Lithostratigraphy of the Palaeoproterozoic Hekpoort Formation (Pretoria Group, Transvaal Supergroup), South Africa

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Abstract

The Palaeoproterozoic Hekpoort Formation of the Pretoria Group is a lava-dominated unit that has a basin-wide extent throughout the Transvaal sub-basin of South Africa. Additional correlative units may be present in the Kanye sub-basin of Botswana. The key characteristic of the formation is its general geochemical uniformity. Volcaniclastic and other sedimentary rocks are relatively rare throughout the succession but may be dominant in some locations. Hekpoort Formation outcrops are sporadic throughout the basin and mostly occur in the form of gentle hills and valleys, mainly encircling Archaean domes and the Palaeoproterozoic Bushveld Complex (BC). The unit is exposed in the western Pretoria Group basin, sitting unconformably either on the Timeball Hill Formation or Boshoek Formation, which is lenticular there, and on top of the Boshoek Formation in the east of the basin. The unit is unconformably overlain by the Dwaalheuwel Formation. The type-locality for the Hekpoort Formation is the Hekpoort farm (504 IQ Hekpoort), *ca*. 60 km to the west-southwest of Pretoria. However, no stratotype has ever been proposed. A lectostratotype, i.e., the Mooikloof area in Pretoria East, that can be enhanced by two reference stratotypes are proposed herein. The Hekpoort Formation was deposited in a cratonic subaerial setting, forming a large igneous province (LIP) in which short-termed localised ponds and small braided river systems existed. It therefore forms one of the major Palaeoproterozoic magmatic events on the Kaapvaal Craton.

Introduction

The Hekpoort Formation forms a widespread and first major volcanic event within the Pretoria Group of the Transvaal Supergroup (Figure 1). The other volcanic events within this group are the *ca.* 2.3 Ga Bushy Bend Lava Member of the Timeball Hill Formation (Eriksson et al., 1994; Reczko et al., 1995) and the *ca.* 2.2 Ga Machadodorp Member of the Silverton Formation (Lenhardt et al., 2020; Humbert et al., 2020). Based on its regional, nearly basin wide extent of *ca.* 100 000 km² throughout the Transvaal sub-basin and an estimated maximum thickness between 700 to 1 100 m (Lenhardt et al., 2012; Humbert et al., 2018a), the Hekpoort Formation represents a Palaeoproterozoic large igneous province (LIP) on the Kaapvaal Craton. Older LIPs or groups of LIPs are the 2.79 to 2.39 Ga Ventersdorp Supergroup (Altermann and Lenhardt, 2012; Gumsley et al., 2020 and references therein) on the central and western Kaapvaal Craton and the 2426 ± 3 Ma Ongeluk Formation (Gumsley, 2017; Gumsley et al., 2017) in the Griqualand West sub-basin of the Transvaal Supergroup.

The magmatism of the Hekpoort Formation coincides with a phase of rifting and subsequent thermal subsidence on the Kaapvaal Craton (Eriksson et al., 2001, 2006). The craton experienced several such rifting or magmatism and subsidence cycles during Transvaal Supergroup times. The oldest such cycle is marked by the voluminous Ongeluk magmatism of the western Kaapvaal craton at 2.426 Ga (Gumsley et al., 2017; Humbert et al., 2019). The *ca.* 2.3 Ga restricted volcanic activity of the Bushy Bend lavas at the transition from the Rooihoogte Formation to the Timeball Hill Formation (Eriksson et al., 2001) possibly coincides with this cycle. The Bushy Bend Member volcanism was, however, short-lived and locally very restricted to the south of the Pretoria depository (Eriksson et al., 1994; Lenhardt et al., 2012). Nevertheless, eventually it led to the formation of the Timeball Hill epeiric sea that covered the Transvaal sub-basin (Eriksson et al., 2001). The second large magmatic cycle of the Palaeoproterozoic Kaapvaal Craton started at *ca.* 2.2 Ga with the formation of the Hekpoort LIP and, after waning of rifting and onset of thermal subsidence, it proceeded with deposition of the Daspoort-Silverton-Magaliesberg sedimentary sequence.

The name "Hekpoort" - after the farm Hekpoort (504 IQ Hekpoort), *ca.* 60 km to the west-southwest of Pretoria – was formally accepted by SACS (1980) upon a proposal by the South African Committee for Stratigraphy (SACS) in 1979. The type area for the formation is the Hekpoort farm, which has now developed into a small village (Figure 1). Due to the limited outcrop quality near the type locality, no stratotype was established in the vicinity of Hekpoort farm. Thus, here, we propose a lectostratotype for the Mooikloof area in Pretoria East that can be enhanced by two reference stratotypes (see section on Stratotypes) (Figure 2).

Stratigraphic position and age

The Hekpoort Formation forms part of the lower Pretoria Group of the Transvaal Supergroup. Stratigraphically, in the central and eastern parts of the Transvaal sub-basin, including the Potchefstroom syncline, the formation sits on top of the Boshoek Formation and below the Dwaalheuwel Formation. Both these formations are of terrestrial deposition. In the western part of the basin, the Hekpoort Formation either unconformably sits on top of the Boshoek Formation, which is here typically lenticular and between 1 to 50 m thick (Schreiber et al., 1990), or unconformably overlies the marine shales of the Timeball Hill Formation (for instance at the B'Sorah farm; 25°51'14.70"S; 27°46'30.36"E).

Although there are several, overlapping, radiometric ages for the Hekpoort Formation there is still no agreement on when this important magmatic event occurred. Burger and Coertze (1973) obtained an age of 2 224 ± 21 Ma (whole-rock Rb-Sr isochron) from the Hekpoort Formation lavas, which has been re-evaluated to 2 184 ± 76 Ma/2 193 ± 71 Ma by Cornell et al. (1996). The most recent (maximum) age of 2 247 ± 10 Ma was acquired by Schröder et al. (2016), by U-Pb SHRIMP dating of detrital zircon from palaeosols or interbedded sedimentary units in the formation. Thus far, a robust high precision date from primary minerals (e.g., zircon, baddeleyite, apatite, etc.) of the Hekpoort Formation has not been obtained.

Geological description

Basic concept and unifying features

In general, the rocks of the Hekpoort Formation are dominated by lava flows that are intercalated with relatively small amounts of volcaniclastic deposits and their reworked counterparts. In most studied areas (e.g., Button, 1973; Sharpe et al., 1983; Humbert et al., 2018a,b) volcaniclastic rocks are generally concentrated near the base of the formation while all overlying rocks are originating from effusive eruptions. Button (1973) estimated the quantity of volcaniclastic rocks as 10% in the east of the preserved Transvaal sub-basin. In contrast, Humbert et al. (2018a) suggested an amount of as little as 1% for the southern preserved part of this sub-basin (solid red rectangles in Figure 1). Only near the type locality of Hekpoort (Figures 1 and 2), are nearly equal portions of volcaniclastic rocks and lavas preserved (Oberholzer and Eriksson, 2000). According to Humbert et al. (2018a), volcaniclastic sedimentary rocks locally dominate over lava in this area.

The majority of the rocks are interpreted as having been deposited in a subaerial environment (Button, 1973, 1986; Eriksson and Reczko, 1995; Oberholzer, 1995). Nevertheless, the occurrence of hyaloclastites, variolites and possibly pillow lavas suggest that some subaqueous deposition must have occurred locally, probably in a lacustrine environment (Humbert et al., 2018a, b).

