The Low Permeability of the Earth's Precambrian Crust

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The large volume of deep groundwater in the Precambrian crust has only recently been understood to be relatively hydrogeologically isolated from the rest of the hydrologic cycle. Currently, the paucity of permeability measurements in the Precambrian crust is a barrier to modeling fluid flow and solute transport in these low porosity and permeability deep environments. Estimates of permeability from prograde metamorphic rocks and geothermal systems have been applied to such groundwater systems, but, as data are few, it is unclear how appropriate this is for Precambrian crust on a global scale. To resolve this, we apply a new approach to constrain permeabilities for Precambrian crust to depths of 3.3 km based on fluid residence times estimated from noble gas analyses. The additional data reveals there is no statistically significant relationship at depths below 1 km, challenging the previous assumption of a global correlation between permeability and depth. Additionally, we show that estimated permeabilities at depths >1 km are at least an order of magnitude lower than previous estimates and possibly much lower. As a consequence, water and solute fluxes at these depths will be extremely limited, imposing important controls on elemental cycling and the distribution of subsurface microbial life.

Introduction

Precambrian crust, which makes up ~72% of the Earth's continents by surface area [1], has been estimated to host between ~8.5 and 13 million km^3 of groundwater [2,3]. This deep store of mostly saline groundwater accounts for 20 to 30% of total continental groundwater reserves. Estimates of groundwater residence times in Precambrian rocks (Figures 1 and 2a), can exceed 1 billion years [2,4–6], with the longest residence times found in Archean age rocks. These deep and ancient groundwaters are estimated to contain a substantial portion of the Earth's biomass, with microbial activity found to depths of up to

2-3 km [7–12]. The degree of hydrogeologic and associated geochemical isolation from near-surface environments exerts control on the habitability, abundance and diversity of subsurface microbial life [6,9,11–13].

The crystalline rocks of the Earth's Precambrian crust are inherently a low permeability hydrogeologic regime where what fluid flow occurs is primarily via fractured rocks. However, despite representing a significant proportion of the crust globally (Figure 1), detailed permeability measurements are few, particularly in deep (>1 km) crystalline rock [14–17]. These permeability values are necessary to constrain fluid and solute fluxes in the crust, to define the degree of interconnectivity that might occur between subsurface biomes, and to provide insights into the distribution and connectivity of fracture networks in deep Precambrian rock.

Previous Permeability-Depth Relationships

Permeability typically decreases with depth due to geomechanical and geochemical processes [14,18,19] and permeability-depth relationships have been derived for a variety of environments using different approaches (Table 1). A prime example of such as relationship was generated using data from geothermal and metamorphic environments [15,20] (Figure 2b) which extended down to depths of 40 km, including the 10 km thickness of brittle crust nearest to the ground surface. This relationship has been widely invoked for a range of applications from studies of generic regional flow systems [21], geomechanical studies of the crust [22], examination of the circulation of deep meteoric fluids[23], biogeochemical cycles[24] and, following scaling for gravity, to study Martian hydrogeology[25]. However, Ingebritsen and Manning[20] noted that stable tectonic settings ('cratons') where a significant proportion of the world's oldest rocks, including those of Archean age, are located, are likely to have even lower permeability values than the models they developed would predict. More recent studies based on compilations of permeability estimated from a range of in situ and laboratory hydraulic testing techniques[14,16] confirm the lower permeability values in crystalline rock down to depths of 1.3 km (Figure 2b), but, as previously noted, relatively few measurements are available from Precambrian rock at greater depths.

Constraining Permeability with Residence Time Estimates

To address this gap, we carried out a novel approach to estimate in situ permeabilities by incorporating noble gas-based residence times of groundwaters in Precambrian rock at depths of up to 3.3 km[2,4,5,26] (Figure 2a). Analysis of the noble gas content of fracture fluids sampled from Canada, Fennoscandia and South Africa have revealed mean fluid residence times ranging from a few thousand to over one billion years.

