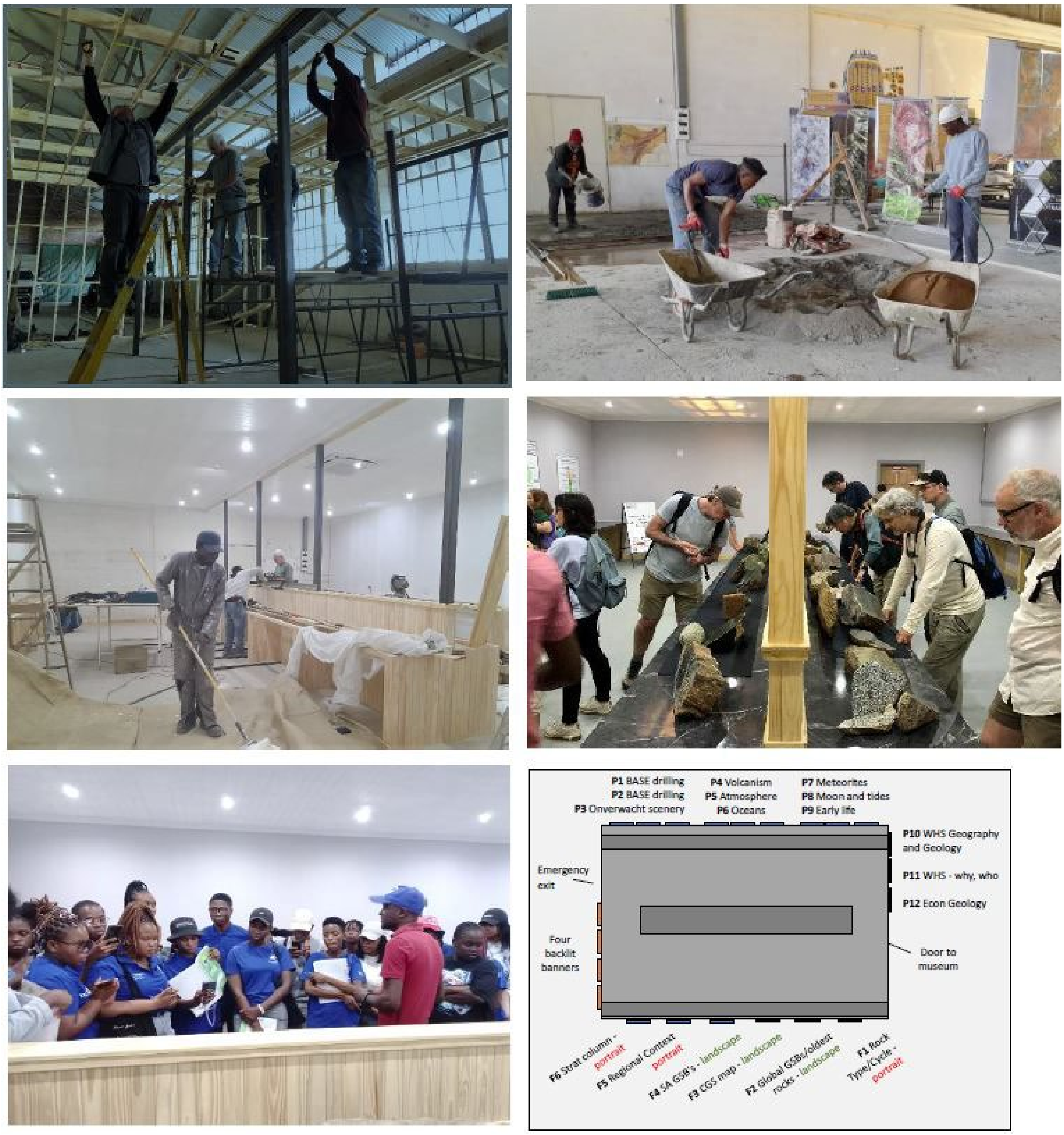


Figure 24: The BASE room – construction, initial use, and layout.

11.2.4. Delegations, VIPs, and Walk-in Visitors

BASE proved popular as a destination for informal and formal delegations. They included the Science Officer of the German Consulate in Pretoria, a delegation of the South African Geological Survey CGS, led by its CEO, a large delegation from the provincial environmental agency MTPA in Nelspruit, the top administrative staff of the University of Mpumalanga, the Emjindini tribal authority and other local traditional leaders, geological field trips from numerous South African (and a Mozambiquan) universities, local civic organizations (Mpumalanga Heritage Society, GSSA Geoheritage Section), and numerous small groups of geoscientists, some affiliated with BASE. We encouraged group visits particularly during February and March 2022 because these groups could easily visit drilling operations at site BASE 2, due to its proximity to and easy access from Barberton, its roadside and scenic location, and the adjacent parking lot. This site was surrounded by a fence, had additional overnight security, sported three informative printed posters (*"drilling not for gold but for knowledge", "taxpayer's money at work",* …) and received, while drilling was ongoing, numerous daily visitors, school classes on guided tours, and official delegations led by members of the onsite geoscience team.

Two sturdy metal signs outside the sliding doors to the BIAS Hall informed casual passers-by about the project and served as informative visual brackets in group photos (Fig. 23). We received numerous individual walk-in visitors, ranging from shoppers to foreign tourist groups passing through Barberton. For them, we had prepared handouts and posters on the fundamental geologic information about Earth evolution, the rock cycle and origin of life, and implications for exploration efforts on other planets. Many visitors, who had previously thought about geosciences only related to rock composition and extractive mining, expressed astonishment about the objectives of BASE.

11.2.5. The BASE annex at the Barberton Regional Museum

Nic Beukes provided a permanent legacy of this project by successfully lobbying for the addition of a room to the adjacent Barberton Museum, to be constructed from CIMERA funds (Fig. 24). This room (windowless for security reasons) was constructed within the BIAS Hall and used the door between the BIAS Hall and the museum as entry. The room measures approximately 14 m long by 7 m wide, is air-conditioned and fully electrified. The display infrastructure is simple and efficient. Walls show posters of the geology of the BGB, the paleoenvironments of early Earth, and the scientific background of the drilling project. A central console displays labelled rock types of the Barberton Greenstone Belt, explained in simple terms.

11.3. EOP Assessment; Outcome

The EOP activity log lists 61 activities between October 27, 2021, and June 28, 2022. They were occasionally strenuous and intense but also attractive to a diverse audience. They served to firmly anchor geoscience research in the local and regional context. Key to its success was the recruitment of local geoscientists who had grown up in the region and the proactive contacting of stakeholders such as school principals, community leaders, and civic organizations.

Our activities were highly successful at the local general, regional educational and institutional, and the international scientific level. The success of the project was recognized by a KLCBT-TUT Provincial Award in the category "Innovation" and by a 2nd place in the UJ Science Faculty Community Engagement Award. We reported on the EOP aspects of BASE in a journal article and on conferences (Mashele et al., 2023).

For the Barberton community, BASE came at an ideal time towards the end of COVID-related restrictions. It was positively received because it communicated the meaning of the nascent World Heritage Site in tangible terms and through a large number of onsite geoscience professionals. Phumelele Mashele was highly effective as a full-time EOP officer. The project also involved a considerable number of locals and their services through whom awareness and recognition spread through the community. Local carpenters, electricians and painters constructed the BASE room in the museum, and local expertise was involved in producing the posters and displays.

12. Subsequent Analyses

A first sampling workshop was conducted at the BGR core repository facilities in Berlin-Spandau September 11-14, 2023; it was attended by 41 scientists. The first morning was spent (re-)familiarizing participants, many of them new PhD students, with the objectives and the data sets; the first cores were inspected in the afternoon. Ample space and favorable weather allowed us to lay out all 503 core boxes in the spacious parking lot. This made for efficient and convenient sampling in the following days (Fig. 25). Participants completed preliminary sample request forms, either after inspecting core photographs beforehand or by hand during core inspection. These data were speedily entered into mDIS and provided the base to print double sets of sample labels (one for the sampling plastic bag, the other for the remaining core). During three days of sampling, three core saws were in constant operation; about 1100 samples were taken. Documentation was entered in the mDIS data bank and is available through the BASE ICDP webpages.

Figure 25: First Sampling Workshop in Spandau, September 11-14, 2023.

13. Conclusions

The project ended slightly under budget because EOP activities had been lower than estimated and because no borehole had drilled beyond 500 m. Drilling took about nine instead of the estimated six months because of frequent rig breakdowns in the first six weeks of operations and due to weather-related delays during an unusually wet summer rainy season. The primary objective, to obtain a significant length of continuous and unweathered core through sections of siliciclastic sedimentary facies changes and pertaining to the surface conditions of early Earth, was fully reached. Surficial weathering reached deeper and fracturing of the rock was higher than predicted. Initial inspection of core and logs did not show evidence of major deviations from predictions but rather confirmed and clarified several assumptions. The project had a high and lasting societal impact.

14. Acknowledgements

The project would have been impossible without the substantial seed funding of ca. 55% of the drilling costs by ICDP which is gratefully acknowledged. It would have been equally impossible to run without the legal, administrative and financial guidance and activities of CIMERA (South Africa's consortium for research drilling) and its staff, led by its former chair, the late Prof. Nic Beukes. ICDP staff in Potsdam provided competent and speedy advice, software and infrastructure. The goodwill and permits by authorities of Barberton, Mbombela Municipality, Mpumalanga Province, the WHS administration, and the local development company BATOBIC are gratefully acknowledged. Landowners, including the Mountainland trust, SAPPI, Barberton Mines, and the Vos Brothers are thanked for allowing access to and drilling on their private land. Many members of the Barberton community, including schools, businesses, and private citizens, provided instant services and were gracious and interested hosts. The BIAS Hall, owned by the Mpumalanga Province Department of Arts, Sports, and Culture, and administered by the Barberton Regional Museum, was a perfect location to combine core processing with outreach activities. Staff of Barberton Community Tourism helped and advised in many day-to-day questions. Astrid Christianson provided professional community hospitality and made sure that all of us found in Barberton a "home from home".

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15. References

Anhaeusser, C.R., 1976, The geology of the Sheba Hills area of the Barberton Mountain Land, South Africa, with particular reference to the Eureka Syncline. Transactions of the Geological Society of South Africa 79, 253-280. URL: https://journals.co.za/doi/pdf/10.10520/AJA10120750_2866

Anhaeusser, C.R., 1984, Structural elements of Archaean granite- greenstone terranes as exemplified by the Barberton Mountain Land, southern Africa. In: A. Kröner and R. Greiling (eds.), Precambrian Tectonics Illustrated. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 57-78.

Anhaeusser, C.R., 2014, Archaean greenstone belts and associated granitic rocks - A review. Journal of African Earth Sci-ences 100, 684-732. https://doi.org/10.1016/j.jafrearsci.2014.07.019

Anhaeusser, C.R., L. J. Robb and M.J. Viljoen, 1981, Provisional geological map of the Barberton greenstone belt and surrounding granitic terrane, eastern Transvaal and Swaziland scale 1:250000. Geological Society of South Africa.

