A 5-km-thick reservoir with > 380,000 km³ of magma within the ancient Earth’s crust

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Several recent studies have argued that large, long-lived and molten magma chambers may not occur in the shallow Earth’s crust. Here we present, however, field-based observations from the Bushveld Complex that provide evidence to the contrary. In the eastern part of the complex, the magmatic layering continuously drapes across a ~ 4-km-high sloping step in the chamber floor. Such deposition of magmatic layering implies that the resident melt column was thicker than the stepped relief of the chamber floor. Prolonged internal differentiation within this thick magma column is further supported by evolutionary trends in crystallization sequence and mineral compositions through the sequence. The resident melt column in the Bushveld chamber during this period is estimated at > 5-km in thickness and > 380,000 km³ in volume. This volume of magma is three orders of magnitude larger than any known super-eruption in the Earth’s history and is only comparable to the extrusive volumes of some of Earth’s large igneous provinces. This suggests that super-large, entirely molten, and long-lived magma chambers occur, at least occasionally, in the geological history of our planet. Therefore, the classical view of magma chambers as ‘big magma tanks’ remains a viable research concept for some of Earth’s magmatic provinces.

For over a century, the classic paradigm of volcanology and igneous petrology has been premised upon the existence of magma chambers, filled by crystal-free melt, forming ‘big tanks’1–10. Such magma chambers gradually lose heat and crystallize from all margins inwards and occasionally supply overlying extrusive centres (volcanoes or fissures) with magma that erupts onto the Earth’s surface1–10. This founding concept has, however, been recently challenged on the basis of observations and evidence from various disciplines. The most often-cited evidence is derived from geophysical surveys that are unable to conclusively identify any present-day magma chambers11. This is supported by thermal modelling12, which indicates that the formation of a large magma body within the upper crust is physically problematic, because it requires a magma accumulation rate that is 1–2 orders of magnitude greater than determined through geochronology11. In addition, out-of-sequence geochronology has been used to argue that the known mafic–ultramafic plutons do not require the existence of large magma chambers but could be produced as a stack of randomly-emplaced amalgamated sills13–15. The conclusion from these studies is that large, predominantly molten magma chambers are likely either transient16 or non-existent11,12 in the geological history of the Earth. As an alternative, it is proposed that intracrustal melt is stored within intergranular pockets of crystal-rich mushes that occupy almost the entire crust, from the Moho towards surface16–21. Periodic tectonic destabilization of the mush may produce small, discrete melt lenses that subsequently aggregate, ascend and erupt as lava. There are, however, some observations from magmatic complexes22–24 as well as thermal modelling constraints12 that conflict with this emerging paradigm16–21. Here we present one well-constrained example from the Bushveld Complex, indicating that the magma chamber appears to have contained, during one stage of its evolution, an enormous volume of resident melt that slowly crystallized from the base upwards to produce a continuous sequence of chemically stratified cumulate rocks.

Incremental growth of the Bushveld Complex. The 2.05 billion-year-old Bushveld Complex in South Africa is the largest mafic–ultramafic layered intrusion into the Earth’s crust. It occupies an area that most likely exceeds 100,000 km² and extends ~ 450 km east–west and ~ 350 km north-south25–28. Despite its enormous size, this complex is merely the remaining portion of an originally much larger intrusion that has subsequently been

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eroded to an unknown extent by surface processes. The complex consists of several parts, of which the western, eastern and northern limbs are the largest, and is stratigraphically subdivided into five major units—the Marginal, Lower, Critical, Main, and Upper Zones, comprising a total thickness of about 7 to 9 km. The Bushveld Complex is widely considered to be a typical example of an open-system magma chamber. Apart from the marginal rocks, its four principal zones are attributed to major replenishing events, with numerous smaller magma recharges contributing to the formation of these zones. During this process, the magma chamber incrementally increased in size through both vertical and lateral inflation. All major replenishing events are marked by regionally extensive magmatic disconformities, local erosive unconformities into previous strata, significant isotopic shifts, and notable changes in whole-rock and mineral compositions. These relationships are best exemplified by the Main Zone (MZ) at the Tonteldoos area of the southeastern Bushveld Complex (Fig. 1), which has a much larger lateral extent than the underlying Critical Zone (CZ), as indicated by the MZ's direct onlapping of the floor rocks in many places. The MZ is commonly attributed to a large influx of new magma that significantly expanded the chamber in both vertical and lateral extent, producing a regional disconformity and locally prominent unconformities with pre-existing CZ cumulates. The base of the MZ is also marked by a substantial isotopic shift towards more radiogenic whole-rock Sr/Sr ratios and an increase in both the An-content of plagioclase and Mg-number of pyroxenes. Successive crystallisation of the entire Bushveld Complex from the Lower and Upper Critical Zone to the Main Zone occurred within ca. 1 million years, between 2055.91 ± 0.26 Ma and 2054.89 ± 0.37 Ma. Attempts to place stricter constraints on the crystallisation of the complex using high-precision U–Pb TIMS ages have proved problematic because zircon isotopic ages in these studies appear to be at odds with basic field relationships.