Thickness

In the south of the Transvaal sub-basin, the preserved thickness of Hekpoort Formation lavas is in excess of 1100 m (Eriksson and Reczko, 1995; Humbert et al., 2018a, and references therein). The 800 m thickness that can be found in the west of the basin, thins out towards the northeast where less than 50 m are found (Button, 1973; Lenhardt et al., 2012). Concomitant with the north-easterly thinning, a reduction in the number of individual lava flows can be observed (Button, 1973). A recent study by Humbert et al. (2018a) determined thicknesses of the Hekpoort Formation as *ca*. 500 m at Mooikloof, *ca*. 1000 m of lavas and hyaloclastites or lahar deposits south of Hekpoort and towards Broederstroom (also see Oberholzer, 1995), *ca*. 800 m in the Fochville monocline, and *ca*. 340 m in the Potchefstroom syncline (Figures 1 and 2). No information is available for the thickness or rock types preserved in the area south of Derdepoort, on the northwest limb of the BC.

Lithology

The Hekpoort Formation is characterised by a wide variety of lithologies, ranging from various lavas and numerous types of primary and secondary volcaniclastic deposits to interbedded siliciclastic sedimentary rocks and palaeosols.

Lava

The lava flows of the Hekpoort Formation (Figure 3a) generally range in thickness between 8 to 60 m. The flow tops (0.5 to 1 m in thickness) are often amygdaloidal with partial or complete filling by quartz, clinochlore, zeolite and calcite (Figure 3b). Close to its type locality, the Hekpoort Formation lavas exhibit locally developed, several metres-thick, flow-top breccias (Oberholzer and Eriksson, 2000; Coetzee, 2001), which are typical of aa lavas (McPhie et al., 1993). Elsewhere, the flow tops are characterised by smooth and sometimes ropy surfaces (Figure 3c), implying that they most probably originated from pahoehoe lava flows (Humbert et al., 2018a).

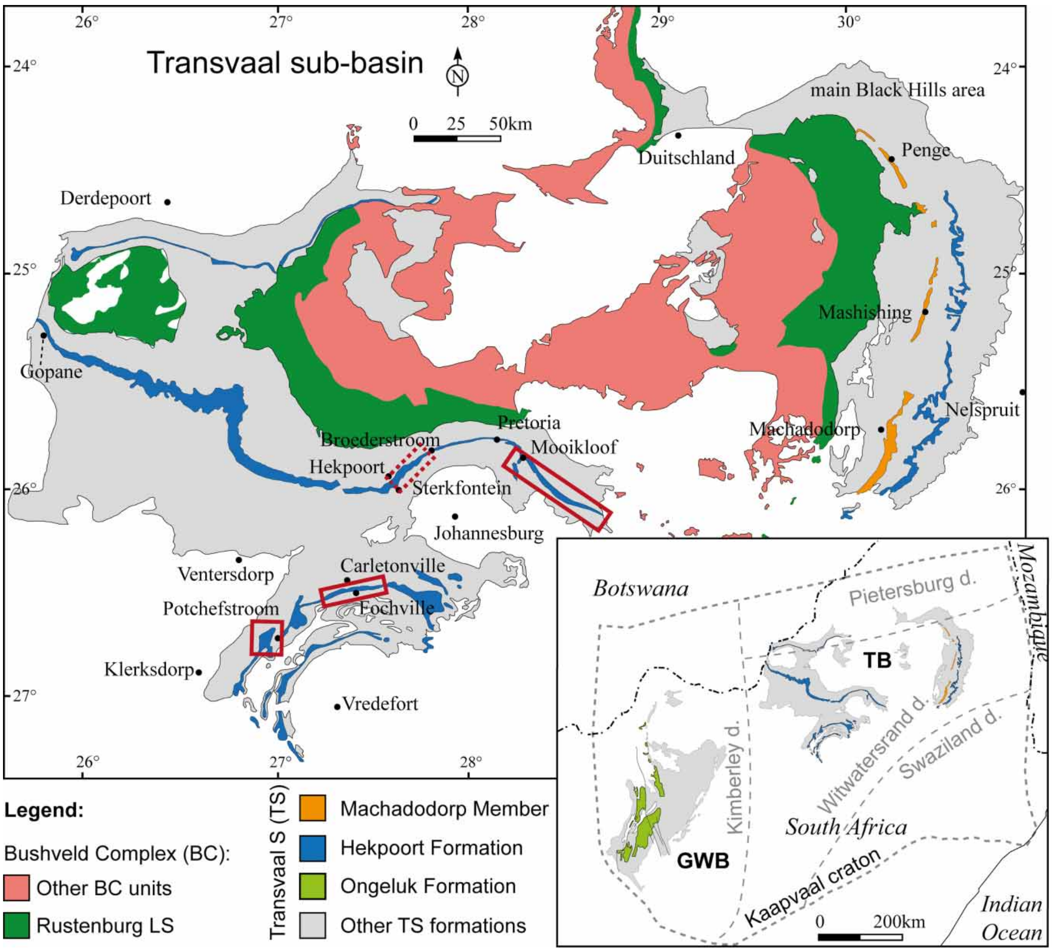

Figure 1. *Distribution of the outcrops of the Transvaal Supergroup with the Hekpoort Formation (2236 Ma; Cornell et al., 1996) within the Transvaal sub-basin (TB). The Bushveld Complex (BC), ca. 2054 Ma (Zeh et al., 2015), units include the volcanic Rooiberg Group, and the extrusive Rashoop Granophyre and Lebowa Granite suites. The location of the Griqualand West sub-basin (GWB) and the Ongeluk Formation (2426 Ma; Gumsley et al., 2017) within the Kaapvaal Craton is shown in the inset. The red rectangles along the Hekpoort outcrops represent areas corresponding to the stratigraphic columns in Figure 2; namely, southwest to northeast, the Potchefstroom syncline, the Fochville monocline and the Mooikloof monocline. The dashed rectangle shows the location of outcrops between the type locality of Hekpoort and Broederstroom towards the northeast. All compiled from 1:250000 South African geological maps (i.e., maps 2228, 2230, 2326, 2228, 2330, 2426, 2428, 2430, 2526, 2528, 2530, 2626, 2628, 2630) and literature (op. cit.).*

The most dominant type of lava flows within the Hekpoort Formation is characterised by thick, successive layers that are interpreted to originate from a single magma pulse, i.e., similar to the 'tabular-classic flows' of Jerram (2002). The flows usually contain layers with variable contents of amygdales, i.e., 1 to 4 cm thick layers enriched in amygdales, intercalated by 0.1 to 1 m thick layers that do not contain any amygdales. These features are commonly attributed to shear-induced outgassing and are