Arndt, N., P. Mason, M. Bau, A. Wilson, A. Hofmann, and G. Byerly, 2009, Peering into the Cradle of Life: Scientific Drilling in the Barberton Greenstone Belt, South Africa. ICDP Proposal, unpublished.

Bender, J., 2023, Stratigraphie und Petrographie der Moodies-Gruppe in der Saddleback Synklinale, Barberton Grüns-teingürtel. BSc thesis (unpublished), Friedrich-Schiller-Universität Jena, 51 p.

Burley, A. J., Evans, R. B., Gillingham, J. M. and Masson Smith, D., 1970, Gravity anomalies in Swaziland: Bulletin of the Geological Survey Swaziland, 7, 4-16.

Darracott, B.W., 1975, The interpretation of the gravity-anomaly over the Barberton Mountain Land, South Africa: Transactions of the Geological Society of South Africa, 78, 123-128. URL: https://journals.co.za/doi/pdf/10.10520/AJA10120750_1219

De Beer, J., and E. Stettler, 2009, Geophysics and the deep structure of the Barberton Belt: a review. 11th SAGA Biennial Technical Meeting and Exhibition, Swaziland, 16-18 Sept. 2009, 2-6. https://doi.org/10.3997/2214-4609-pdb.241.debeer_paper1

de Beer, J.H., E.H. Stettler, J.G. du Plessis, and J. Blume, 1988, The deep structure of the Barberton Greenstone Belt. South African Journal of Geology, 91, 184-197. URL: https://journals.co.za/doi/pdf/10.10520/AJA10120750_1020

De Wit, M. J., de Ronde, C. E., Tredoux, M., Roering, C., Hart, R. J., Armstrong, R. A., Green, R. W. E., Peberdy, E. and Hart, R. A., 1992, Formation of an Archaean continent. Nature, 357, 553. https://doi.org/10.1038/357553a0

Eriksson, K.A., 1979. Marginal marine depositional processes from the Archaean Moodies Group, Barberton Mountain Land, South Africa: Evidence and significance. Precambrian Research, 8, 153-182. https://doi.org/10.1016/0301-9268(79)90027-5

Eriksson, K.A., Simpson, E.L., and Mueller, W., 2006. An unusual fluvial to tidal transition in the meso-Archaean Moodies Group, South Africa: A response to high tidal range and active tectonics. Sedimentary Geology 190, 13-24. https://doi.org/10.1016/j.sedgeo.2006.05.011

Eulenfeld, T., and Heubeck, C., 2023, Constraints on Moon's orbit 3.2 billion years ago from tidal bundle data. Journal of Geophysical Research: Planets, 128, e2022JE007466. https://doi.org/10.1029/2022JE007466 https://doi.org/10.1029/2022JE007466

Hessler, A.M., and Lowe, D.R., 2006, Weathering and sediment generation in the Archaean: An integrated study of the evolution of siliciclastic sedimentary rocks of the 3.2 Ga Moodies Group, Barberton Greenstone Belt, South Africa. Precambrian Research 151, 185-210. https://doi.org/10.1016/j.precamres.2006.08.008

Hessler, A.M., Lowe, D.R., Jones, R.L., and Bird, D.K., 2004, A lower limit for atmospheric carbon dioxide levels 3.2 billion years ago. Nature 428, 736-738. https://doi.org/10.1038/nature02471

Heubeck, C., 2019, The Moodies Group - A high-resolution archive of Archaean surface and basin-forming processes; in: A. Kröner and A. Hofmann (eds.), The Archaean Geology of the Kaapvaal Craton, Southern Africa. Springer (Regional Geology Reviews), pp. 203-241. https://doi.org/10.1007/978-3-319-78652-0_6

Heubeck, C. 2022, In welchen Umgebungen und unter welchen Bedingungen entwickelte sich Leben auf der frühen Erde? In: GMIT (Geowissenschaftliche Mitteilungen), June 2022, p. 22-23. https://doi.org/10.23689/fidgeo-5423

Heubeck, C., and Lowe, D.R., 1994a, Depositional and Tectonic Setting of the Archean Moodies Group, Barberton Greenstone Belt, South Africa: Precambrian Research 68, 257-290. https://doi.org/10.1016/0301-9268(94)90033-7

Heubeck, C., and Lowe, D.R., 1994b, Late Syndepositional Deformation and Detachment Tectonics in the Barberton Greenstone Belt, South Africa: Tectonics 13, 1514-1536. https://doi.org/10.1029/94TC01809

Heubeck, C., J. Engelhardt, G.R. Byerly, A. Zeh, B. Sell, T. Luber, and D.R. Lowe, 2013, Timing of deposition and deformation of the Moodies Group (Barberton Greenstone Belt, South Africa): Very-high-resolution of Archaean surface processes: Precambrian Research 231, 236- 262. https://doi.org/10.1016/j.precamres.2013.03.021

Heubeck, C., S. Bläsing, N. Drabon, M. Grund, M. Homann and S. Nabhan, 2016, Geological constraints on Archean (3.22 Ga) coastal-zone processes from the Dycedale Syncline, Barberton Greenstone Belt: South African Journal of Geology 119, 495-518. https://doi.org/10.2113/gssajg.119.3.495

Heubeck, C., Beukes, N., and the BASE Onsite Geoscience Team (Dora Paprika, Phumelele Mashele, Chris Rippon, Ryan Tucker, Rodney Tucker, Tony Ferrar, Astrid Christianson), 2022a, ICDP research drilling in the Moodies Group of the Barber-ton Greenstone Belt is underway. Geol. Soc. South Africa Newsletter March 2022, p. 18-21.

Heubeck, C., N. Drabon, G. Byerly, I. Leisgang, U. Linnemann, D.R. Lowe, R. Merz, A. Gonzalez-Pinzon, T. Thomsen, A. Zeh, Y. Rojas Agramonte, and A. Kröner, 2022b, Constraints by detrital zircons on the provenance of the Archean Moodies Group, Barberton Greenstone Belt, South Africa and Eswatini. American Journal of Science. https://doi.org/10.2475/02.2022.01

Heubeck, C., Reimann, S., and Homann, M., 2023, Stromatolite-like Structures Within Microbially Laminated Sandstones of the Paleoarchean Moodies Group, Barberton Greenstone Belt, South Africa. Astrobiology 23(9); https://doi.org/10.1089/ast.2023.0014

Homann, M., C. Heubeck, A. Airo, and M.M. Tice, 2015, Morphological adaptations of 3.22 Ga-old microbial communities to Archean coastal habitats (Moodies Group, Barberton Greenstone Belt, South Africa): Precambrian Research 266, 47-64. https://doi.org/10.1016/j.precamres.2015.04.018

Homann, M., C. Heubeck, T.R.R. Bontognali, A.-S. Bouvier, L.P. Baumgartner, and A. Airo, 2016, Evidence for cavity-dwelling microbial life in 3.22 Ga tidal deposits: Geology 44, 51-54. https://doi.org/10.1130/G37272.1

Homann, M., Sansjofre, P., Van Zuilen, M., Heubeck, C., Gong, J., Killingsworth, B., Foster, I. S., Airo, A., Van Kranendonk, M. J., Ader, M., and Lalonde, S.V., 2018, Microbial life and biogeochemical cycling on land 3,220 million years ago. Nature Geoscience 11, 665-671. https://doi.org/10.1038/s41561-018-0190-9

Hose, L.D., 1990. The Geology and Stratigraphic Evolution of the North-Central Part of the Barberton Greenstone Belt, South Africa. PhD dissertation, Louisiana State University, 382 p. URL: https://repository.lsu.edu/gradschool_disstheses/4922

Janse van Rensburg, D., Heubeck, C., and Reimann, S., 2021, Volcanoes in the estuaries: Insights into earth's oldest (3.22 Ga) terrestrial microbial habitats, Moodies Group, Barberton Greenstone Belt. Research 365, 106325. https://doi.org/10.1016/j.precamres.2021.106325

Javaux, E.J., Marshall, C.P., and Bekker, A., 2010, Organic-walled microfossils in 3.2-billion-year-old shallow-marine si-liciclastic deposits. Nature 463, 709-840. https://doi.org/10.1038/nature08793

Kütter, S., U. Weckmann, and M.J. de Wit, 2016, A deep electrical conductivity structure of the southern Barberton Greenstone Belt, South Africa, derived from magnetotelluric measurements. South African Journal of Geology, 119, 273-290. https://doi.org/10.2113/gssajg.119.1.273

Lippold, W., 2011, Geological map of the upper Moodies Group, Saddleback Syncline, Barberton Greenstone Belt, South Africa. Project Report (unpublished), Freie Universität Berlin.

Lowe, D.R., and Byerly, G.R., 2007. An overview of the geology of the Barberton Greenstone Belt and vicinity: Implications for early crustal development, in: van Kranendonk, M.J., Smithies, R.H., Bennett, V.H.(Eds.), Earth's Oldest Rocks. Elsevier (Developments in Precambrian Geology) 15, 481-526. https://doi.org/10.1016/S0166-2635(07)15053-2

Lowe, D.R., Byerly, G.R., and Heubeck, C., 1999. Structural divisions and development of the west-central part of the Barberton Greenstone Belt, in: D.R. Lowe and G.R. Byerly (Eds.), Geologic Evolution of the Barberton Greenstone Belt, South Africa. Geological Society of America Special Paper 329, 37-82. https://doi.org/10.1130/0-8137-2329-9.37

Lowe, D.R., Byerly, G.R., and Heubeck, C., 2012, Geologic Map of the west-central Barberton Greenstone Belt. In: South Africa, scale 1:25,000: Geological Society of America Map and Chart Series No. 103.

Luber, T., 2014, Archaean Geology of the east-central Stolzburg Syncline, Barberton Greenstone Belt, South Africa. MSc thesis (unpublished), Freie Universität Berlin.

MacAlauy, D., 1987, Lithologic-structural sketch drawings of the Lomati Water tunnel walls. Unpublished. Scanned, obtainable through C. Heubeck.

Mashele, N., Heubeck, C., Geoscience Team, BASE Onsite; Christianson, A., 2023, Drilling in a World Heritage Site. Conference abstract, Annual Meeting Deutsche Geologische Gesellschaft, Berlin, 467.

Nabhan, S., M. Wiedenbeck, R. Milke, and C. Heubeck, 2016a, Biogenic overgrowth on detrital pyrite in 3.2 Ga Archean paleosols. Geology 44, 763-766. https://doi.org/10.1130/G38090.1

Nabhan, S., T. Luber, F. Scheffler, and C. Heubeck, 2016b, Climatic and geochemical implications of Archean pedogenic gypsum in the Moodies Group (~3.2 Ga), Barberton Greenstone Belt, South Africa: Precambrian Research 275, 119-134. https://doi.org/10.1016/j.precamres.2016.01.011

Nakajima, R., Y. Ohmoto, T. Otake, T. Kakegawa, and T. Sato, 2016, Biosignatures recorded in geochemical correlations between organic matter and Fe-bearing minerals in 3.2Ga banded iron formations, Barberton Greenstone Belt, South Africa. Goldschmidt Conference 2016 (Yokohama), Abstract Volume, 2217.