We estimate permeabilities by assuming that these fluids have travelled less than 10 km based on the dimensions of regional groundwater flow in the Canadian Shield[27] and previous treatment of flow system dimensions in metamorphic and geothermal environments[15] (see methods section). This distance provides an upper bound for flow system size in Precambrian rocks, where flow systems will likely be shorter and driven by factors other than topography.

The permeabilities estimated from the noble gas residence times had the following relationship with depth (Figure 2):

$$\log k = -16.74 - 0.96 \log z \qquad [1]$$

This linear regression has an R^2 value of 0.229, which is significant at a p-value of 0.001. The vast majority of the locations examined here are from Archean settings, with only one sample from Sweden and one from Finland both in Proterozoic rock. Whether Archean cratons and other Precambrian rocks of Proterozoic age that reflect a broader range of structural features such as rifts, accretionary complexes, and/or metasediments have significantly different permeability-depth relationships is beyond the scope of this paper as permeability measurements or estimates for a diverse global set of Proterozoic settings are even fewer than for the Archean systems.

Equation [1] produces log k values that are 1.2 lower than the Ingebritsen and Manning (1999) at a depth of 3 km. Log k estimates would increase by 1.0 if either hydraulic gradients were decreased by approximately an order of magnitude or flow systems were increased by an order of magnitude. These higher permeabilities are unlikely because longer flowpaths are uncommon in Precambrian rock due to the limited geologic continuity and the hydraulic gradient of 10^{-3} used here is at the low end of the range of global values[28]. It is plausible these noble gas samples were collected in systems that had higher hydraulic gradients in the geologic past, perhaps approaching the global median value of 1.3×10^{-2} [28], which would result in a decrease in our estimated permeabilities by approximately an order of magnitude. There is also considerable evidence that solute transport in deep Precambrian rock is dominated by diffusion [6,29,30], which indicates that permeabilities less than 10^{-20} m^2 are common[31].

This study's finding is in overall agreement with that found by analyzing in situ tests compiled by Achtziger-Zupancic et al. (2017; Table 1) for stable crust (i.e. cratons). The upper limit of permeabilities estimated here are slightly greater than those predicted by a relationship proposed for batholiths (large masses of relatively homogeneous intrusive igneous rock)[16] (Table 1; Figure 2), which likely reflect the lower-end of permeability relative to Precambrian rock as a whole. Permeability is elevated in the upper 1 km in Precambrian rock, which supports the concept that enhanced permeability in shallow (<1 km) crystalline rocks is largely a function of weathering rather than unloading or tectonics [32,33](Figure 3). This zone also corresponds to the approximate depth where meteoric and paleometeoric waters are typically found to penetrate in the Canadian Shield, Fennoscandian Shield and Witwatersrand Basin [5,23], suggesting that groundwater flow is more active in the upper 1 km and limited by permeability at greater depths.

A notable finding of this exercise is that below this 1 km zone, there is no significant correlation between estimated permeability and depth (log k and log z, respectively) at the $p = 0.1$ level. In sedimentary environments, permeabilities generally decrease from the ground surface to depths of several km due to compaction and diagenesis[19,34] but a similar trend is not obvious in Precambrian rock below 1 km. Any trends related to geomechanical and geochemical processes that are a simple function of depth could be overwhelmed by the long and often complex burial and exhumation histories of Precambrian rocks[35]. The apparent increase in permeability from Canada to Fennoscandia to South Africa hint at the importance of differences in the geological histories of these settings that promise to be important issues for future studies. The presence of younger groundwaters at depth in the Witwatersrand Basin, and in the Sudbury Impact Crater on the Canadian Shield, may be the result of the high degree of fracturing related to the impact event forming the basin (Warr et al. 2018; 2022). The widespread presence of paleometeoric waters at depth in the Fennoscandian Shield (Osterholz et al., 2022) suggests the presence of interconnected fracture network and elevated permeability.