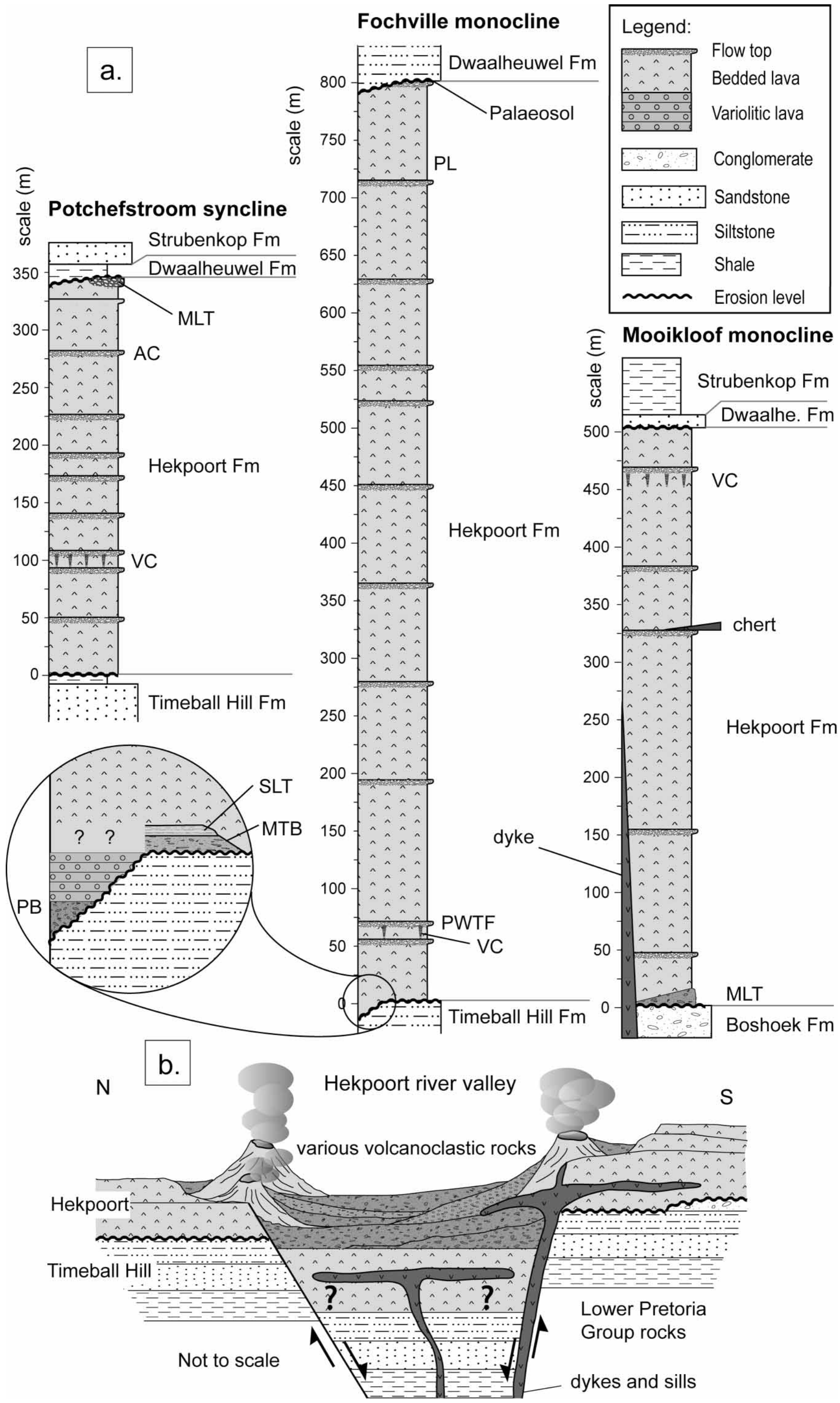

Figure 2. ***(a)*** *Composite vertical sections of the three main zones represented by the solid red rectangles in Figure 1. AC=amygdale layer rich in clinochlore; MLT=massive lapilli-tuff; MTB=massive tuff breccia; PB=pyroclastic breccias; PL=pahoehoe lava; PWTF=palaeo-weathered flow top; SLT=stratified lapilli-tuff; VC=layer rich in vesicle cylinders.* ***(b)*** *north–south schematic cross-section of the Hekpoort Formation northeast of the type locality, where deposition took place in a graben system (dashed red rectangle in Figure 1).*

Figure 3. ***(a)*** *Typical outcrop of the Hekpoort Formation lavas, usually forming gentle hills;* ***(b)*** *amygdaloidal flow top of a Hekpoort Formation lava flow;* ***(c)*** *ropy surface of a lava flow top, typical for pahoehoe lava flows;* ***(d)*** *vesicle cylinder;* ***(e)*** *example of a variolitic lava flow increasing in size and density of the varioles towards the flow top, near Fochville;* ***(f)*** *close-up of a lava flow rich in varioles.*

the result of differential flow during the spreading of a lava lobe due to heterogeneities in lava rheology (*cf.* Shields et al., 2016). These 'tabular-classic flows' may locally exhibit a variety of intersecting vesicle cylinders (Figure 3d), increasing in diameter towards the top. The length of these cylinders range from 1 to 3 m, with diameters at the top of up to 30 cm. The largest vesicle cylinders were observed in the northern part of the Potchefstroom syncline and in the Mooikloof area of Pretoria east (Figure 1; Humbert et al., 2018a). The vesicle filling within the cylinders is by quartz, zeolites and clinochlore. The cylinders have most probably formed after the host lava had come to rest and before reaching the glass transition temperature (McPhie et al., 1993; Santos Barreto et al., 2014; Humbert et al., 2018a).

Variolitic lava flows (Figure 3e) within the Hekpoort Formation may reach up to 30 m in thickness and can extend for up to 1 km along strike. These flows occur in the Fochville and Wedela areas (Humbert et al., 2017, 2018a, b) where they are characterised by high concentration of varioles (up to 10 cm in diameter) in the upper part of each flow unit. According to Humbert et al. (2018b), these varioles (Figure 3f) consist, primarily, of radially oriented clinopyroxene needles (1 µm in width) and formed due to super-cooling of the lava, probably within a subaqueous environment. A localised subaqueous lacustrine environment is supported by the occurrence of possible pillow lavas towards the top of the Hekpoort Formation in the Potchefstroom area (Humbert et al., 20018a). However, these outcrops are highly weathered and inconclusive; the uppermost section of the Hekpoort Formation might have been extensively eroded at this location. Nevertheless, associated volcaniclastic rocks in the same area were interpreted as hyaloclastites (see below), which supports the presence of pillow lavas.

Only few lava flows with a recognisable ropy surface were encountered in the area near Fochville (Figure 1) and were interpreted as originating from pahoehoe lava flows (Figure 3c). Nevertheless, the absence of any carapace of the 'tabular-classic flows' and variolitic lava flows also implies that they originated from sheet flows, similar to pahoehoe lava flows.

Primary volcaniclastic rocks

Primary volcaniclastic rocks within the Hekpoort Formation are attributed to a variety of eruptional, transport and depositional processes, ranging from explosive, subaerial eruptions and pyroclastic density current (PDC) formation to hyaloclastites that formed *in-situ* during quench-fragmentation of surrounding pillow lavas.

Deposits from PDCs are preserved as stratified and massive lapilli-tuffs, and tuff breccias. All these deposits generally range from <1 m to *ca.* 60 m in thickness and are composed of a fine-grained ash matrix of crystals and vitric material, and larger lithic clasts ranging from 3 mm to more than 20 cm in diameter (Figure 4a). Mafic clasts may be interpreted as juvenile fragments whereas the clasts of siliciclastic origin are interpreted to be accidental clasts from underlying formations such as the Timeball Hill or Rooihoogte/ Duitschland formations (Lenhardt et al., 2012; Humbert et al., 2018a).

At two locations, near Potchefstroom and at Mooikloof, the massive lapilli-tuffs were interpreted as hyaloclastites due to