Noffke, N., Eriksson, K.A., Hazen, R.M. and Simpson, E.L., 2006, A new window into Early Archaean life: Microbial mats in Earth's oldest siliciclastic tidal deposits (3.2 Ga Moodies Group, South Africa). Geology 34, 253-256. https://doi.org/10.1130/G22246.1

Nwaila, G., and H. Frimmel, 2019, Highly siderophile elements in Archaean and Palaeoproterozoic marine shales of the Kaapvaal Craton, South Africa. Mineralogy and Petrology. https://doi.org/10.1007/s00710-018-0650-3 https://doi.org/10.1007/s00710-018-0650-3

Reimann, S., Heubeck, C., Janse van Rensburg, D.J., Fugmann, P., Serre, S. H., Thomsen, T.B., Zametzer, A., 2021, Syndepositional hydrothermalism selectively preserves records of one of the earliest benthic ecosystems, Moodies Group (3.22 Ga), Barberton Greenstone Belt, South Africa: South African Journal of Geology 124, 253-278. https://doi.org/10.25131/sajg.124.0012

Seifert, F., 2023, Oberflächen- zu Untertagekorrelation der archaischen Moodies-Gruppe, Moodies Hills Block, Barberton Grünsteingürtel. -BSc. Thesis (unpublished), Friedrich-Schiller-Universität Jena, 26 p.

Simpson, E.L., Eriksson, K.A., and Mueller, W., 2012, 3.2 Ga eolian deposits from the Moodies Group, Barberton Greenstone Belt, South Africa: Implications for the origin of first-cycle quartz sandstones. Precambrian Research 214/215, 185-191. https://doi.org/10.1016/j.precamres.2012.01.019

Stutenbecker, L., Heubeck, C., and Zeh, A., 2019, The Lomati Delta Complex: A prograding tidal delta in the Archean Moodies Group, Barberton Greenstone Belt. Journal of South African Geology 122, doi:10.25131/sajg.122.0002. https://doi.org/10.25131/sajg.122.0002

Toulkeridis, T., Clauer, N., Kröner, A. and Todt, W., 2015, A Mineralogical, Chemical and Isotopic Investigation of Shales from the Barberton Greenstone Belt, South Africa, To Constrain Source Materials and Post-Deposition Evolution. South African Journal of Geology 118, 389-410. https://doi.org/10.2113/gssajg.118.4.389

van Wyk, B.C., 1985, Lomati Tunnel. Geotechnical investigation for the Barberton Town Council. Volume 1: Report; cross sections. 86 p, unpublished.

Viljoen, M.J., and Viljoen, R.P., 1969a, An introduction to the geology of the Barberton granite-greenstone terrain. Special Publication, Geological Society of South Africa 2, 9-28.

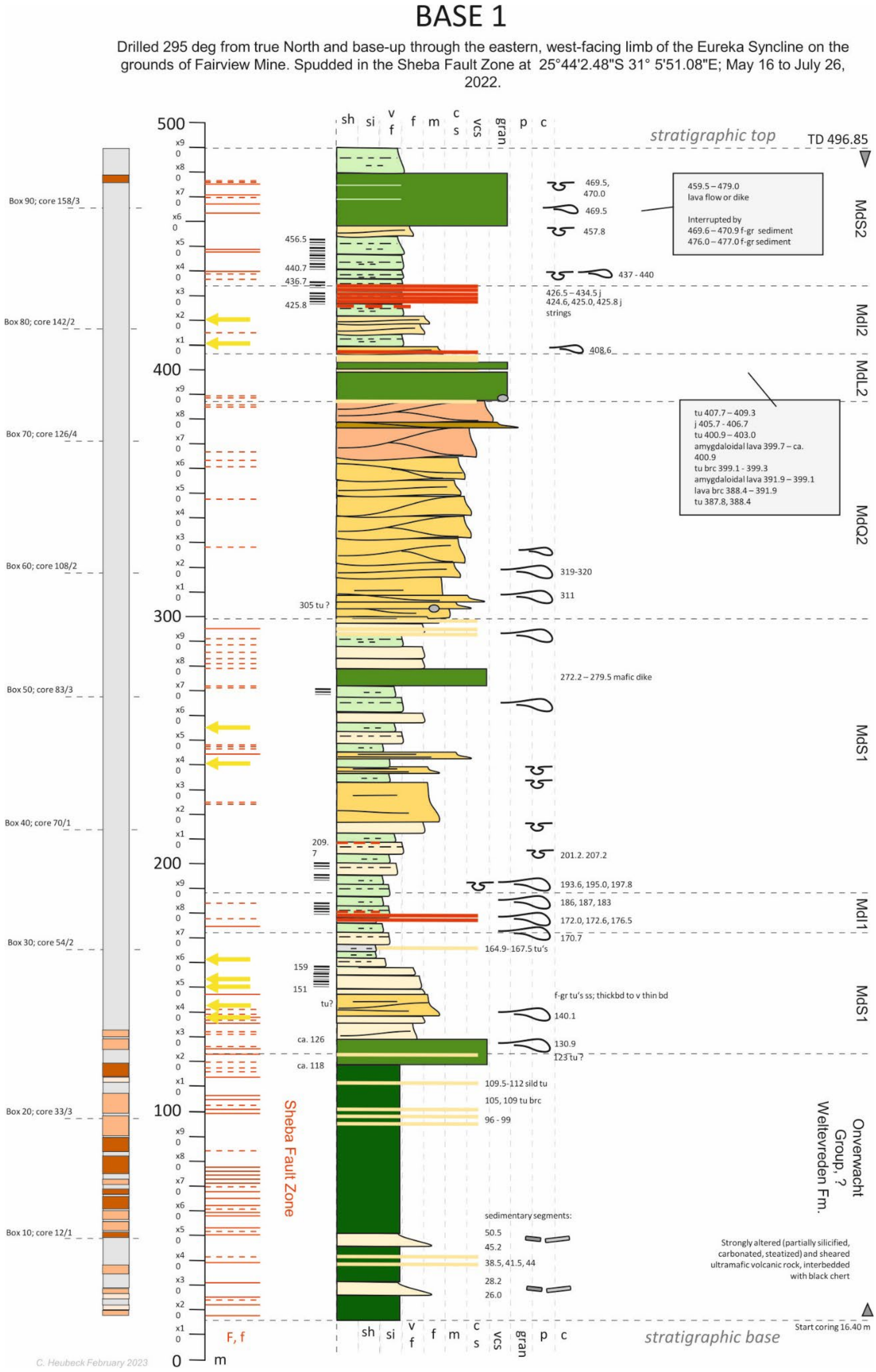
Viljoen, M.J., and Viljoen, R.P., 1969b, The geology and geochemistry of the lower ultramafic unit of the Onverwacht Group and a proposed new class of igneous rocks. Special Publication, Geological Society of South Africa 2, 55-85.

Viljoen, R.P., and Viljoen, M.J., 1969c, The geological and geochemical significance of the upper formations of the Onverwacht Group. Special Publication, Geological Society of South Africa 2, 113-151.

Voosen, P., 2022, Earth's oldest land ecosystem spotted in drilled cores. Science 376 (6590), p.228-229. https://doi.org/10.1126/science.abq4274