These estimated permeability values provide an upper bound for actual values because the transit distances of groundwater in Precambrian rock are likely substantially less than the 10 km used in the test case outlined here (Figure 3). If a value of 1 km[36] were used, rather than the value of 10 km[20], estimated permeabilities would be an order of magnitude lower than the upper estimates presented here, reinforcing the overall conclusion arising from this study. The noble gas analyses determine the period of hydrogeologic isolation from atmospheric recharge events, but it is important to note that these fracture fluids are the net product of groundwater circulation, original syn-depositional fluids, and subsequent fluid history and water-rock reaction [4,5]. Hence burial, negative buoyancy, and tectonic forcing may have been important mechanisms that would result in shorter transit distances and lower permeability estimates, as would the inherently hydrogeologic discontinuous nature of sparsely fractured rock.

In this study the overall good coherence between the He-Ne-Ar-Xe derived noble gas residence times at each site support a model of hydrogeologic isolation. However, As Warr et al 2022[6] recently demonstrated, these settings actually represent a spectrum from being fully isolated to fully open. At sufficiently low diffusion coefficients (10^{-15} m^2/s), there will be no appreciable losses of any noble gases [29]. At slightly higher diffusion coefficients, noticeable diffusive transport of He and Ne will occur while Ar, Kr, and Xe will be retained [6,29]. Relating these low rates of diffusion to permeability is not straightforward – there is no universally agreed upon relationship between permeability and diffusion coefficient. However, laboratory testing of core samples have found correlations between permeability and diffusion coefficients [37–39]. The lowest diffusion coefficients found in those studies were a few orders of magnitude higher than those required to prevent differential diffusion of noble gases and were accompanied by suggesting permeabilities > 10^{-21} m^2. If the relationships found by Kuva et al. (2015) holds for lower diffusion coefficients, bulk permeabilities in Precambrian crust could be as low as 10^{-25} m^2.

Differential transport rates of different noble gases have been noted at Sudbury, Canada[2] and Moab Khotsong, South Africa[6]. In these studies the evidence for diffusive loss of the light noble gases (He, Ne) versus the heavier Ar, Kr, Xe was hypothesized to be related to increased fracturing of the basement due, in both cases, to their history as impact craters[5,6]. The resulting bulk diffusion coefficients have similar values to the 10^{-11} to 10^{-9} m^2/s range considered by Manning and Ingebritsen[15], who suggested a transition between diffusion-dominated environments and advection-dominated environments occurs at permeability of 10^{-20} m^2.

Permeability and Life in the Deep Subsurface

Studies of the deep subsurface biosphere have to date suggested there is evidence for a depth component associated with microbial communities, with Proteobacteria-dominated communities at shallower depths of ~1 km [10], while Firmicutes-dominated communities are thought to be more common at depths > 1 km. This pattern has been observed in South Africa [10,40,41] and Fennoscandia [42,43]. This boundary corresponds to a general geochemical transition with changes observed in salinity, Eh and a general transition from meteoric and paleometeoric waters to shield-type brines that plot to the left of the global meteoric water line (GMWL) [5,44,45]. This shift in the δ^2H and $\delta^{18}O$ values of waters at depths > 1km to lie to the left of the GMWL is the result of water-rock reactions including oxygen isotopic exchange between waters associated with hydrothermal/metamorphic activity and the host rocks over very long (Ma+) time periods

[5,46]. The position of this transition zone approximately corresponds to the transition from the upper more permeable zone of Precambrian crust to lower permeability environments at depth (Figure 3). The reduced permeability at these depths restricts fluid and solute fluxes and transport is likely dominated by diffusion in some areas. These lower fluxes can affect cycling and migration of critical elements in the subsurface (e.g. CHNOPS) and may potentially exert an important control on the distribution and composition of microbial communities.

Large shifts in hydrologic conditions such as continental-scale glaciations [47–50], regional uplift [44], or erosion by large rivers [51] can result in mixing of meteoric fluids with saline and reduced groundwater from depths exceeding 1 km and, in such cases spur microbial activity by re-inoculation or by introduction of a larger pool of nutrients associated with the meteoric and/or paleometeoric waters [52–54]. These events are most commonly documented in sedimentary basins, where permeability is considerably higher than for Precambrian rocks, but similar patterns have been suggested to explain the changes in the deep biosphere observed in the Witwatersrand Basin for instance [45,55,56].