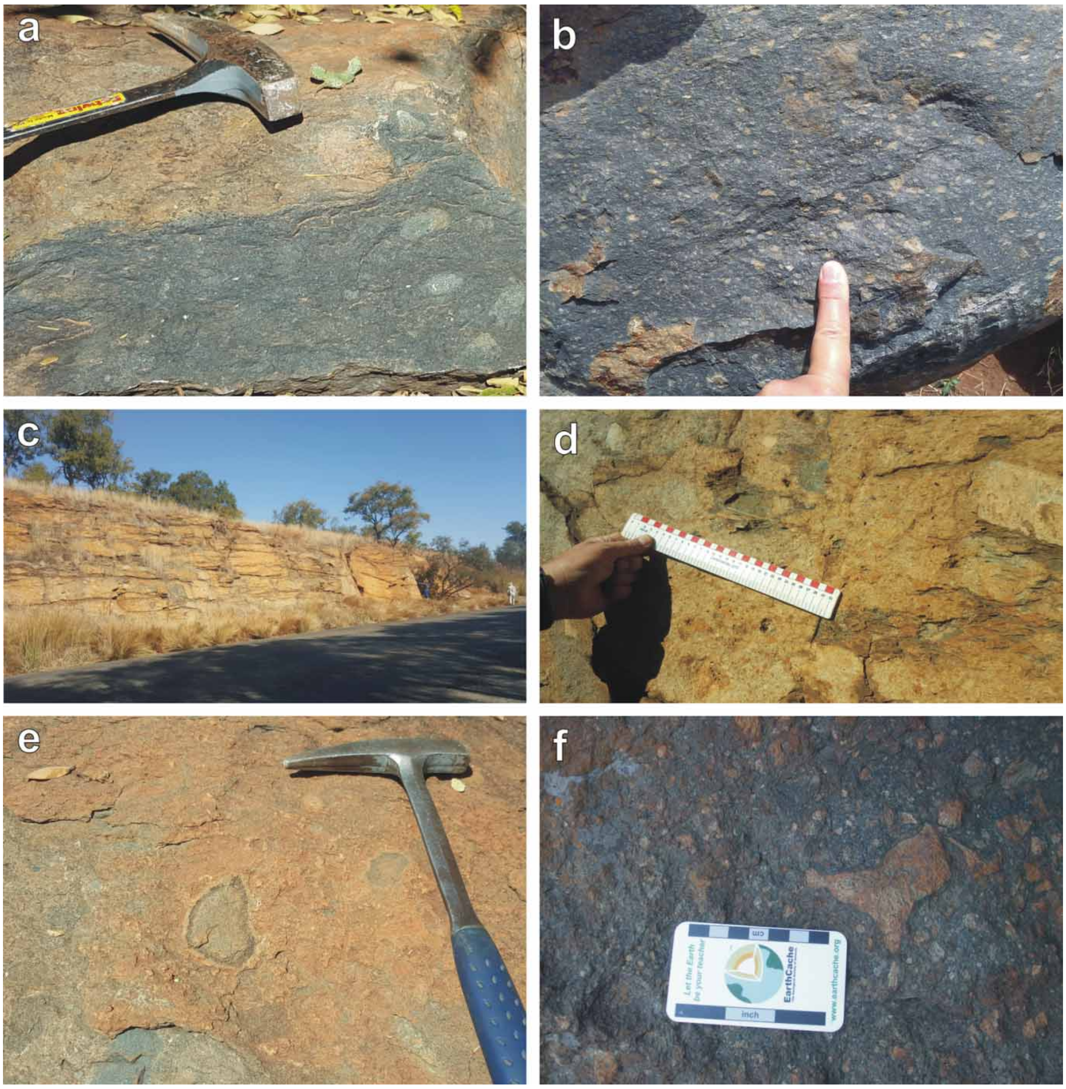

Figure 4. *(**a**) Example of a massive lapilli-tuff (MLT) within the Hekpoort Formation interpreted as PDC deposit; (**b**) example of a massive lapilli-tuff (MLT), interpreted as hyaloclastite, at the base of the formation at Mooikloof; (**c**) lahar deposits in the at B'Sorah farm along the R400 road; (**d**) close-up of lahar deposit; (**e**) reaction rim around clast incorporated into a lahar deposit; (**f**) amoeboid-shaped clast in a lahar deposit. The clasts in (**e**) and (**f**) indicate the incorporation of hot clasts into the wet mass flow directly from an ongoing eruption.*

their different clast content (Humbert et al., 2018a). At the Potchefstroom outcrop, they occur towards the top of the formation (Humbert et al., 2018a). In contrast, the hyaloclastites at Mooikloof can be found at the very base of the formation (Figure 4b). In both cases, the hyaloclastites consist, primarily, of a breccia of angular, jigsaw fit, aphanitic clasts set in fine-grained matrices. Rounded fragments, rich in amygdales and euhedral pyrite, appear to be "floating" in the matrix. Several fragments exhibit pervasive alteration interpreted as early palagonitization (Humbert et al., 2018a).

Secondary volcaniclastic rocks

A variety of predominantly matrix-supported tuffaceous breccias interpreted as deposits from lahars and associated mass flows (Eriksson and Twist, 1986; Oberholzer, 1995; Oberholzer and Eriksson, 2000; Humbert et al., 2018a) have been described from south and northeast of Hekpoort (Figures 1 and 4c to f) and especially at the B'Sorah farm, not far from the type locality. The beds are characterised by a weak alignment and occasional imbrication of clasts, of variable composition, size, and degree of rounding, "floating" in a sandy matrix (Figure 4d). Clast sizes can reach up to 3 m in diameter. Humbert et al. (2018a) describe reaction rims around some of the small lava clasts that may indicate the incorporation of hot clasts into the wet mass flow directly from an ongoing eruption (Figure 3e and f).

Siliciclastic sedimentary rocks

Siliciclastic sedimentary units, intercalated within the lavas, have been described from a number of locations. Button (1973) described primarily shales, slightly metamorphosed, but also some rare argillaceous quartzites forming lens-shaped occurrences in the lower third of the Hekpoort Formation from southeast of Machadodorp (eNtokozweni) in Mpumalanga and in the Penge area in Limpopo (Figure 1). Humbert et al. (2018a) described several lenses of metre-thick, silicified cherty shales from outcrops in the east of Pretoria (Mooikloof; Figure 5a). The shales contain layers of iron-oxide/hydroxide and can be traced for several tens to hundreds of metres laterally. On one bedding plane within these laminated and tuffaceous silicified shales, putative raindrop imprints (Figure 5b) were found, which may have originated in or close to a lacustrine shore environment (Altermann, 2019). At the B'Sorah farm (25°51'14.70"S; 27°46'30.36"E), trough cross-bedded sandstones with ripple surfaces were found (Figure 5c). These sandstones are medium grained, well rounded, probably tuffaceous, and have been interpreted as fluvial, braided stream channels, flowing mainly towards southwest to southeast directions (Figure 5d). Micaceous surfaces with mud partings intercalated with these deposits are probably related to shallow ponds between the braids.

Palaeosols

The best-studied, non-volcanic sedimentary unit within the Hekpoort Formation is probably the "Hekpoort Palaeosol" originally described by Button (1973) from exposures the village of Waterval Onder in Mpumalanga (Figure 6). The palaeosol is described as a regional paleo-weathering horizon developed on top of the lavas and cut by an erosional contact at the base of the overlying Dwaalheuwel Formation. Since this initial description, the palaeosol has been documented from more than 200 locations in drill cores and outcrops throughout the Transvaal sub-basin including Potchefstroom, Fochville (Figures 1 and 2a), and Lobatse in Botswana (e.g., Button, 1979; Button and Tyler, 1981; Rye and Holland, 2000; Yang and Holland, 2003; Yamaguchi et al., 2007; Retallack et al., 2013). The outcrops in the central and eastern parts of the Transvaal sub-basin are considered to be partially preserved sections with the upper part of the palaeosol eroded during or prior to the deposition of the Dwaalheuwel Formation (Beukes et al., 2002). In contrast, drill core information from Lobatse provides a complete record of the palaeosol (Yamaguchi et al., 2007). The complete sequence of the palaeosol includes from base to top:

- fresh basaltic lava,
- partially altered lava (saprolite),
- a Fe-depleted pallid zone,
- a Fe-enriched mottled zone,
- a lateritic horizon, and
- a reworked laterite or ferricrete (Rye and Holland, 2000; Beukes et al., 2002; Yang and Holland, 2003; Yamaguchi et al., 2007).

This palaeosol serves as one of the main arguments in the discussion of the timing and nature of the oxygenation of the atmosphere (i.e., GOE – Great Oxygenation Event; Ohmoto, 1996, 2004; Holland, 2006; Luo et al., 2016).

