GROUNDWATER EXPLORATION

The challenges and rewards of deep groundwater exploration

A new study funded by the Water Research Commission (WRC) offers groundbreaking insights into deep groundwater systems within the Bushveld Igneous Complex. It is one of the most detailed hydrogeological investigations conducted on deep fractured aquifers in South Africa. Petro Kotzé reports.

Amy Allwright

Drill rods to be used at the rig became progressively smaller, the deeper the drill team went down the igneous rock.

Deep groundwater remains an unexplored resource in South Africa and globally. Deep aquifer systems are expensive to explore, and those that do, like mines, are more interested in generating geological than hydrogeological data. As a result, we don't know what potential water resources lie down there – either for residential, agricultural, or industrial use, or even space for more controversial uses, such as storing carbon to offset the impacts of climate change.

A WRC-funded study aimed to shed new light on deep groundwater systems in one of South Africa's most geologically significant formations — the Bushveld Igneous Complex (BC). Conducted in collaboration with the International Continental Scientific Drilling Programme (ICDP)-funded Bushveld Complex Drilling Project (BVDP), this research is leading to significant advances in understanding groundwater flow, chemistry, and structure in deep, fractured aquifers hosted in crystalline rock.

The knowledge was hard to come by, and specifics will take time to unravel, but the results are already raising questions about what we thought we knew and how these unexplored places should be responsibly used in the future.

Drilling into the BIC

The Bushveld Igneous Complex is a large layered igneous intrusion within the Earth's crust, which has been tilted and eroded and now outcrops around what appears to be the edge of a great geological basin. The vast and ancient geological formation spans 65 000 km^2 across the provinces of Limpopo, Mpumalanga, North West, and Gauteng. Its three sections, an eastern and western lobe, and a northern extension, were formed about two billion years ago. These were created when vast quantities of molten rock from the Earth's mantle were brought to the surface through long vertical cracks in the crust. The effects of these injections of molten rock over time, combined with the crystallisation of different minerals at different temperatures, resulted in the formation of a structure rather like a layered cake consisting of distinct rock strata, including three layers, referred to as reefs, that bear the world's largest reserves of platinum Group Metals (PGMs).

The research cohort for the first trip to the drilling site: Fanie de Lange (University of the Free State(UFS)) and Amy Allwright (Stellenbosch University); Rolene Lubbe (PhD student, UFS) and Leor Bester (Honours student, UFS); Yohey Suzuki (Japanese colleague (University of Tokyo) working on microbiological research) with Mpho Molautsi (University of Limpopo MSc student); and Jared van Rooyen (SU alumni; Eawag; Uni. Basel (Switzerland)) for the online gas analysis system (miniRuedi).

The Bushveld Igneous Complex is thus globally renowned for its mineral wealth, and the PMG reserves of platinum, palladium, osmium, iridium, rhodium, and ruthenium are the world's largest. There are also vast quantities of iron, tin, chromium, titanium and vanadium.

The broader goal of the BVDP, run by a large team of experts led by Prof Susan Webb of the University of the Witwatersrand, is to acquire two complete reference profiles through the entire six- to eight-kilometre thickness of the iconic Rustenburg Layered Series, including the ore horizons within it. This is to be achieved through donated core from the mining industry from all the limbs of the Bushveld Igneous Complex, and then a single drilled hole to complete the sequence below the resource, which is not typically drilled.

This information will answer questions about the nature of the magma sources, melting processes, chambers and emplacement that gave rise to enormous magma volumes and rich mineralisation so many millennia ago.

However, drilling that deep also created a rare opportunity that supported the WRC's hydrogeological ambitions, even though sceptics doubted its importance. Stellenbosch University lecturer, Amy Allwright, the WRC project leader and co-project leader on the BVDP, says the general feeling was that there's nothing that deep down in the solid, impermeable rock. Still, Allwright was keen to see what they would find along the planned 2 500 m borehole. The resulting WRC-supported project aimed to gather hydrogeochemical, isotopic, and structural information. This knowledge would be critical to understanding the behaviour of water in these ancient, fractured rock systems.

Though undertaking a deep drilling project of this scope would likely always entail some challenges, the extent of the logistical,

Amy Allwright

Core trays containing the first core from the borehole. The WRC-funded project managed to drill to 950 m before its time at the site came to an end; however, drilling continued as part of the larger Bushveld Complex Drilling Project.

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The project site was at the remote Impala Marula Mine in the Limpopo Province. The larger project is aiming to drill a transect through the Bushveld Igneous Complex.

technical, and financial difficulties took even seasoned scientists and drill experts by surprise.