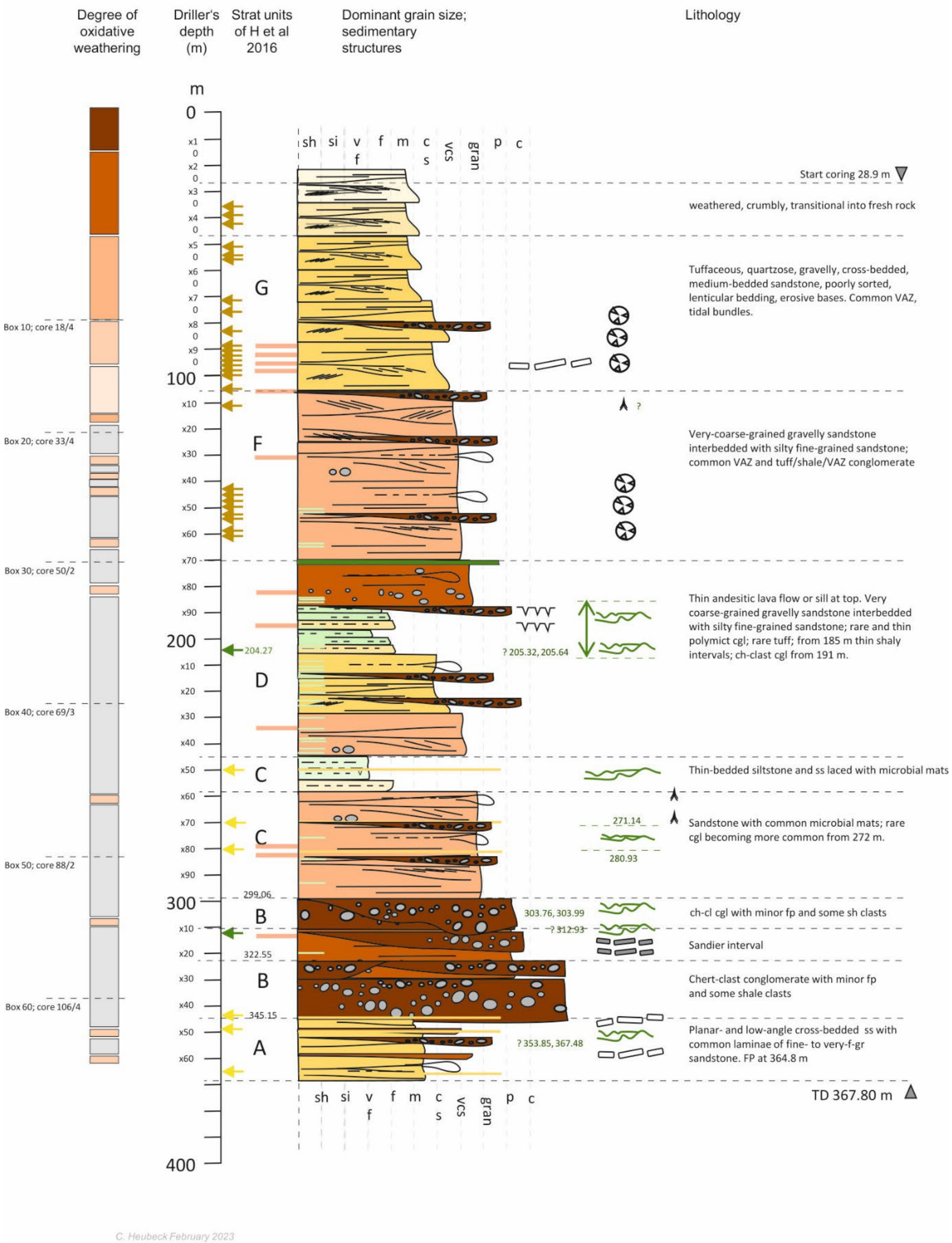
1. Appendices

Appendix A – Preliminary Stratigraphic Columns



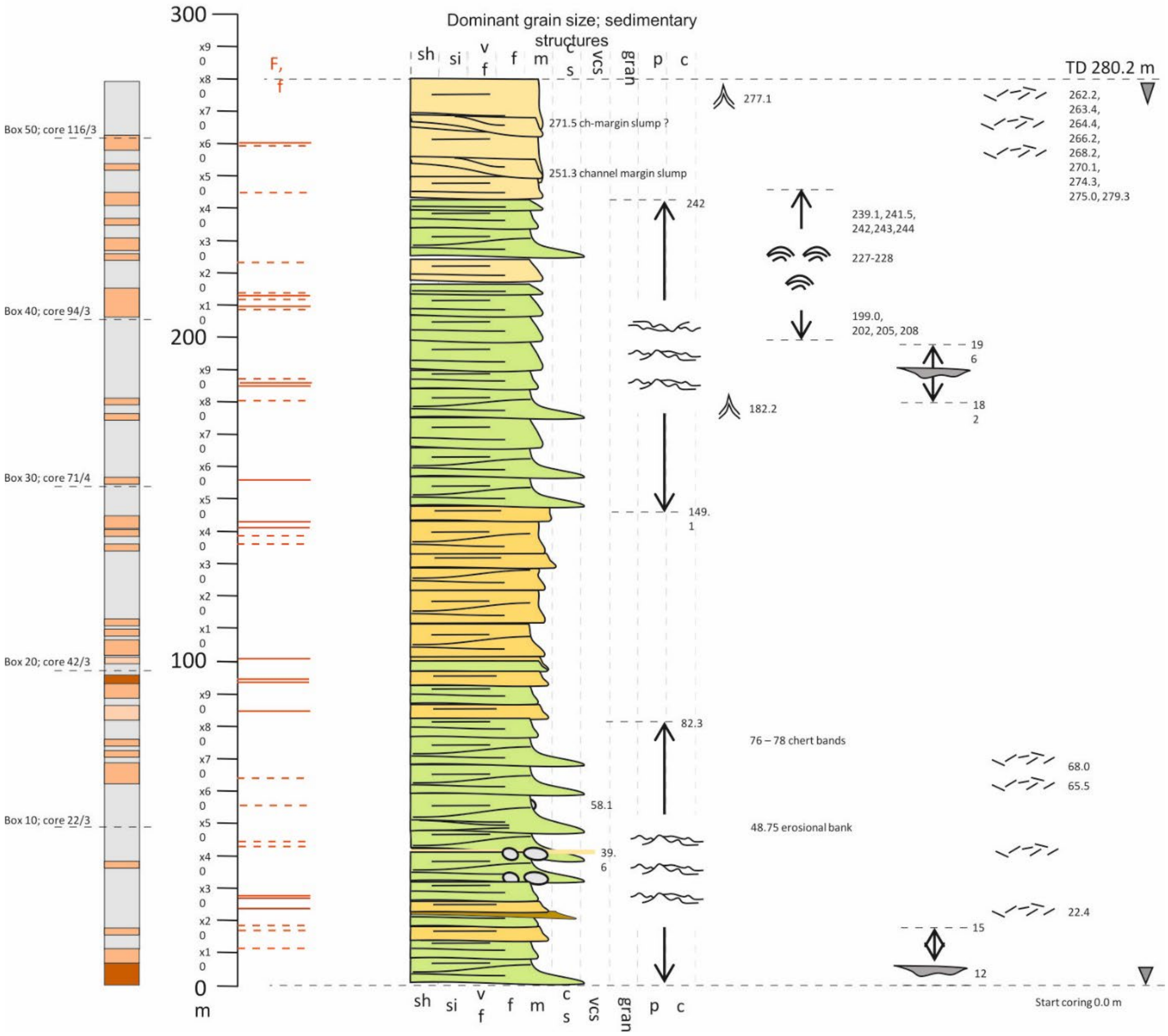
BASE 2

Drilled top down, 313 deg from True North on the southeast-dipping limb of Dycedale Syncline. The borehole spudded just north of the R40 Geotrail „*Tidal Sandstone*" parking lot (-25.793817°, 31.083763°). February 3 to March 15, 2022.



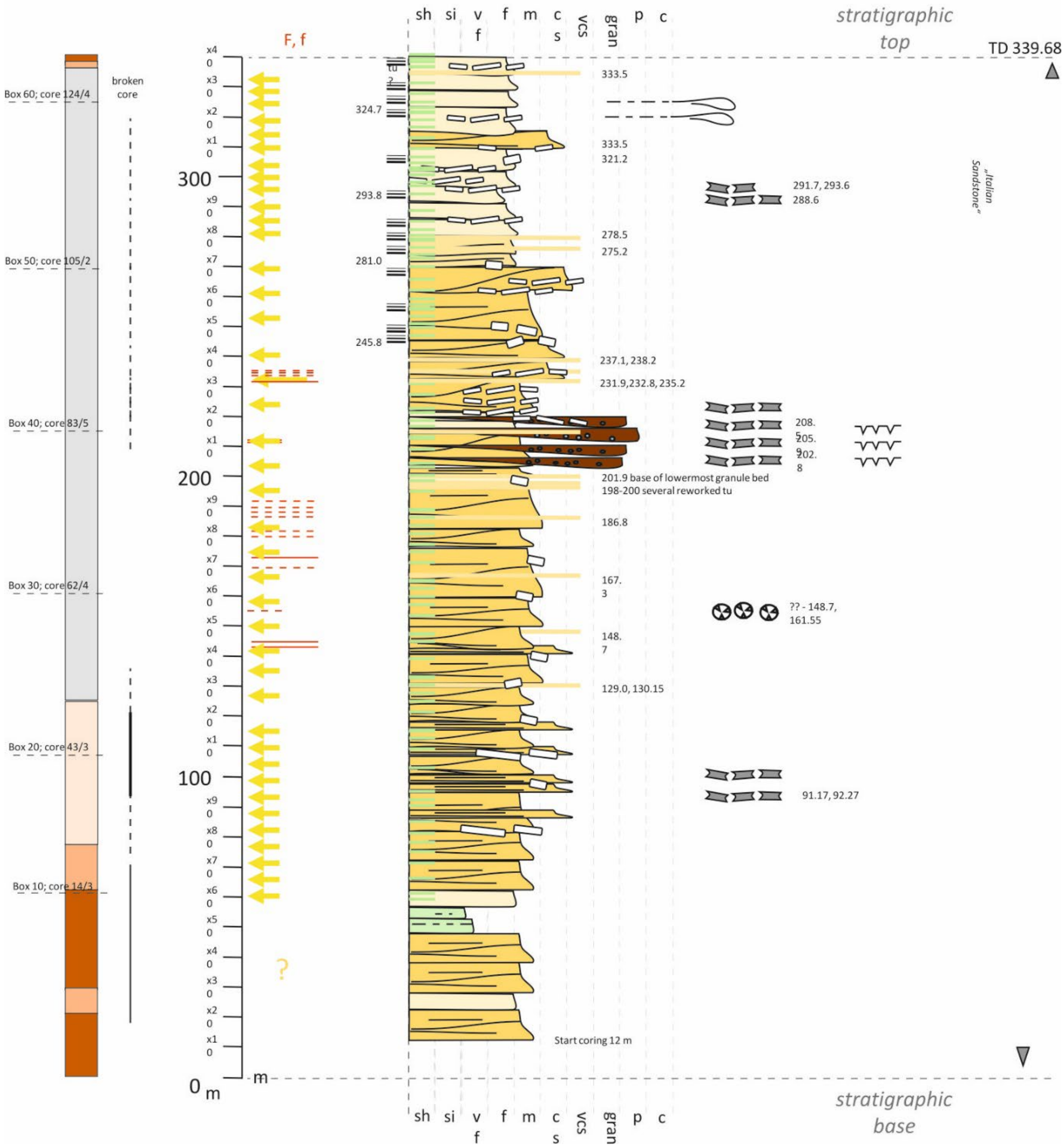
BASE 3

Drilled 319 deg from True North and base-up on the south-dipping southern limb of the NE-SW trending Saddleback Syncline. The borehole spudded at 25°49'48.39"S 31° 5'26.88"E; Nov. 25 to Jan. 26, 2022.