Conclusions

Residence times estimated from noble gas analyses of deep groundwaters suggest that the permeability of Precambrian rock is at least approximately 2 orders of magnitude lower than previous estimates of prograde metamorphic and geothermal environments. A regression-based on permeabilities estimated from noble-gas derived fluid residence times globally provided a similar decrease with depth to that based on hydraulic tests in the upper 1.3 km of Precambrian rock [14]. However, permeability estimates deeper than 1 km no longer show a statistically significant correlation with depth. The limited diffusion rates in these environments imply that the permeabilities are likely even lower than those estimated here and considerably more dependent on lithologic setting and geological history, including events such as impact fracturing, than previously considered.

The low permeabilities of Precambrian rock suggest that microbiological processes in this deep biosphere are more likely to be limited by fluid and solute fluxes and more dependent on diffusive transport than they are in other environments. As a consequence, microbial communities at depths in Precambrian rock will likely be more isolated than in other geological environments and, as a consequence, will be slower to respond (if at all) to changes in surface and near-surface Earth system processes.

Methods

Groundwater residence time (τ) is calculated with:

$$\tau = \frac{L}{\frac{k\rho g}{\mu\eta}\nabla h} \qquad [2]$$

L is flow system length, k is permeability, ρ is fluid density, μ is viscosity, η is porosity, and ∇h is the hydraulic gradient (Figure 1). Here, we rearrange this equation to estimate permeability (k):

$$k = \frac{L\nabla h\mu\eta}{\tau\rho g} \qquad [3]$$

An upper limit of 10 km was used for L, based on the dimensions of regional groundwater flow in the Canadian Shield[27] and previous treatment of flow system dimensions in metamorphic and geothermal environments[15].We assume a hydraulic gradient of 10^{-3}, which is in line with the topographic gradients of Precambrian environments[23]and less than the global median water table gradient value of 0.013 [28]. Based on a number of previous studies that have reviewed porosity in Precambrian rocks [2,3,17,28,30](Ferguson et al., 2021; Gleeson et al., 2016; Sherwood Lollar et al., 2014; Stober & Bucher, 2007; Warr et al., 2018), we use a porosity of 1% in our permeability estimates. We use the residence times compiled by Warr et al.[5] along with additional data on the depth of sample collection from the original studies (Table S1).

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Table 1: Permeability-depth relationships derived from previous studies.

Environment	**Permeability-Depth Relationship**	**Method**	**Maximum Depth (km)**
Prograde metamorphic[15,20]	$\log k = -14 - 3.2 \log z$	Geothermal and metamorphic	28.4
Tectonically active continental crust (dynamic)[57]	$\log k = -11.5 - 3.2 \log z$	Metamorphic and seismic analysis	38
Upper crust[58]	$\log k = -25.4 + 13.9(1+z)^{-0.25}$	Various	5
Crystalline rock (various environments)[14]	$\log k = -16.36 - 1.53 \log z$	Hydraulic testing	5.45 (>4000 measurements below 1 km, 26) measurements below 2 km)
Stable shields and platforms[14]	$\log k = -16.16 - 1.35 \log z$	Hydraulic testing	1.3
Canadian Shield[16]	$\log k = -21 +(5.55/[1+(z/1.51)^{4.2}]^{0.1919}$	Hydraulic testing	1.3 (22 measurements below 1 km)