Deformation

The Hekpoort Formation is typically only weakly deformed within the Pretoria Group succession. Around the BC, regional dips might steepen towards the centre of the intrusion, locally attaining 40° and more. Along the southern flanks of the BC, however, for instance at the B'Sorah farm, the bedding of the lahar deposits and other secondary volcaniclastic deposits is sub-vertical (dips of 75 to 90° towards 110 to 140° and towards 290 to 300°, *ca.* north-northeast–northeast strike), without exhibiting pronounced cleavage or schistosity, which can perhaps be attributed to syn-sedimentary deformation in a rift environment. In the Mooikloof area, east of Pretoria, small, approximately east–west striking synclines and anticlines paralleling the strike of the margin to the BC have been mapped out (Robinson, 2015).

Deposition of the entire formation generally took place during rifting and subsidence of the Kaapvaal Craton (Eriksson et al., 2001, 2006; Lenhardt et al., 2012).

General petrology

The majority of the Hekpoort Formation lavas exhibit aphanitic to hypocrystalline textures. Petrologic study confirms low-grade greenschist facies metamorphism related to burial, in addition to

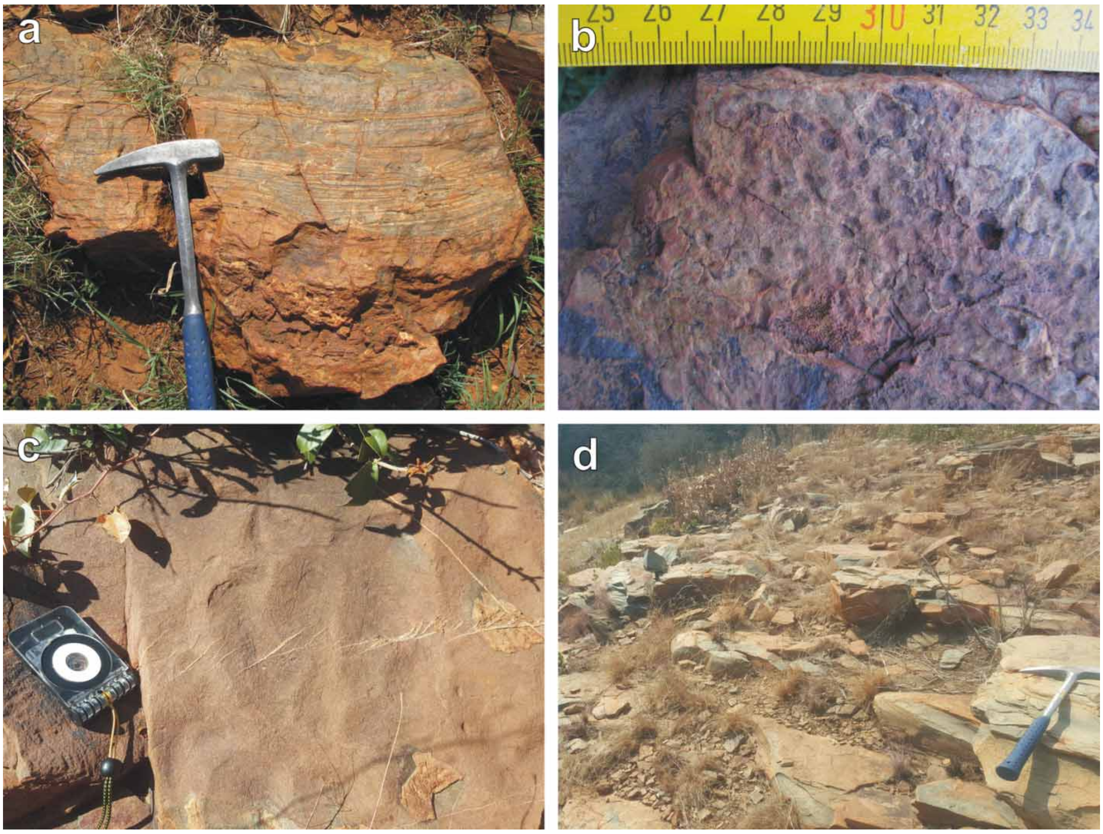

Figure 5. *(**a**) Silicified cherty shales at Mooikloof containing layers of iron-oxide/ hydroxide; (**b**) possible raindrop imprints at the surface of silicified shales; (**c**) ripple surfaces on trough cross-bedded sandstones at B'Sorah farm; (**d**) typical outcrop of the Hekpoort Formation sandstones at B'Sorah farm.*

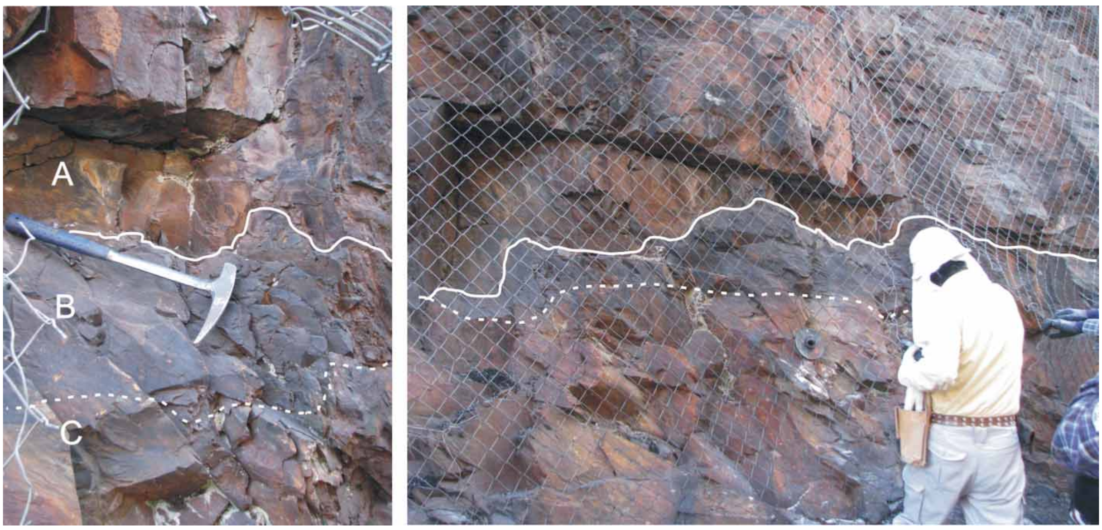

Figure 6. *Hekpoort palaeosol outcrop at Waterval Onder, main highway N7 towards east, 25°38'43.19"S; 30°21'27.63"E. Layer A is a trough cross-bedded quartzite, hydrothermally altered, with abundant pyrite cubes, Dwaalheuwel Fm. White solid line delineates the unconformity; Layer B shows the Waterval Onder palaeosol, hydrothermally altered, no pyrite cubes, interpreted as surface cumulic swales or gilgai by Retallack et al. (2013); Layer C is the tuffaceous Waterval Onder palaeosol, less altered than above, representing a vertisol according to Retallack et al. (2013). Layers B and C are composed of fine tuffaceous material with some shale (clay minerals), mainly in the cumulic swales. The photographs are taken at the same locality as Retallack et al. (2013) (Figure 2A), but the outcrop is now covered by a rockfall protective fence, which has been partly removed (and reinstalled) for sampling. White dashed line marks approximately the lower boundary of the gilgai lense. Hydrothermal alteration may be due to diabase intrusion in the direct vicinity.*

metasomatic alteration principally indicated by silicification, K-metasomatism and albitization (Reczko et al., 1995; Humbert et al., 2018a). Preserved primary minerals are mostly clinopyroxenes (Figure 7a to d), Mg-rich augite ± pigeonite in less differentiated samples and augite or diopside in the more differentiated samples. Augite, when present, displays Fe-rich rims. Relics of pyroxenes, fully pseudomorphed by clinochlore or actinolite (Figure 7b), have been interpreted as orthopyroxene. Microliths of Mg-rich hornblende are rarely found (<1%). Plagioclase (labradorite, An52-68) can be present as 0.8 to 1.2 mm wide phenocrysts or as 0.5 to 1 mm euhedral grains (Figure 7e), but most commonly occurs as acicular crystals (Figure 7f). Most of the plagioclase has been albitised, and the released Ca formed secondary calcite (Figure 7a), epidote (Figure 7e) and, rarely, titanite. Some plagioclase crystals are also partially replaced by sericite and K-feldspar (Humbert et al., 2018a).