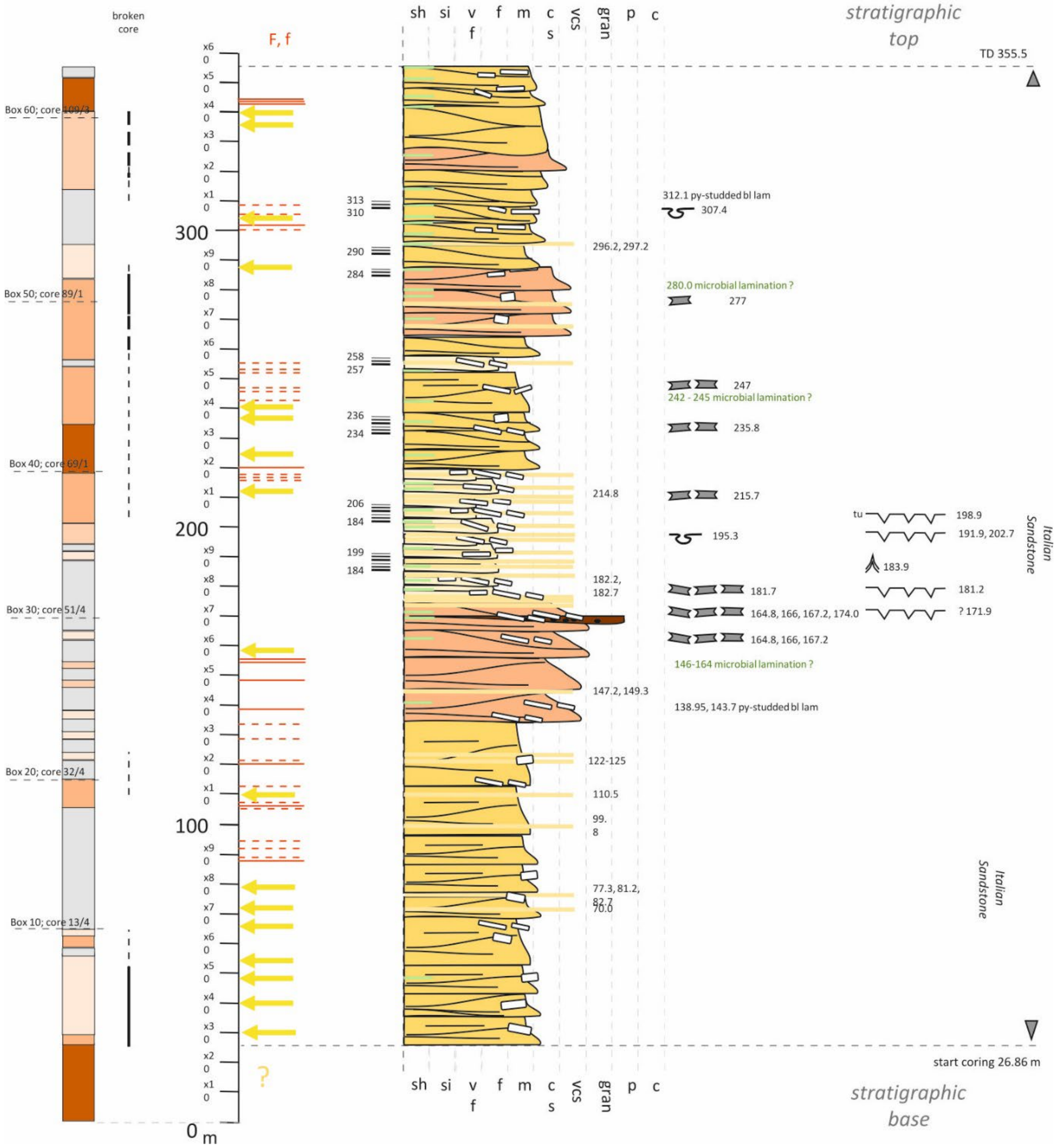
BASE 4A

Drilled toward 319 deg from True North and base-up through the overturned southern limb of the Saddleback Syncline. The borehole spudded at 25°44'2.48"S 31° 5'51.08"E; Nov. 17, 2021 to Jan. 26, 2022.



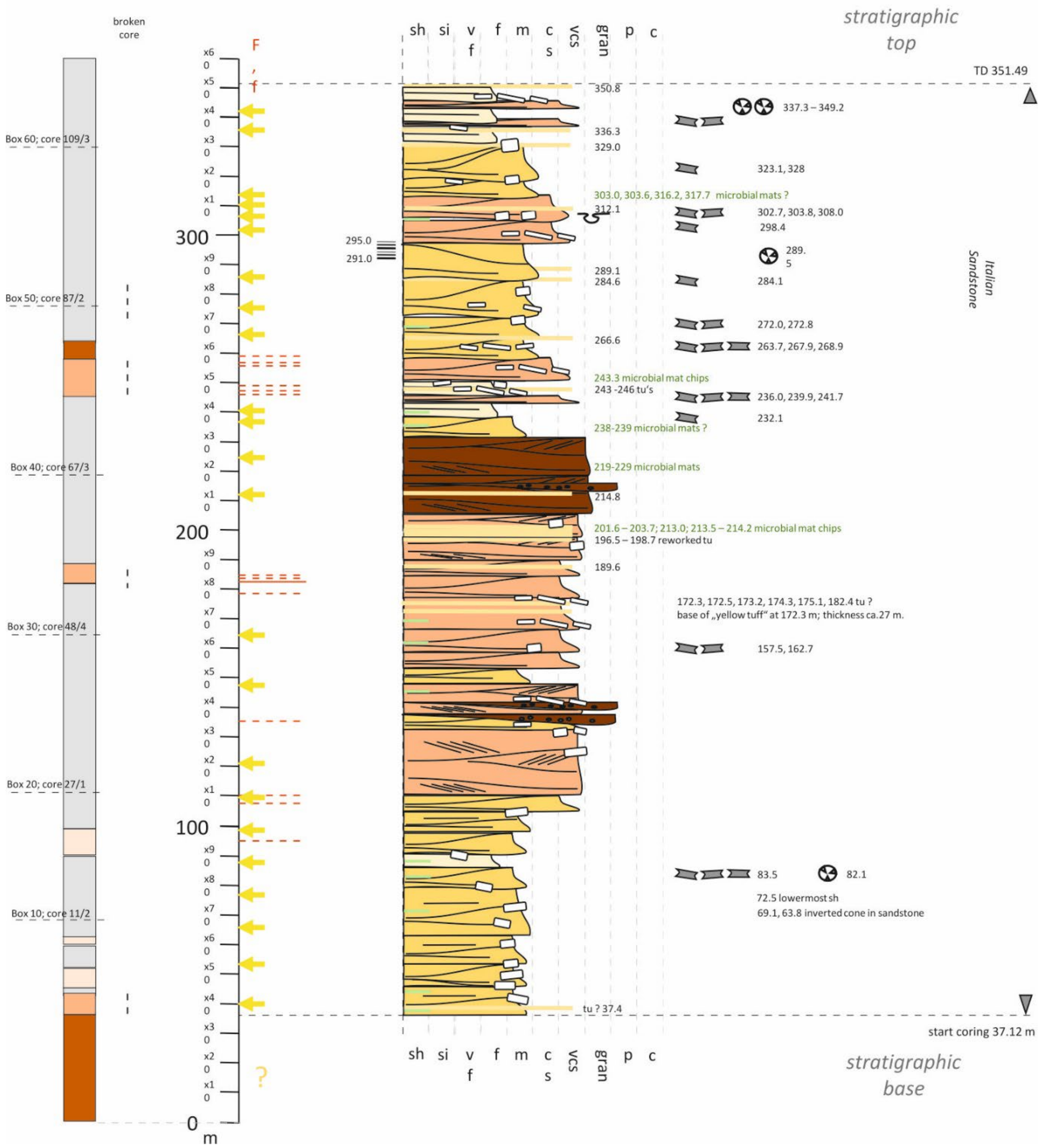
BASE 4B

Drilled towards 336 deg from True North and base-up through the overturned southern limb of the Saddleback Syncline. The borehole spudded at 25°51'11.77"S 31° 2'54.81"E; Feb. 9 to March 23, 2022.



BASE 4C

Drilled towards 336 deg from True North and base-up through the overturned southern limb of the Saddleback Syncline. The borehole spudded at 25°51'39.38"S 31° 2'3.41"E; Feb. 11 to April 22, 2022.



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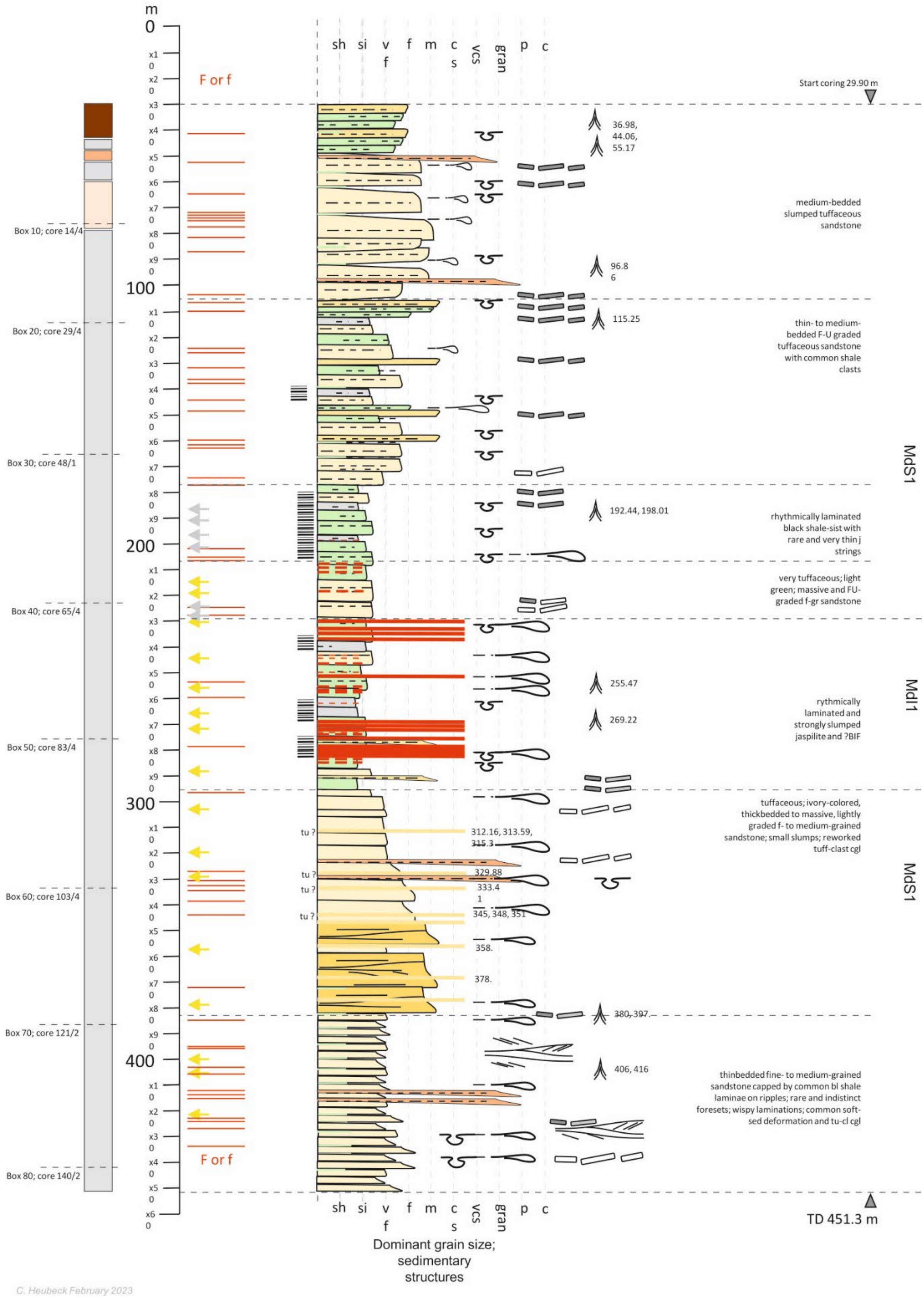
BASE 5A

Drilled northward (009°) and top-down on the south-dipping northern limb of the E-W trending Stolzburg Syncline. Spudding 25°54'13.32"S 30°50'44.68"E; April 5 to May 18, 2022.