The resident melt column of the Bushveld Complex. The stratigraphy of the Bushveld Complex is most commonly thought to have progressively accumulated from the overlying resident melt by deposition of crystals on the chamber floor, although there are several alternative views. A critical unknown parameter is the volume of resident melt at any particular time during the evolution of the magma chamber. We present here a potential solution through field mapping of the southeastern Bushveld Complex. The mapped geology exposes no evidence for any major syn-magmatic (e.g., the floor subsidence) or post-emplacement (e.g., fault displacement) structural deformation of the country rocks. The host stratigraphy was intruded by precursor Bushveld Complex sills that are sharply truncated by the main plutonic phase of the Bushveld Complex. The mapped geology exposes no evidence for any major syn-magmatic (e.g., the floor subsidence) or post-emplacement (e.g., fault displacement) structural deformation of the country rocks. The sediments are best exemplified by the Main Zone (MZ) at the Tonteldoos area of the southeastern Bushveld Complex (Fig. 1), which has a much larger lateral extent than the underlying Critical Zone (CZ), as indicated by the MZ's direct onlapping of the floor rocks in many places. The MZ is commonly attributed to a large influx of new magma that significantly expanded the chamber in both vertical and lateral extent, producing a regional disconformity and locally prominent unconformities with pre-existing CZ cumulates. The base of the MZ is also marked by a substantial isotopic shift towards more radiogenic whole-rock Sr/Sr ratios and an increase in both the An-content of plagioclase and Mg-number of pyroxenes. Successive crystallisation of the entire Bushveld Complex from the Lower and Upper Critical Zone to the Main Zone occurred within ca. 1 million years, between 2055.91 ± 0.26 Ma and 2054.89 ± 0.37 Ma. Attempts to place stricter constraints on the crystallisation of the complex using high-precision U–Pb TIMS ages have proved problematic because zircon isotopic ages in these studies appear to be at odds with basic field relationships.
Figure 1. The geological map of the southeastern part of the Bushveld Complex in the Tonteldoos area. The complex transgresses upwards through the Transvaal Supergroup over the northern 35 km of this sector and the floor of the complex steps up by approximately 6 km. The basal part of the Main Zone has three continuous markers layers termed the Lower, Middle, and Upper Mottled Anorthosites that extend along the entire area. The position of cross-sections in Figs. 2 and 6 and seven major traverses across Anorthosite Markers in Figs. 3, 4, 5 (see also Supplementary Data) are indicated. Regional geology digitised from the 1:250,000 scale geology maps 2528 Pretoria and 2530 Barberton (Geological Survey of South Africa), with additional detail from mapping by Van der Merwe⁴⁹, Bevington and Hornsey (2010, Nuplats Ltd, unpublished mapping), and Latypov and Chistyakova (2021, unpublished mapping). The figure was prepared by Richard Hornsey using Micromine 2021 Release 21.5.
the resident melt column must have been thicker than the ∼4.0 km height of the Tonteldoos step. The lithological interpretation is supported by a systematic decrease in An-content of plagioclase and Mg-number of orthopyroxene through the ∼3.0-km-thick MZ stratigraphy of the Roossenekal sub-chamber, indicating internal differentiation of a resident melt column that was thicker than the crystallised sequence (Fig. 6). The transition to the overlying Pyroxenite Marker is defined by an up to 0.5-km-thick reversal towards more primitive mineral composition (Fig. 6), which has been interpreted to result from mixing of a residual MZ melt with new magma entering the chamber, causing further vertical expansion. Mass balance calculations based on Sr-isotopic data indicate that the residual melt comprised 60–70% of the resulting hybrid magma, which subsequently crystallized to form a >3.0 km thick sequence overlying the Pyroxenite Marker (Fig. 2). If correct, the residual melt of the MZ must still have been ∼2-km-thick prior to the Pyroxenite Marker magma influx, thereby indicating an initial ∼5 km thickness of the MZ melt column; consistent to earlier estimates based upon thermal modelling of the Bushveld Complex. We concur with previous studies that the instantaneous top of the cumulus pile during deposition in this region was gently basinal, with the Stoffberg remnant partially separating the Roossenekal and Belfast sub-chambers. This is best indicated by the concave geometry of the Pyroxenite Marker.
Marker within the Roossenekal sub-chamber, resulting in this layer being almost 2 km stratigraphically lower at the centre of this sub-chamber, compared to the Stoffberg remnant (Fig. 2). This field evidence implies that the ~ 1.0 km and ~ 3.0 km thick MZ in the Roossenekal and Belfast sub-chambers, respectively, formed synchronously from the same interconnected resident magma, further substantiated by similar An-content of plagioclase at the base of the MZ at both sub-chambers (67.5%39,60 and 71%40,41, respectively). The greater thickness of MZ cumulates in the Roossenekal sub-chamber may be related to the greater thickness of this unit, due to redeposition of crystals inside this depression and/or prevailing crystallization in the deeper parts of the magma chamber, due to pressure-induced increase in the liquidus temperature of the melt9,54,61.

