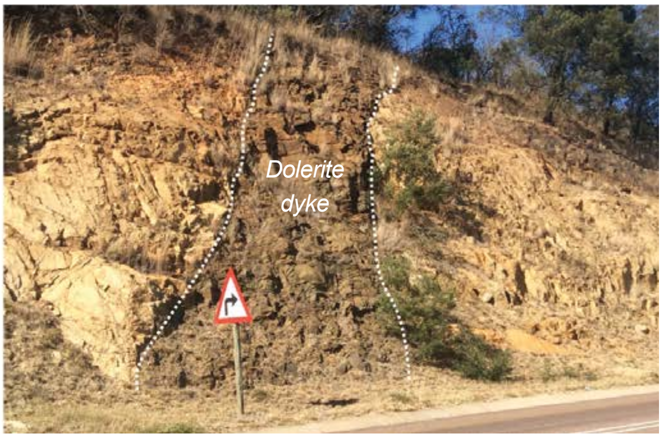
Tracking continents in deep time

Michiel de Kock reveals how the Earth's magnetic field is recorded in rocks, providing the basis for the palaeomagnetic dating method

Michiel de Kock

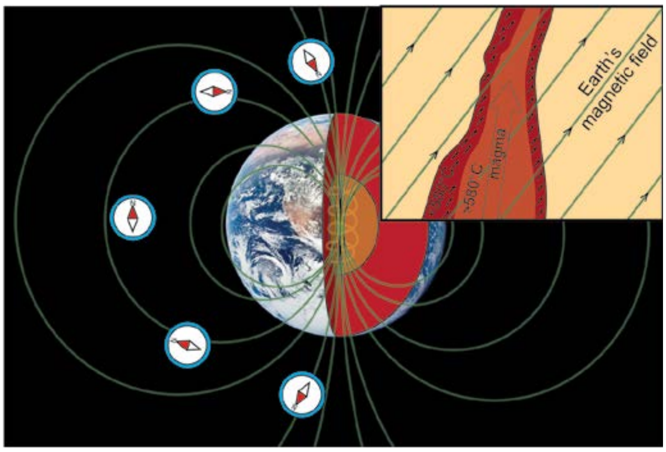


Palaeomagnetic core samples are collected from dolerite dykes, which are approximately 1 850 million years old.

The chainsaw engine pushes back with a whine as the diamond-tipped bit cuts deeper into the dolerite rock. My PhD student, Cedric Djeutchou, is ensuring that the bit stays cool by maintaining a steady flow of water from a small pump can. I need to cut another centimetre or so to complete the core.

Cedric and I are palaeomagnetists, and we are interested in the record of the Earth's magnetic field in rocks. We have collected over 372 cores from 61 separate dolerite dykes. Each of these cores is 2.5 cm in diameter, nearly 8 cm long, and oriented according to the direction and angle that it was drilled. The dykes are remains of an ancient 'plumbing system' of mostly northeast–southwest running cracks that fed molten rock called magma – subsequently cooled and solidified to dolerite – to the surface some 1 850 million years ago.

Geologists know from the rock record that continental fragments were assembling to form the supercontinent Columbia at that time. Most people have heard of the last supercontinent, named Pangea, which broke apart to form the modern continents. Unlike Pangea, we only have a vague idea of what Columbia looked like, and no idea where the ancient landmass of southern Africa – known as the Kalahari craton – was located. Cedric is hoping to change that, and was lead author of a recent paper outlining some of our findings (Djeutchou et al., 2021).



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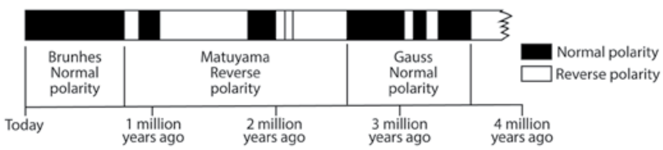
Earth's magnetic field is dipolar, produced in the outer core, and aligned with the spin axis. Magma that contains magnetite will record the Earth's magnetic field if it cools below 580°C.

Magnetic declination and pole-flipping

Electric currents in the molten iron-nickel outer core of the Earth produce a magnetic field according to Faraday's Law. The molten outer core gets whipped into helical flow due to cooling of the outer core and the Earth's fast rotation. This produces a looping current and an induced magnetic field that comes out of the loop in a doughnut shape. Magnetic field lines emerge steeply near the South Pole, become flatter towards the equator, and steepen up again near the North Pole. On the surface, a compass needle aligns with these field lines to point to magnetic north, which differs from the spin axis – the imaginary line passing through the North and South Poles – by an amount known as the magnetic declination.