Other secondary minerals observed are almost pure K-feldspar and quartz. The latter is the main mineral filling the amygdales, but quartz is also found around ferromagnesian minerals (bottom-right of Figure 7b). The other minerals filling amygdales are chlorite (clinochlore), calcite and, less commonly, zeolites. The LOI in the Hekpoort Formation rocks is quite constant relative to the Mg number (Mg# = molar [MgO/(MgO + FeO*)]), i.e., between 2.5 to 3.7 wt%; it is mostly attributed to the high chlorite content in the samples (Humbert et al., 2018a, b, 2019). This suggests that, overall; the rocks of the Hekpoort Formation have not been intensively altered. However, the roughly constant SiO_2 content versus the evolution of Mg# strongly suggests that these rocks were affected by widespread silicification (Humbert et al., 2018a).

Geochemistry and origin of the magma

Lavas of the Hekpoort Formation are mostly fractionated basalts, (Figure 8a), with variable whole rock Mg# evolving from 69 to 50 and MgO between 5.0 and 11.3 wt%; (mean: 7.0 ± 1.7 wt%; data from Humbert et al., 2018a, b). The differentiation of the lava is related to fractionation of orthopyroxene, clinopyroxene ± spinel, and plagioclase in the later, and more advanced, stages of differentiation (Humbert et al., 2018a).

The Hekpoort basalts show a strong enrichment of light REE values relative to heavy REE, the La/Lu normalized to chondrite is between 7 to 10 (Figure 8b). These basalts also show an arc-like trace element signature, mainly represented by remarkably negative Nb-Ta anomalies (in normalized trace element patterns; Figure 8c), and also exhibit relatively high contents of Th and U and high Th/Nb ratios, which sharply contrast with Archaean basaltic units. This denotes the source of the magma as the subcontinental mantle lithosphere, that was possibly intensively metasomatised by past subduction (Humbert et al. 2018a, 2019). These authors interpreted the Hekpoort Formation rocks as probably representing a late stage in a progressive differentiation series (by crystal fractionation) from a single parental magma with variable degrees of crustal assimilation (which also contributed to the relative high Th and U contents and negative Nb-Ta anomalies).

Genesis

The Hekpoort Formation was formerly described as deposited in a subaerial setting (e.g., Button, 1973; Sharpe et al., 1983; Engelbrecht, 1986; Eriksson and Twist, 1986; Oberholzer, 1995; Reczko et al., 1995) that was characterised by relatively flat morphologies of the Hekpoort flood basalts as major continental flood basalts of the Kaapvaal Craton. It is possible that basin-wide deposition within the Pretoria Group was rapid and lasted only a few million years but the lack of radiometric ages does not allow firm conclusions to be drawn. However, the existence of PDC deposits suggests the localised presence of some elevated point sources such as smaller stratovolcanoes. Especially the lahar deposits in the south and north-east of the type area suggest the existence of a graben system with volcanic shoulders during the time of deposition. In addition, the presence of various fine-grained, intercalated sediments, hyaloclastites and possibly pillow basalts points to deposition in a variety of ponds and lakes and probably smaller braided streams where clastic sedimentation and magma-water interaction could take place (*cf.* Lenhardt et al., 2012; Humbert et al., 2018a). Such large igneous provinces are usually characterised by fast deposition (Ernst, 2014).

Economic potential

There is no published information on any economic concentration of base metals. Due to the continental, subaerial, nature of deposition, the economic potential is considered to be low. However, the Hekpoort Formation basaltic lavas form very fertile soils and serve as a stable construction ground in the Gauteng Province.

Boundaries

Lower boundary

Naturally, through the positively weathering lavas, overlying negatively weathering sedimentary rocks (either the Timeball Hill or Boeshok formations), exposure of the base of the Hekpoort Formation is poor. Within the Potchefstroom syncline, in eastern Pretoria (Mooikloof) and from there towards the east of Mpumalanga, the Hekpoort Formation rests conformably on the poorly outcropping and probably lenticular, fluvial (previously often wrongly described as glacial; *cf.* Altermann et al., 2018) Boshoek Formation conglomerates and sandstones (Cheney, 1996; Eriksson et al., 2006; Eriksson and Altermann, 2013). At Mooikloof, eastern Pretoria, fragments of the underlying Boshoek Formation fine conglomerate occur a few decimetres below outcropping Hekpoort rocks. The actual boundary is, however, obscured by soils. Towards the west of these areas and especially northeast of Hekpoort, e.g., on the B'Sorah farm, the formation sharply overlies mudrocks of the Timeball Hill Formation with an erosional contact. Direct contacts between the lenticular Boshoek Formation and the overlying Hekpoort Formation have also been described from the western part of the Transvaal sub-basin (Schreiber et al., 1990).