Rather than implying that the entire ~ 5.0 km thick column formed from a single large magma influx, it is proposed that the intrusion progressively grew to its final size (from the Roossenekal sub-chamber towards the Belfast sub-chamber) through emplacement of numerous magma influxes, yet over a much shorter time scale than solidification. During this period of repeated injections, each replenishment effectively mixed with the resident melt in the chamber, thereby delaying or impeding the onset of crystallization. Thus, crystallization commenced within a completely filled, large and homogenized magma chamber, which can thereby be modelled as having crystallized as a ‘single pulse’ of magma (Fig. 7a). Our model is therefore substantially different from those where the melt crystallization and cumulate pile growth of the MZ occurred concurrent to magma chamber replenishment37. Our model conforms better to liquidus phase equilibria predictions for a basaltic parent, such as systematic changes in pyroxene assemblages (e.g., Opx-Aug through Opx-Aug-Pig to Aug-Pig)62 and continuous decreases in both the An-content and Mg-number of cumulus plagioclase and orthopyroxene, respectively (Figs. 6 and 7b). Both the crystallization sequence and mineral compositional trends are reproduced.

Figure 3. Photos of field outcrops of the three Anorthosite Markers along the traverse I-I of the Roossenekal sub-chamber of the southeastern part of the Bushveld Complex. All photos were taken by Sofya Chistyakova or Rais Latypov.
by fractional crystallization of the parental melt (Extended Data, Extended Data Fig. 2) using the alphaMELTS software. It should be noted, however, that the modelling results are not unique (e.g., they are greatly dependent on the choice of a parental melt composition) and cannot, therefore, be considered as solid evidence of the model developed in this study. Such unidirectional evolutionary trends are also inconsistent with models that attribute the formation of the MZ to externally-derived crystal-rich slurries, because these would result in either constant or irregular trends in mineral compositions through the MZ stratigraphy. It is quite conceivable, however, that during protracted fractionation of the MZ resident melt, the chamber may have been further replenished by additional minor magma pulses with or without phenocrysts since minor local reversals in the An-content of plagioclase are discernable within the overall decreasing trend (Fig. 6). In fact, the Anorthosite Markers themselves may be associated with magma chamber replenishments. Such occasional and relatively small magma chamber recharges do not, however, modify our major conclusion with respect to the initial resident melt column thickness, prior to the onset of crystallization at the first anorthosite marker (i.e., LMA in Fig. 2). It was only after a protracted and relatively quiet period of continuous crystallization of the MZ, that a major influx of orthopyroxene-saturated magma incrementally mixed with the magma chamber’s resident melt, while concomitantly crystallizing a succession of cumulates both below and above the Pyroxenite Marker (see Thermodynamic modeling in Extended Data).

Implications for the ‘big tank’ magma chamber paradigm. The 5-km-thick resident melt column that produced the chemically stratified MZ cumulate sequence, including its three prominent Anorthosite Markers, indicates that during this stage the Bushveld chamber was exceptionally large and entirely molten.