Rolling in the deep

The borehole (BVDP-2) was drilled at the remote Impala Marula Mine in Limpopo (in the eastern limb of the Bushveld Igneous Complex), a place that felt like you were in the middle of nowhere, in a different county, Allwright recalls. Power was supplied by generators, internet access had to be negotiated, temporary offices consisted of containers, temperatures were extreme, and site operators worked extended hours.

Technically, the drilling process was complex and multi-phased. The borehole was drilled in progressively smaller diameters, with casing inserted to stabilise the hole at various depths. Water samples had to be collected quickly before the borehole casing prevented further access. "I had a small window to collect those samples," says Allwright. "Once it was cased, that was it."

Researchers also had to take cognisance of the drilling fluid, a viscous lubricant that seriously complicates water filtration and impacts the integrity of the sample.

From the outset, the borehole experienced total water loss for the first 300 m, when all drilling fluid disappeared into the rock, never returning to the surface. Despite this, progress was steady until around 950 m. Then, the problems and surprises surfaced.

"The drill rods started twisting under pressure, the borehole began to deviate, and we had to insert wedges to straighten it — not an easy fix," Allwright explains. "It totally blew our timeline. We went from 950 to just 1,200 m over several months, and eventually hit a lamprophyre dyke, which brought a whole new set of complications." Here, cementing efforts between 1 150 and 1 270 metres failed repeatedly due to persistent groundwater inflows — an unexpected and revealing hydrological behaviour in rock usually considered impermeable at depth.

The idea that there was any active water movement in these deep systems surprised many of us, Allwright says. The water chemistry, the pressure zones, the role of dykes — all of it pointed to more complexity than first thought.

Still, the complications resulted in long delays and ballooning costs. "You understand now why people don't collect water samples at these depths — from some perspectives, it's just not a reasonable investment," she explains.

Then, when the borehole was flushed with clean water, a dark, strong-smelling fluid was expelled from the hole, an unexpected anomaly that raised questions about deep hydrogeological and geochemical processes (analysis results are pending). Finally, the team managed to drill up to a depth of 950 m before the time and funds for the hydrogeological investigations ran out. Although the original aim was to reach 2 500 m by this time, the data collected still delivered valuable insights. And, as the larger BVDP project continues, Allwright says that they will collect the final water samples from the deeper section of the hole once drilling has finished.

Insights from the deep

The findings called for a revision of the existing hydrogeological model for the eastern Bushveld limb. Updates include evidence of two distinct systems — a shallow and a deeper one — based on water quality analysis. The difference in water quality supports the assumption, also made in the western limb, that shallow aquifers are generally not connected to those deeper than 300 m.

A second revision includes that a fractured aquifer between 100 and 500 m shows signs of higher hydraulic conductivity. At around 800 m, a high-density fracture zone (deep aquifer) was identified, with potential for groundwater flow. Then, the dark, strong-smelling fluid that was expelled suggests possible interaction with hydrothermal fluids, brines, or deep organic processes at depths between 1 150 and 1 270 m, where significant groundwater inflows were found.

At approximately 1 265 to 1 270 m, a lamprophyre dyke may act as either a conduit or a barrier for fluid movement, depending on the orientation and density of the fractures. The connectivity of faults and fractures controls localised recharge and groundwater flow.

This updated information reflects the complexity of the Bushveld Igneous Complex's groundwater systems, with variable hydraulic properties and flow patterns. The system incorporates deep fracture-controlled aquifers, helping assess groundwater potential at depth.

According to the final report, published in May, the findings indicate that deep groundwater systems within the Bushveld Igneous Complex could serve as a resource for industrial and mining applications, particularly in regions where surface water is scarce. Additionally, the elevated temperatures and gas anomalies suggest a potential for geothermal energy, warranting further investigation.

Another key challenge was the influence of drilling fluids during sampling, which introduced complexities in the hydrochemical and isotopic analyses. Still, the fact that valuable hydrogeological information was successfully collected demonstrates the potential for further deep groundwater research in the Bushveld Igneous Complex.

Allwright says they hope to get the opportunity to do precisely that. Since BVDP-2 is such a rare opportunity to study a deep groundwater system relatively unaffected by the shallow aquifer, they are hoping to keep it open. Usually, once a borehole like this is drilled, it's closed or cemented shut, especially in mining areas. The plan, explains Allwright, is to let BVDP-2 rest for about a year, allowing the drilling fluids to clear out and the system to stabilise. "It's almost like a natural lab," she says. Then, if funding allows, they will go back with more time, better tools, and fewer constraints. Then they want to collect samples that haven't been contaminated by drilling fluid.