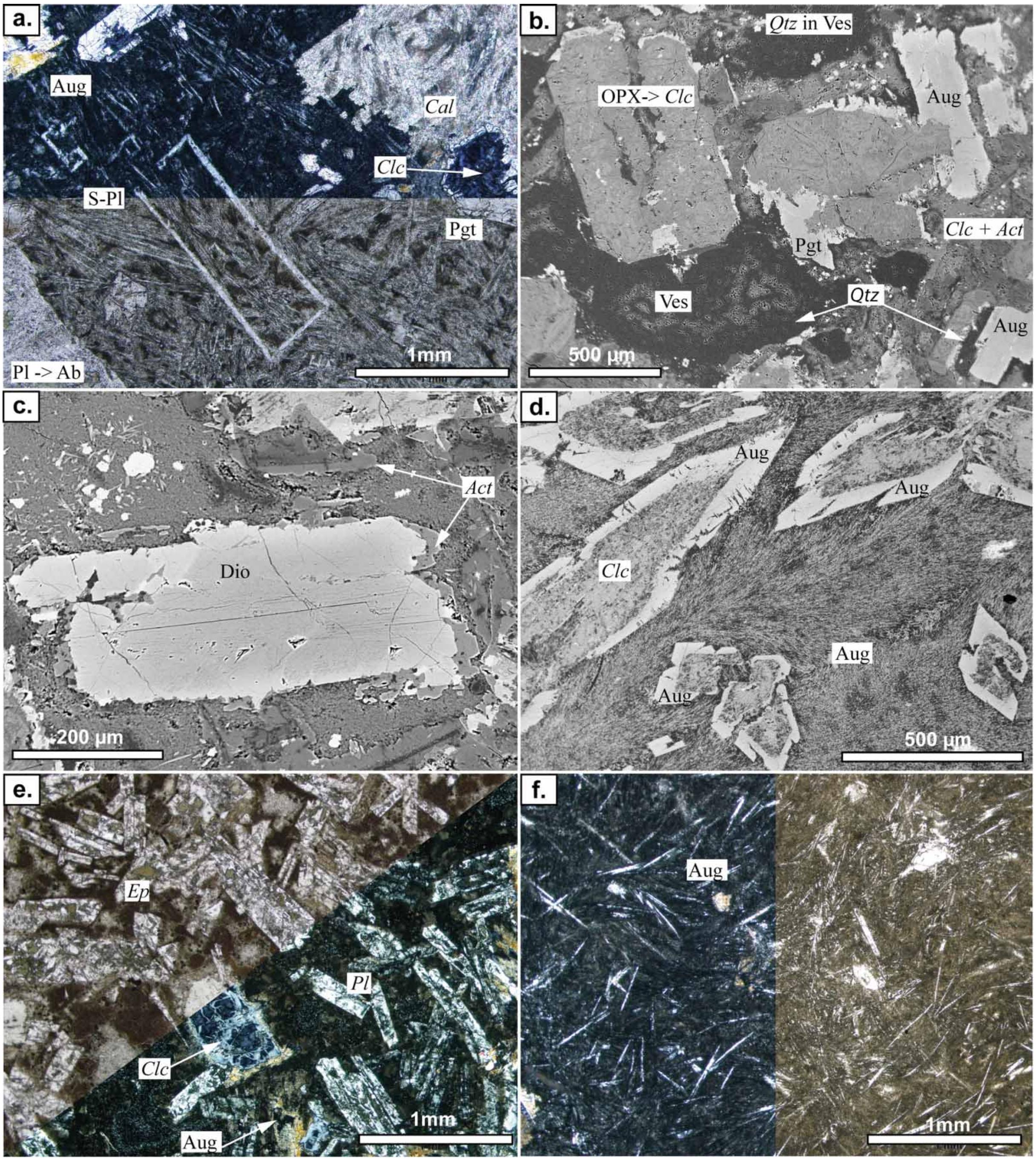

Figure 7. *(**a**), (**e**) and (**f**) Thin sections combining PPL and XPL modes, and (**b**) to (**d**) backscattered electron images. (**a**) microlitic texture surrounding a skeletal plagioclase. Pseudomorphosed euhedral pyroxenes in between two vesicles (ves) filled by quartz (**b**) and actinolite overgrowth on a preserved diopside (**c**). (**d**) interior of a variole showing skeletal clinopyroxene phenocrysts with a core pseudomorphosed by clinochlore in basal and longitudinal cross-section. The skeletal clinopyroxenes are surrounded by acicular micrometric clinopyroxenes composing the varioles. All clinopyroxenes are augites. (**e**) intersertal texture showing euhedral plagioclase, orthopyroxene (pseudomorphosed by clinochlore ± quartz) and clinopyroxene. (**f**) detail of a microlitic (hyalopilitic) texture. Primary minerals: Aug=augite; Opx=orthopyroxene; Pl=plagioclase; Pgt=pigeonite; S-Pl=skeletal plagioclase. Secondary minerals (in italics in the images): Act=actinolite; Cal=calcite; Clc=clinochlore; Ep=epidote.*

Upper boundary

In most places, the upper part of the Hekpoort Formation has been erosionally removed shortly after the lava extrusion, forming an unconformity at the base of the overlying fluvial quartzites of the Dwaalheuwel Formation (*cf.* Schreiber and Eriksson, 1992). Locally, this unconformity is represented by the Hekpoort oxic palaeosol (Figure 2a), which is, however, also often incompletely preserved (see section on Palaeosols).

Lateral boundaries

The Hekpoort Formation has no lateral boundaries within its distribution area.

Subdivision

The Hekpoort Formation has not been further subdivided.

Palaeontology

The well documented palaeosol at the top of the Hekpoort Formation (see above), may be a possible evidence-site for an early appearance of the first terrestrial eukaryotes (Retallack et al., 2013). The putative fossils found there and named *Diskagma buttoni* Retallack gen. et sp. nov. are urn-shaped with a flared rim and are closed below the flare. Superficially, these mm-sized objects are comparable with lichens such as *Cladonia* (Ascomycota) and *Geosiphon* (Glomeromycota), but biological affinities of *Diskagma buttoni* remain uncertain because organic walls or matter (e.g., remains of mucilage, kerogen, etc.) were not found in these alleged microfossils (Retallack et al., 2013). Thin section investigation of palaeosol, sampled from the same outcrop by W. Altermann, was unable to confirm the presence of these possible microfossils. This study showed the palaeosol to be a tuffaceous rock, hydrothermally altered together with the quartzite of the overlying Dwaalheuwel Formation.

Regional aspects

Geographic distribution

The Hekpoort Formation has a basin-wide extent throughout the Transvaal sub-basin (Figure 1). Northwest of the BC, the Hekpoort Formation can be traced from a point (24°55'21.68"S; 25°56'14.85"E) 7 km southeast of Ramotswa in Botswana to east of Ramoshibitswana in the North West Province (24°57'25.63"S; 26°56'54.53"E). South of the BC, the formation generally extends from Gopane (25°16.18"S; 25°49'20.96"E) in the west towards east of Mooikloof (25°52'05"S; 28°22'32"E) in the East. East of the BC, the Hekpoort Formation extends from northeast of Carolina in Mpumalanga (26°03'56.86"S; 30°06'59.81"E) to north of Burgersfort (24°40'53.34"S; 30°20'03.55"E).

The Hekpoort Formation lavas and intercalated sedimentary rocks usually form gentle hills and valleys that make sporadic good outcrops that are not covered by dense vegetation (Figure 3a). For instance, the Potchefstroom syncline and Fochville monocline (the two lower solid red rectangles in Figure 1) represent the only areas where outcrops of the Hekpoort can be observed in the southernmost part of the Transvaal sub-basin. Much of the Hekpoort outcrop area is occupied by settlements, urban and agricultural areas, including the hills of eastern Pretoria, Fochville, Potchefstroom and the circum-Bushveld hill and mountain chains. In the latter, the strata dip towards the centre of the BC intrusion and the different lava flows form parallel small ridges in the topography. The Mooikloof area in east Pretoria (Figure 1) for which the lectostratotype is proposed can be reached by following the M30 towards the east. After the Mooikloof Heights and opposite the Grootfontein Country Estates, follow Tier Road towards the