The angle at which the magnetic field lines exit or enter the surface is called the magnetic inclination. The magnetic



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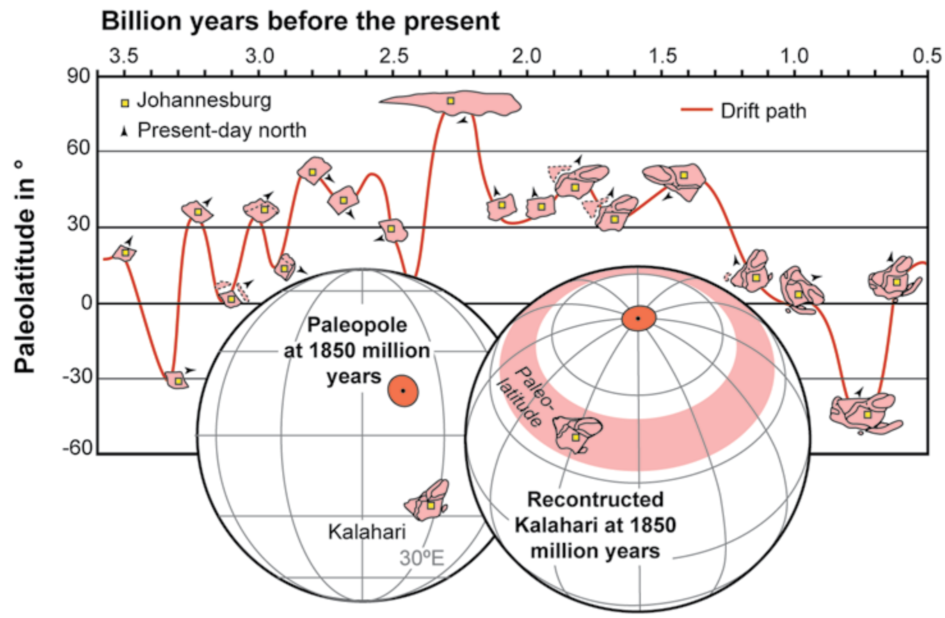
Polarity of the Earth's magnetic field for the past four million years. The current polarity interval, the Brunhes interval, started 780 000 years ago. Before that, during the Matuyama interval, a compass would have pointed south instead of north.



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Drift and growth of the Kalahari craton. The inclination at a specific time, here 1 850 million years ago, reveals the location of the North Pole relative to the craton. The craton is reconstructed by moving the 1 850-million-year-old pole to the spin axis while keeping the distance between the craton and the pole locked.

field is the result of dynamic processes, and the position of magnetic north oscillates around the spin axis. However, when averaged over long periods of time, this variation disappears, making magnetic north and the spin axis the same. Magnetic inclination varies depending on where it is measured and can be expressed as $Tan(I) = 2Tan(\lambda)$, where I is the inclination and λ is the latitude.

The polarity of the Earth's magnetic field can flip and has changed many times in the past. These polarity intervals occur irregularly, sometimes flipping in quick succession and sometimes remaining stable for millions of years. The sequence and tempo of magnetic polarity reversals is unique for any specific time interval – kind of like a barcode – and can be used to date rocks.

Remanence and the Curie temperature

Rocks can become magnetised and retain a record of the Earth's magnetic field. This is known as a remanent magnetisation or remanence. A rock records and retains remanence for a long time if it contains minerals of the right chemical composition, and if those minerals are of the right size. Magnetic minerals such as magnetite (Fe_3O_4) or hematite (Fe_2O_3) are needed, and crystals should not be too small or too big. Both size extremes would result in an unstable remanence that can easily be overwritten. Luckily for geologists, many rock types contain these and other magnetic minerals that are also of the desired grain-size to retain remanences for millions to billions of years.

When an iron- and magnesium-rich magma cools in a crack near the surface from its initial 1 200°C to below 580°C, small crystals of magnetite will become magnetised in the direction of the Earth's magnetic field. The temperature where specific minerals become magnetised (and above which they lose their magnetisation) is called the Curie temperature. For small and pure crystals of magnetite, this is 580°C. As the magma cools and solidifies to form dolerite, the magnetic record becomes 'frozen in'. The dolerite will only lose this remanence if it is remagnetised through crystallisation of new magnetic minerals, through later heating of the rock to above the Curie temperature, or by exposure to a very strong magnetic field.

Reading the magnetic record

To read the magnetic record in rocks, the collected core samples must be returned to our palaeomagnetic laboratory at the University of Johannesburg. The laboratory is equipped with a sensitive superconducting rock magnetometer that can measure very weak magnetisations like those recorded in rocks. Our laboratory is the only one on the African continent with this equipment.

The prepared cores are slowly stripped of their magnetic record in a process known as demagnetisation to reveal the most stable kernel of the dolerites' remanence. The inclination of this remanence reveals where the Kalahari craton was when the dolerite intruded 1 850 million years ago. This allows palaeomagnetists to turn back the clock and to reconstruct the Kalahari craton to its original latitude. Using rocks of different ages, we can track the movement of the Kalahari craton back 3.5 billion years.

- Djeutchou, C, De Kock, MO, Wabo, H, Gaitán, CE, Söderlund, U & Gumsley, AP, 2021. Late Paleoproterozoic mafic magmatism and the Kalahari craton during Columbia assembly. *Geology* v. 49, https://doi.org/10.1130/G48811.1

Prof. Michiel de Kock is the head of the Department of Geology at the University of Johannesburg. He supervised Dr Cedric Djeutchou, who completed his PhD in 2020 and is now conducting postdoctoral research at the University of Johannesburg.

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