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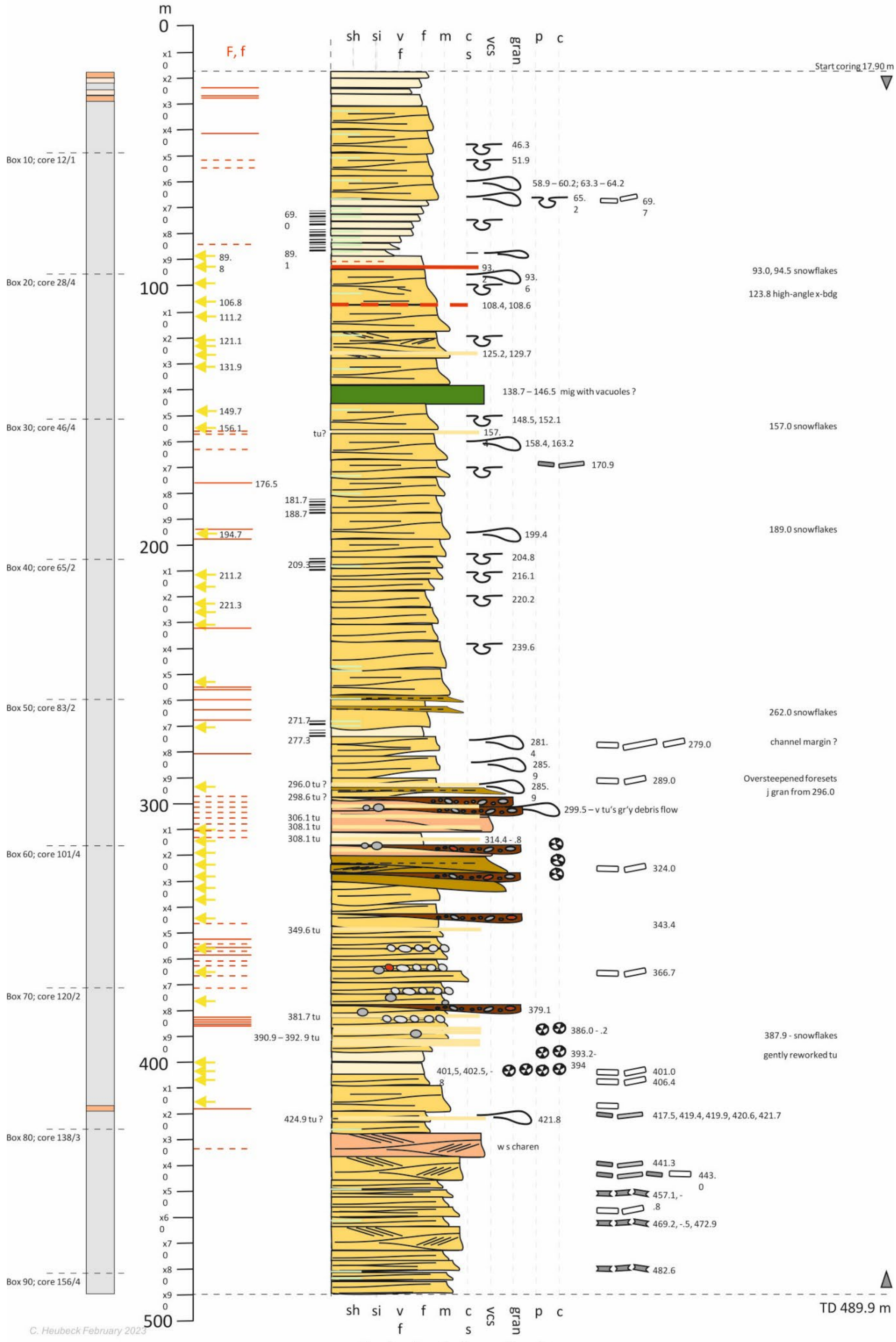
BASE 5B

Drilled northward (013°) and top-down on the south-dipping northern limb of the E-W trending Stolzburg Syncline. The borehole spudded at 25°54'2.80"S 30°50'49.06"E; June 3 to July 17, 2022.



Dominant grain size; sedimentary structures

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Legend

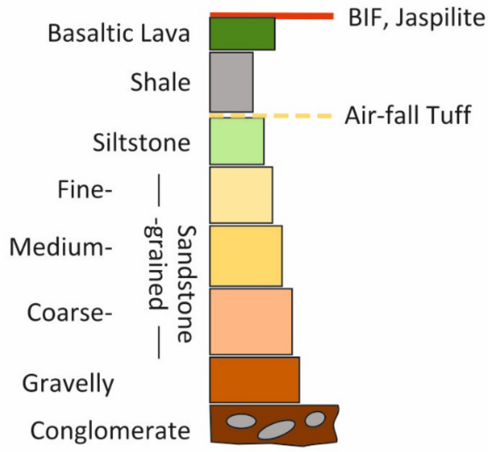
Sedimentary Structures

- carbonate microstromatolites
- well-developed rhythmic bedding
- ball-and-pillow structure
- cross-bedding
- rippled surfaces, low-angle cross-bedding
- upper plane bed horizontal bedding
- lamination in shale or siltstone
- mudcracks
- gravel string; isolated pebble / cobble
- concretions, largely silicified
- rip-up clasts; (nearly) in place
- tuff clasts (bed; common; rare)
- shale clasts
- slump, distorted bedding
- bedding-parallel chert veins
- microbial laminae and mats
- flame (fluid-escape) structure
- microbial-chip conglomerate

Points / laminae / single clasts

- Fault or shear zone
- Fracture; fracture zone
- Shale lamina
- Concretion
- Microbial mat
- Tuffaceous sediment

Dominant grain size



Degree of oxic alteration

- pervasive, complete, soil
- very high; crumbly, widespread
- high, friable, common
- moderate, local
- slight, rare, thin, local,
- none noticeable

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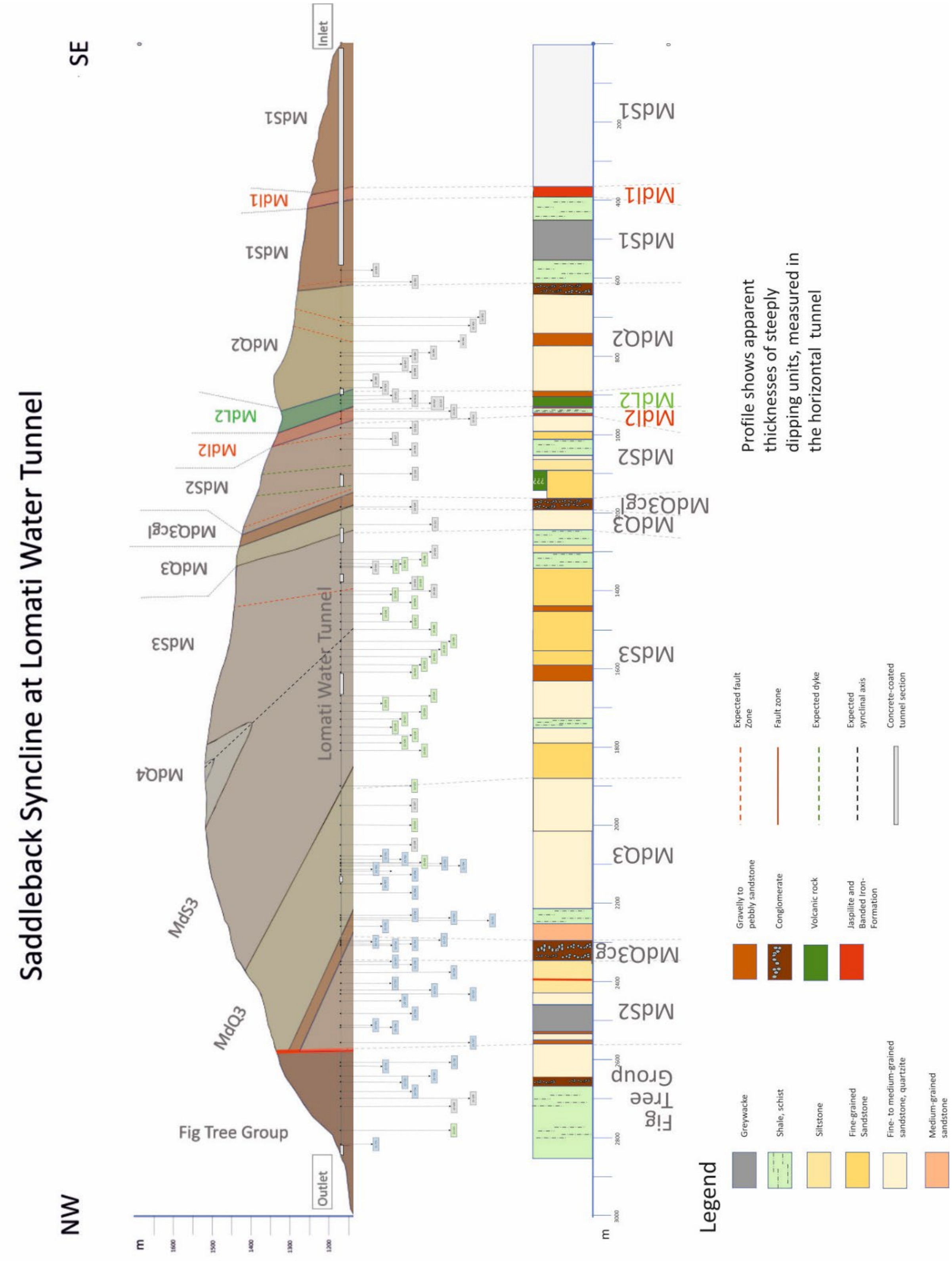
Appendix B – Geologic cross section of the Lomati water tunnel showing lithologies and sampling locations (Bender, 2023)