In the meantime, work on the existing samples is ongoing. A PhD student is working on the hydrogeological characterisation of the water samples, investigating the impact and consequences of drilling fluid contamination and a third topic, studying the geochemical and structural indicators for hydrothermal fluid migration in the Bushveld Igneous Complex.

More information, more questions

There are broader implications, too. Allwright asks how we can manage, protect, or even use these systems if we do not understand them. With the pressure on for energy transitions, mining, and carbon sequestration, the deep subsurface is becoming more critical. However, we're currently moving into these areas without a clear understanding of the groundwater implications. For instance, injecting CO_2 into deep formations may not affect surface water, but it does alter groundwater chemistry and microbiology, and, she says, we don't know what that means long term.

What we do know, according to this project, is that the Bushveld Igneous Complex is more complex than previously thought, with potentially important consequences for water resources management.

It also identifies key areas for further study, including geothermal energy, isotopic dating, and long-term fluid monitoring. BVDP-2 is already the deepest hydrogeological characterisation in this region. The data reveal real potential for development, but most importantly, they show that deep groundwater is not just a blank space below — it's an active, complex system that we need to understand before we start altering it.

To access the original research report, ***Research-based exploration of deep groundwater within the eastern limb of the Bushveld Igneous Complex for hydrogeological characterisation and potential future water resource identification***, visit: https://www.wrc.org.za/wp-content/uploads/mdocs/3200.pdf

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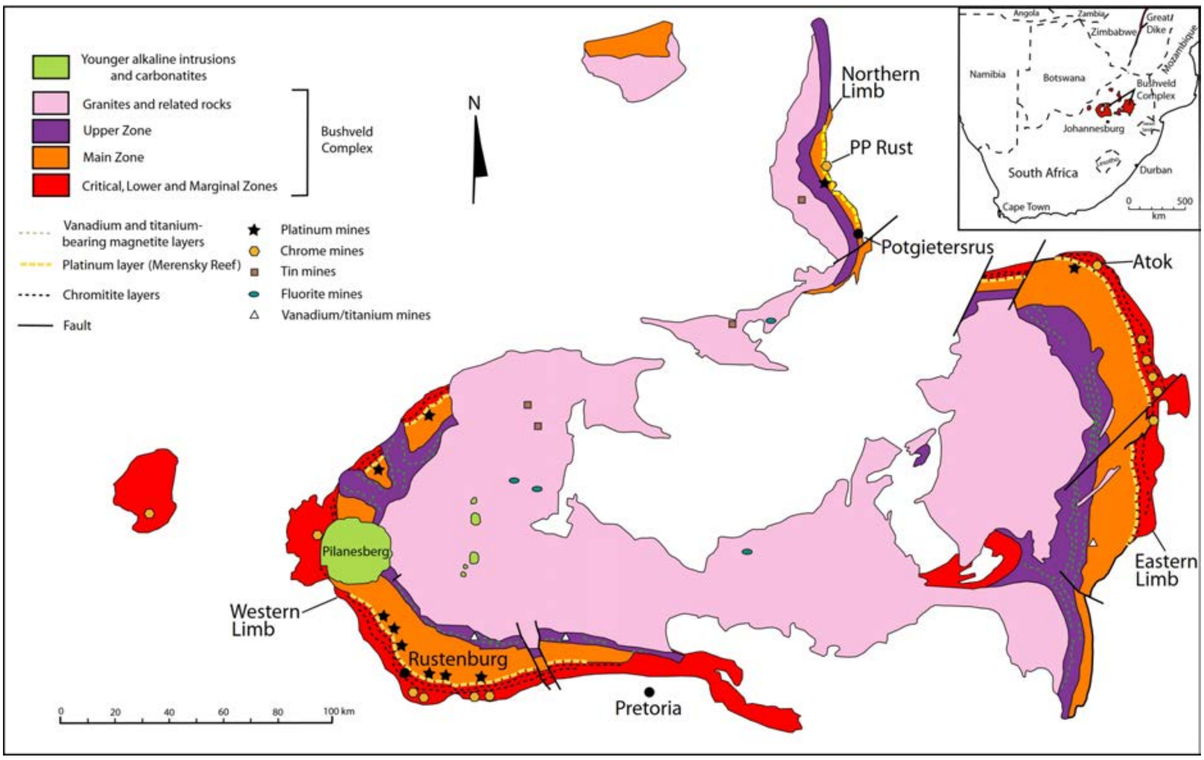

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