Figure 4. Photos of field outcrops of the three Anorthosite Markers along the traverse IV-IV at the Tonteldoos step of the Roossenekal sub-chamber of the southeastern part of the Bushveld Complex. All photos were taken by Sofya Chistyakova.
The formation of such a cumulate sequence, at a typical solidification rate for large mafic intrusions (~1 cm/year\textsuperscript{30,66}) would take ~300,000 years indicating that the intrusion was also long-lived. These conclusions are at odds with an emerging paradigm that such ‘big tank’ magma chambers were ephemeral at any given time throughout Earth’s geological history\textsuperscript{16,19,20,67,68}. The total volume of resident MZ melt may be estimated as follows. The MZ melt column varied between ~5.0 km in the thicker and, at least, 1.0 km thick in the thinner parts of the intrusion. Based on reconstructions of the lateral extent of the MZ\textsuperscript{29}, it is estimated that the thicker areas occupied ~70% of the MZ, and the remaining ~30% were thinner zones. The estimated Bushveld Complex area is approximately 100,000 km\textsuperscript{2}\textsuperscript{26,28} and therefore the total volume of the MZ resident melt is ~380,000 km\textsuperscript{3} (5 km * 70,000 km\textsuperscript{2} + 1.0 km * 30,000 km\textsuperscript{2}). This volume is several orders of magnitude larger than the largest ignimbrite/tuff super-eruptions in Earth’s history (e.g., Bishop tuff—600 km\textsuperscript{3} and Youngest Toba eruption—up to 13,200 km\textsuperscript{3})\textsuperscript{69}. It is only comparable to estimates of some of Earth’s large igneous provinces, such as the Karoo (367,000 km\textsuperscript{3})\textsuperscript{70} and Afar (350,000 km\textsuperscript{3})\textsuperscript{71}. Thus, during emplacement of the MZ, the Bushveld magma chamber was a repository of an enormous volume of resident melt and may be regarded as a ‘big tank’ open-system within the Earth’s crust. Therefore, the current tendency in modern volcanology\textsuperscript{16,19,20} and petrology\textsuperscript{13–15} to discard the existence of such large and molten magma chambers\textsuperscript{4–7} appears to be premature. There is also no compelling reason to believe that ‘big tank’ magma chambers, such as the 2.05 Ga Bushveld Complex, are restricted to a long-forgotten past of our planet, such as the Precambrian. This is indicated by the 55 Ma Skaergaard intrusion in Greenland whose spectacular chemical stratigraphy indicates that before the onset of crystallization it was a ‘big tank’ of crystal-free tholeiitic parent magma up to 4 km in thickness and up to 300 km\textsuperscript{3} in volume\textsuperscript{2,73}. Another example is the 1.3 Ga Kislaapait intrusion in Labrador with 3500 km\textsuperscript{3} of magma in a >8 km thick magma chamber that shows a continuous differentiation sequence with little or no magma recharge\textsuperscript{74,75}. It is therefore

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**Figure 5.** Photos of field outcrops of the three Anorthosite Markers along the traverse VI-VI of the Belfast sub-chamber of the southeastern part of the Bushveld Complex. All photos were taken by Sofya Chistyakova.
conceivable that such magma chambers have developed throughout the entire Earth's evolution. Even if some regions of the Earth's crust may behave as giant crystal mushes (e.g., mid-ocean ridges or deep roots of continental arcs)\textsuperscript{16,17,20,76}, this does not automatically imply that 'big tank' magma chambers are absent from other regions (e.g., stable cratons with layered intrusions)\textsuperscript{5–7}. Moreover, since layered intrusions such as the Bushveld Complex are rare throughout geological time\textsuperscript{77}, it is not surprising that there are currently no active examples of large and molten magma chambers in Earth's crust which can be detected geophysically\textsuperscript{11}.

**Methods**

**Map and cross-sections constructions.** The maps were created by digitally capturing the 1:250,000 geological survey maps (2528 Pretoria, and 2530 Barberton, Geological Survey of South Africa) into Micromine software (http://www.micromine.com). Additional details come from mapping by Van der Merwe\textsuperscript{49}, Bevington and Hornsey (2010, Nuplats Ltd, unpublished mapping), and Latypov and Chistyakova (2021, unpublished mapping). Micromine is a commercially available geological software package widely used for exploration and mine planning to model geological datasets in 3d space. The version used for the latest iteration of the model was Micromine 2021 Release 21.5. The maps were digitally captured as polygons, which were then draped onto a digital terrain model downloaded from the USGS Earth Explorer website (https://earthexplorer.usgs.gov). The terrain data were used to create a digital terrain model wireframe (DTM) that was cut into separate entities using the geological polygons and attributed according to the lithological unit. To create the geological section, the geological model was rotated using Micromine to enable visualisation of the data as a section looking down the plunge of the Bushveld Complex. The detailed geology was then manually digitised from the 3-dimensional section as a planar section that was then attributed to show the lithological units using the same colour scheme as for the plan. The imagery was exported from Micromine as formatted plans and sections. These were then...
imported into MSPowerpoint software, within which the labelling and legends were added. The final product was then exported as an image for inclusion into the research paper. The geological section therefore illustrates the entire stratigraphy and relationships between the Bushveld Complex and its host stratigraphy showing the “as-mapped” relationships and geometries in their correct spatial location. The maps are all in WGS84 Datum, UTM zone 36 South.

**Data availability**
The authors declare that all relevant data are available within the article and its Supplementary Information Files.
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Author contributions
R.L. and S.C. conceptualized the original research idea of this study, undertook field work in this area, including traversing, small-scale mapping and sampling of outcrops, wrote a draft of the paper and prepared some figures. The original field mapping of the Anorthosite Markers across the entire study area was undertaken by M.M. R.H. constructed a 3-dimensional geology model of the Eastern limb from which the geological map and longitudinal sections of the study area were produced. G.C. performed thermodynamic modelling and participated in interpretation of data, editing the paper as well as in improving clarity of figures. All co-authors discussed the results and problems and contributed to producing a final draft for peer reviews.

Competing interests
The authors declare no competing interests.

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