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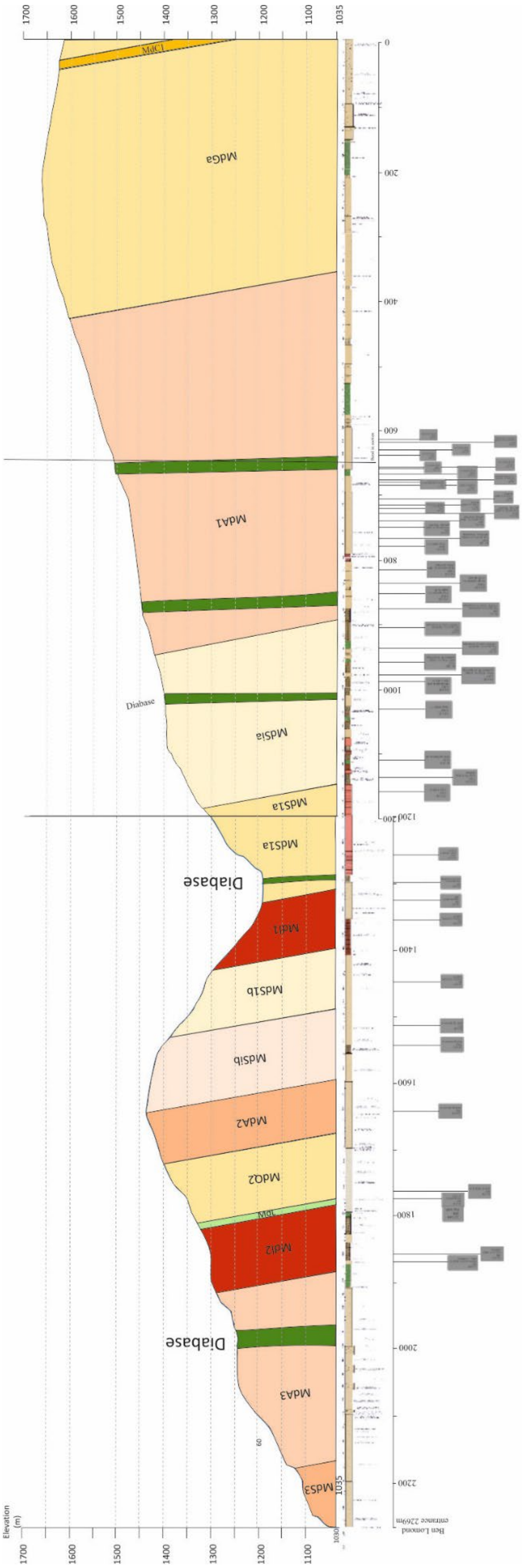
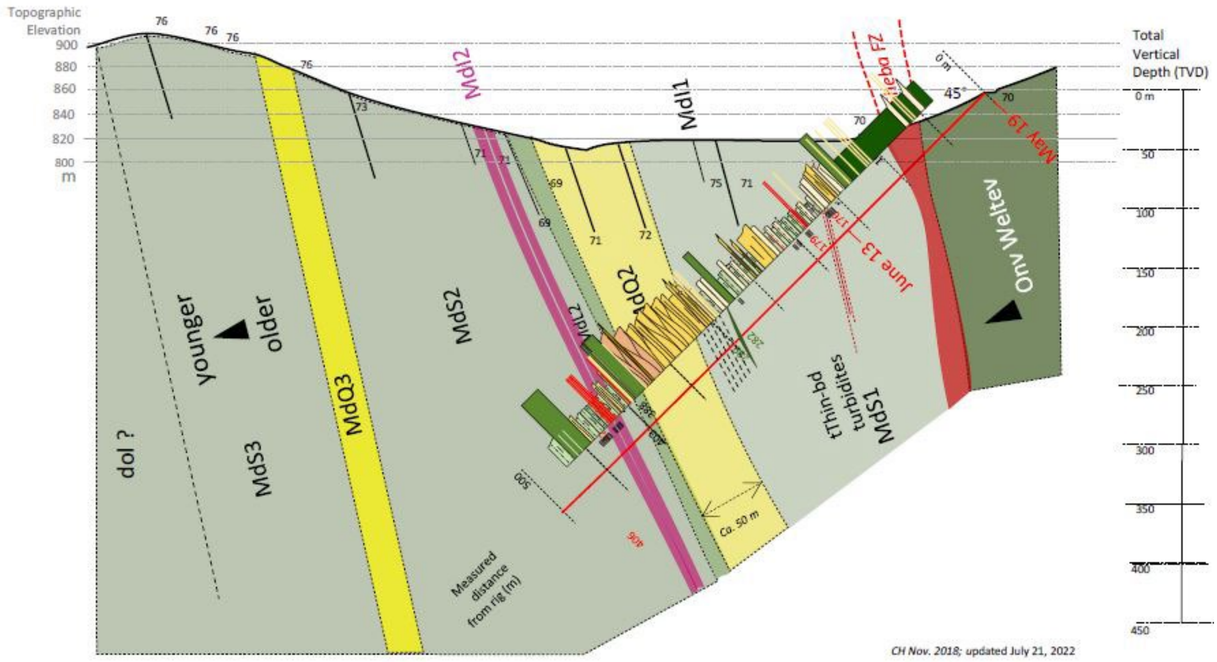
Appendix C - Cross sections, Ben Lomond tunnel of Agnes Mine (Seifert, 2023), showing sampling locations.

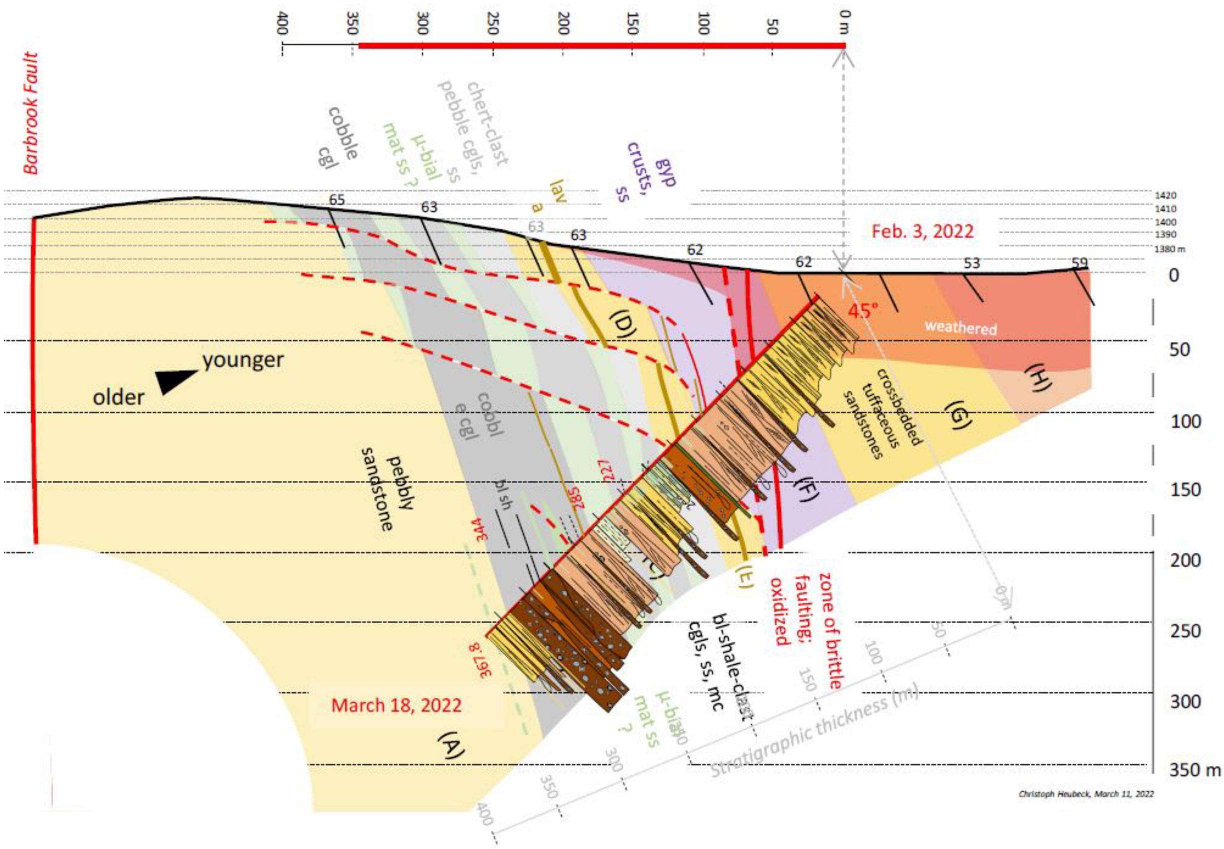


Appendix D – Geological Cross Sections

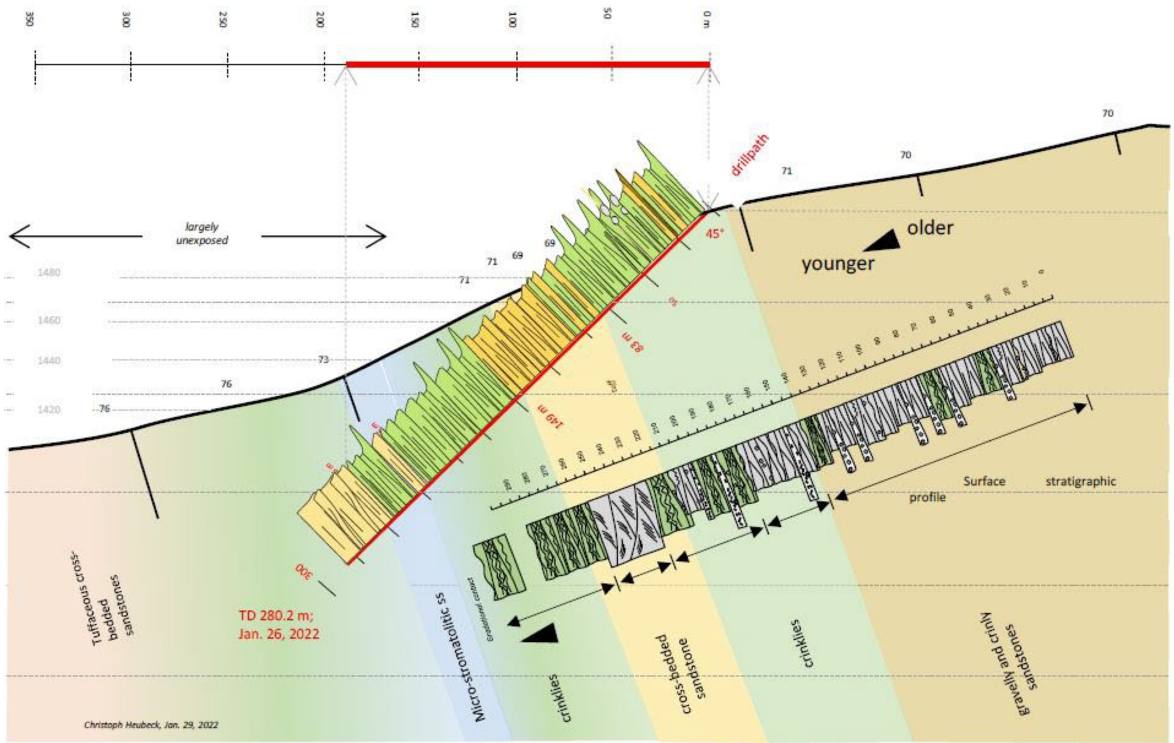
Post-drill geological cross section, Site 1
(Fairview Mine, Eureka Syncline)