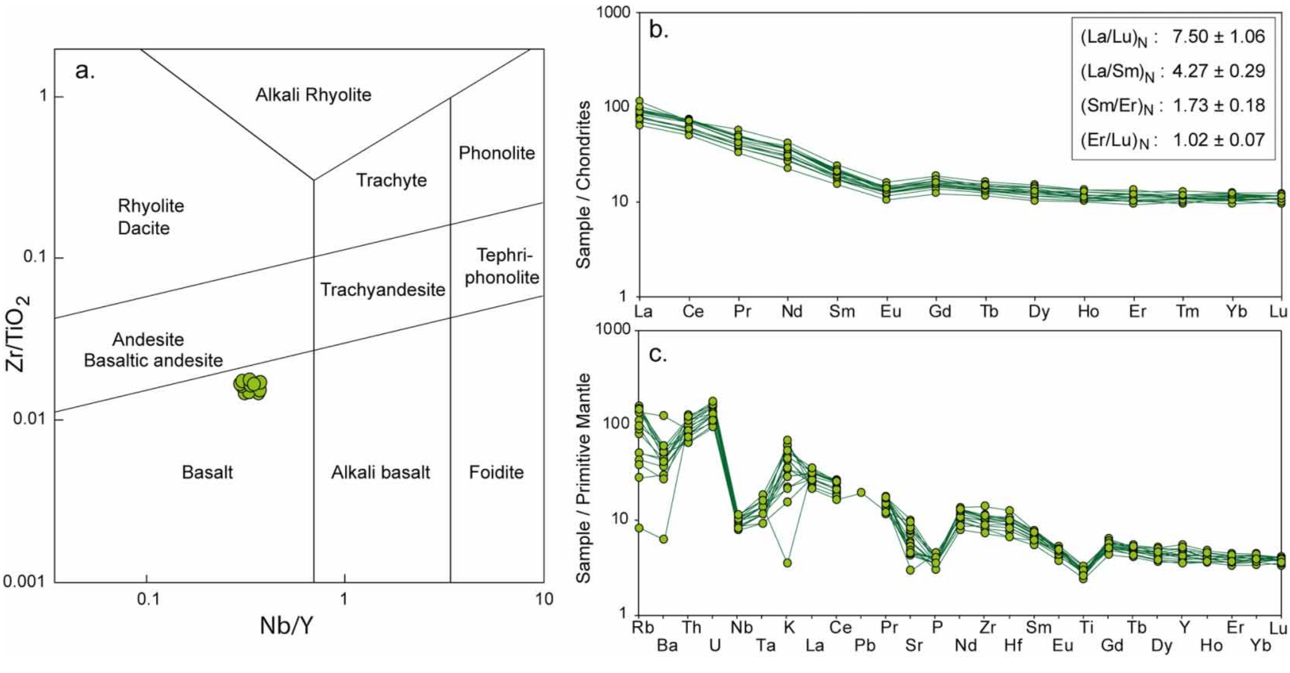

Figure 8. *(**a**) Classification diagram of Pearce (1996) with the Hekpoort samples from Humbert et al. (2018a; Table 1). Due to the likelihood of alkali and silicon mobility during metamorphism or metasomatic alteration, this plot is preferred to the traditionally used TAS diagram. REE (**b**) and multi-element diagrams (**c**) of the same samples respectively normalized to chondrites and to primitive mantle, after Palme and O'Neill (2014).*

northeast. The Hekpoort outcrops can be found predominantly northeast of the Leribisi Road on both sides of Tier Road.

The B'Sorah farm (25°50'45.09"S; 27°46'39.62"E) northeast of the type locality can be reached via the R3 from Pretoria. Following the R3 (that soon changes into the R400) towards the west, the best outcrops of lahar deposits can be found at the coordinates 25°50'36.11"S; 27°46'06.12"E (Figure 4c). From here, following the R563 towards the north and hence, towards Hekpoort village, exposure of the Hekpoort Formation can be found along both sides of the road. The accessibility and the outcrop conditions in this area are very good. Note that all these areas are private properties and access depends on the cooperation of the landowners from whom permission must be sought. In the Fochville monocline (Figure 1), coming from Johannesburg via the N12, good outcrop of the Hekpoort Formation can be found at the Danie Theron monument (26°27'06.60"S; 27°26'14.43"E) opposite the Mponeng Gold Mine. Following the N12 further to the small town of Wedela (26°28'15.06"S; 27°22'36.27"E), numerous large exposures of the Hekpoort Formation can be seen in the immediate vicinity of the town. Driving down Alfred Kobi Street towards Wedela, outcrops with variolites are found between the Kusasalethu mine tailings and the town (26°28'25.63"S; 27°22'02.84"E). All these outcrops are easily accessible. Further outcrops occur to the northwest of Potchefstroom.

Additional sparse outcrops in the east (Mpumalanga Province) can be found by following the R36 from Carolina towards the north. After *ca.* 4.5 km, follow a gravel road towards the east. After further 21 km, outcrops at 25°56'45.56"S; 30°19'13.96"E are found in an otherwise relatively flat area. The original outcrop of the palaeosol (25°38'43.19"S; 30°21'27.63"E) near Waterval Onder can be found after passing through the Daspoort tunnel along the N7, coming from Pretoria, but before reaching the village.

Lateral variation

As previously mentioned, no major facies changes in the Hekpoort Formation have been documented across the Transvaal sub-basin and the dominating lithology in nearly all outcrops is lava originating from sheet flows. Small and poor outcrops of pillow lava and pahoehoe lavas occur sporadically and are locally restricted. The only exception to this can be seen northeast of the type locality where deposition took place in a graben setting and where almost equal proportions of lava and volcaniclastic rocks can be found.

Correlation

In the pre-2017 literature, the Hekpoort Formation was correlated with the Ongeluk Formation of the Postmasburg Group (Figure 1). Although there are strong geochemical similarities between the two formations (Cornell et al., 1996; Humbert et al., 2018a, 2019), recent dating of the Ongeluk Formation at 2426 ± 3 Ma (U-Pb isochron on baddeleyite), by Gumsley et al. (2017) has demonstrated that the Hekpoort and Ongeluk formations are separated by *ca.* 200 Myr. Instead, the Hekpoort Formation could correlate with the Tsatsu Formation of the Kanye sub-basin (Botswana) towards the west of the Transvaal sub-basin (*cf.* Franchi and Mapeo, 2019). Similar to the Hekpoort Formation, the Tsatsu Formation is predominantly characterised by grey lavas of basaltic to andesitic composition. Confirmation of this correlation will require an in-depth study of the petrology, geochemistry and geochronology of the Tsatsu Formation.

Palaeomagnetic correlations

The palaeomagnetic study of the Hekpoort Formation by Humbert et al. (2017) reveals a complicated history with several magnetic overprints. However, a regionally common magnetic component that is resistant to thermal demagnetisation is potentially a primary magnetisation recorded during cooling of the Hekpoort Formation lavas. The timing of the acquisition of this remanence is further constrained by positive fold tests and the presence of magnetic reversals (Humbert et al., 2017). As also noted by Humbert et al., (2017) a secondary origin of the remanence cannot be excluded, but what is clear is that it is older than ~2.0 Ga.

The steep inclination of the possible primary magnetisation (~80°) seen in the Hekpoort Formation (Humbert et al., 2017) is in strong contrast with the 21° inclination of the known primary magnetisation for the older Ongeluk Formation (Gumsley et al., 2017). So far the magnetisation of the Hekpoort Formation only resembles magnetisations reported from ~2.2 Ga dykes (i.e., the Mashishing dyke swarm of Wabo et al., 2019) and a <2.46 Ga magnetic overprint seen in the Ghaap Group carbonates and shales of the Griqualand West sub-basin (i.e., the SD direction of de Kock et al., 2009).

Stratotypes

The holostratotype for the formation, as designated by the proposer SACS (1980), should have been near Hekpoort village (25°52'59.85"S; 27°36'59.94"E) but has never been established. The reason for this might be the relatively flat morphology and the sparse outcrops in the largely farming area. For this reason, a lectostratotype is proposed for the Mooikloof area in east Pretoria in order to provide a formal definition of the Hekpoort Formation. In addition, two reference stratotypes are proposed for areas in the Fochville monocline and the Potchefstroom syncline (see Figures 1 and 2a). All three sections, the lectostratotype and the reference stratotypes, are composite sections. Thicknesses were acquired from measurements in the field and through GPS measurements, used in ArcGIS, and subsequent re-calculation of true thickness.

At Mooikloof, the Hekpoort Formation unconformably starts with the occurrence of a hyaloclastite and several metres-thick massive lapilli tuff. The tuff, in turn, is overlain by *ca.* 500 m of lava characterised by up to 60 m-thick sheet flows. The only major disruption of this relatively monolithic sequence is at *ca.* 325 m, where several lenses of m-thick, silicified cherty shales occur. Above a maximum thickness of 500 m at this location, an erosive boundary at the top of the Hekpoort Formation lavas towards the overlying rippled, fine-grained sandstones of the Dwaalheuwel Formation marks an unconformity between the two formations.

The Fochville and Potchefstroom reference stratotypes are also included in Figure 2a. However, apart from the thickness (*ca.* 800 m for the Fochville and *ca.* 350 m for the Potchefstroom stratotypes), the lithologies of these two stratotypes do not significantly differ from the lectostratotype defined at Mooikloof. The Fochville lectostratotype is characterised by the occurrence of a palaeosol at its top. Similarly, the Potchefstroom lectostratotype exhibits a layer of hyaloclastites at the top, shortly before the unconformity with the overlying Dwaalheuwel Formation.

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