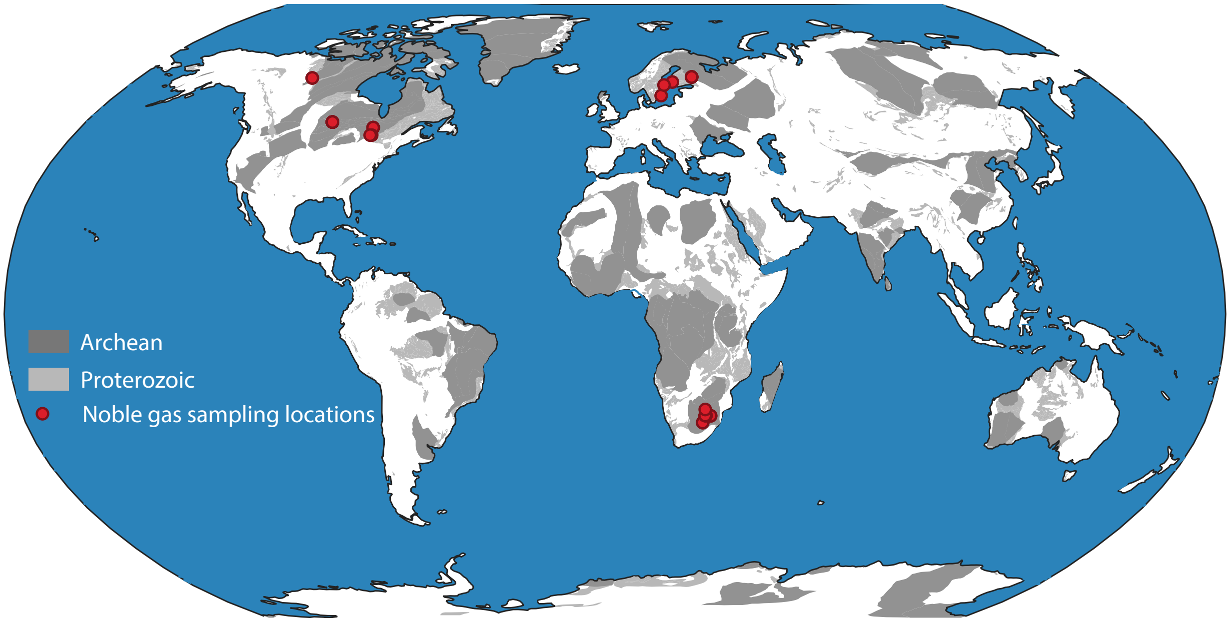

Figure 1: Global distribution of Archean cratons (exposed and buried)[59] and Proterozoic rock[60] showing locations of noble gas-derived residence time data used to estimate permeabilities in this study.