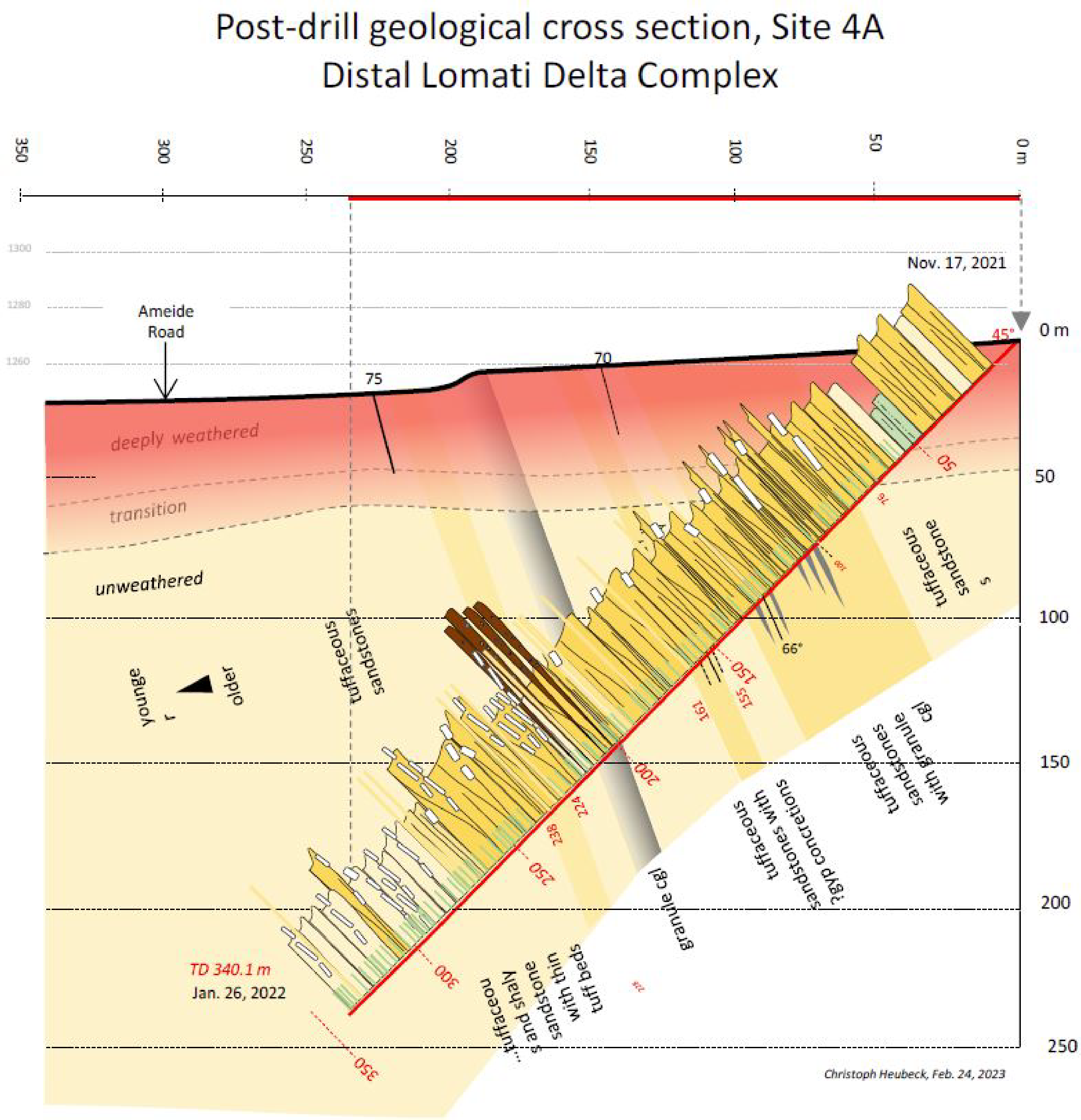


Post-drill geological cross section, BASE 2
(Dycedale Syncline)

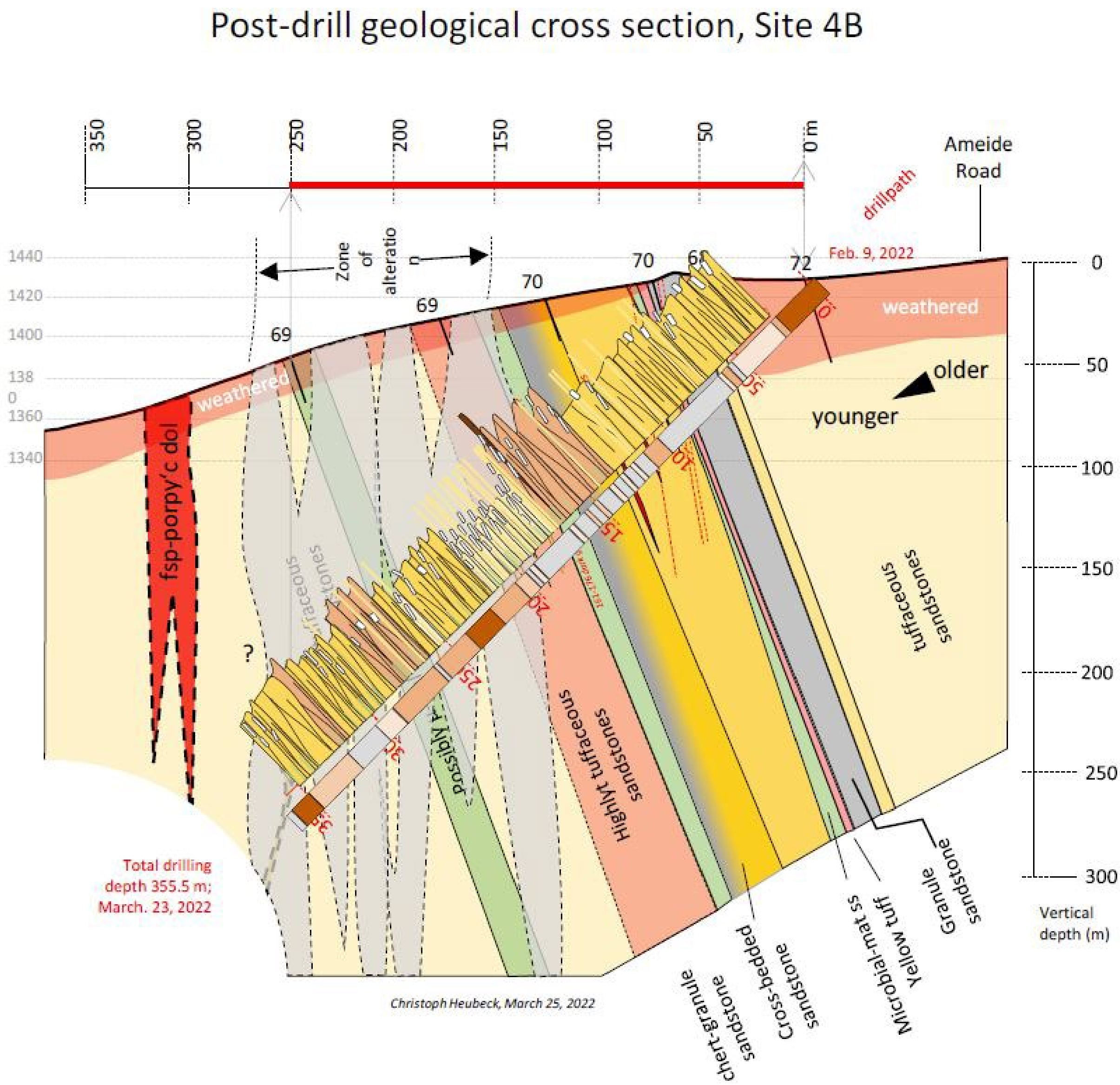


Post-drill geological cross section, Site 3
(MdQ1 of Saddleback Syncline, Farm Oosterbeek)

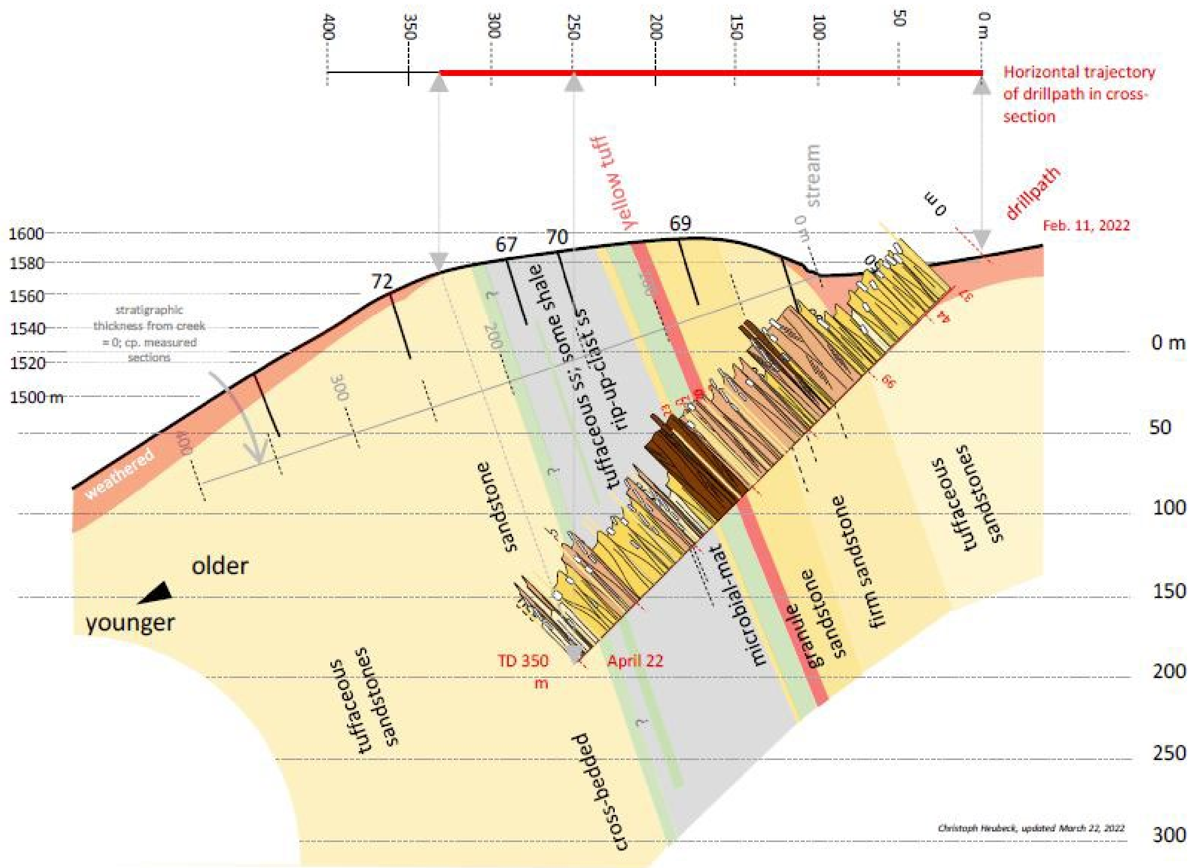



Post-drill geological cross section, Site 4A
Distal Lomati Delta Complex
Nov. 17, 2021
Ameide Road
deeply weathered
transition
unweathered
tuffaceous sandstones
tuffaceous sandstone
tuffaceous sandstones with granule cgl
tuffaceous sandstones with ¿gyp concretions
granule cgl
tuffaceous and shaly sandstone with thin tuff beds
TD 340.1 m
Jan. 26, 2022
younger
older
0 m
50
100
150
200
250
Christoph Heubeck, Feb. 24, 2023

INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM



Post-drill geological cross section ,Site 4C
Proximal Lomati Delta Complex



Post-drill geological cross section, Sites 5 A and B
(eastern Stolzburg Syncline)