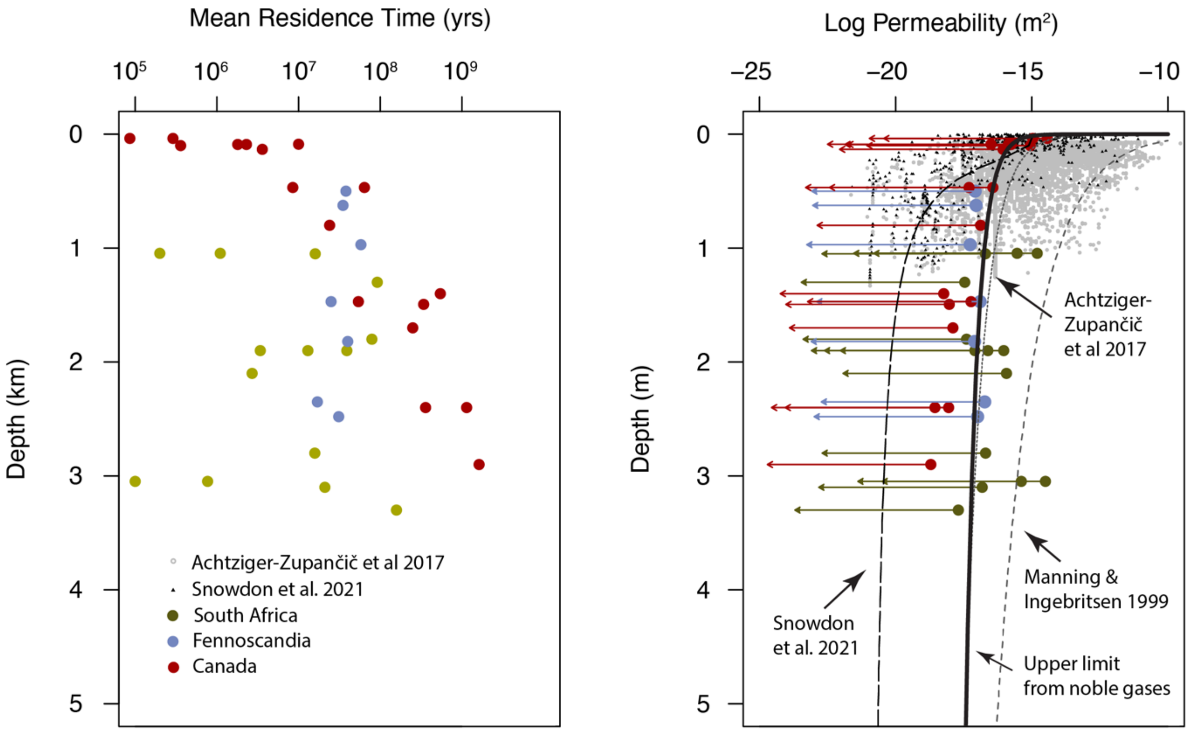

Figure 2a) Distribution of fracture water residence times estimated from noble gas analyses from Warr et al.[5] and references therein and b) permeabilities estimated from those ages. Permeability estimates from groundwater residence times are lower than those expected from Ingebritsen and Manning's[20] permeability-depth relationship but in close agreement with the relationship for stable provinces found by Achtziger-Zupančič et al. [14]. Measurements for Precambrian rock in Canada[16] and globally[14] to depths of 1.3 km suggest that there is likely considerable variability in permeability at depth that may be difficult to capture with the approach used here.

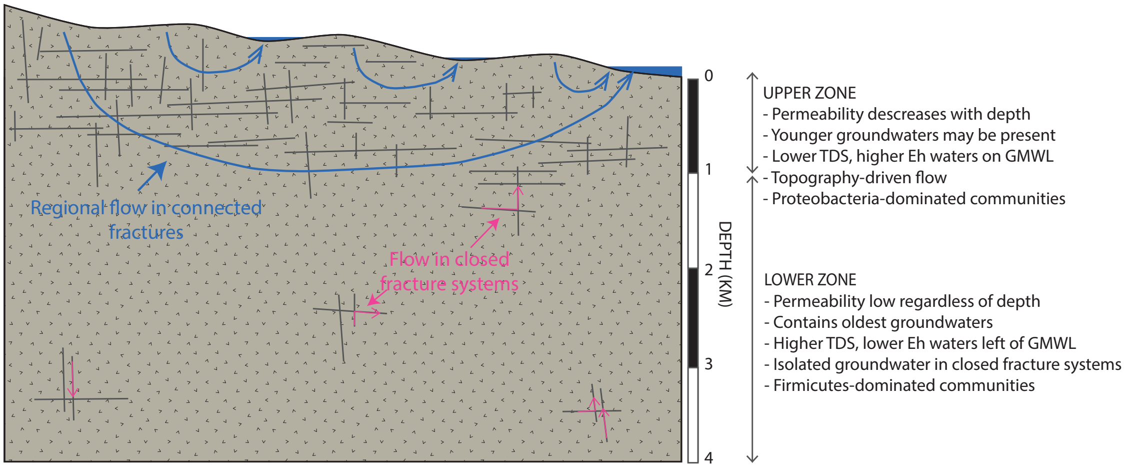

Figure 3: The permeability estimates in this study are consistent with the conceptual model of an upper zone characterized by decreasing permeability with depth that contains lower TDS, higher Eh waters that plot near the GMWL; and a lower zone characterized by low permeability without a strong relationship with depth that contains higher TDS, lower Eh waters that plot to the left of the GMWL [5,45,55,56]. The upper zone hosts protobacteria-dominated communities, while the lower zone tends to contain Firmicutes-dominated communities [10,41].