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Key Points:

- Groundwater is the largest continental store of water, liquid or otherwise
- The volume of deep saline groundwater is similar to shallow potable groundwater
- Deep groundwater systems remain largely unexplored

Supporting Information:

Supporting Information may be found in the online version of this article.

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Crustal Groundwater Volumes Greater Than Previously Thought

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Abstract Global groundwater volumes in the upper 2 km of the Earth's continental crust—critical for water security—are well estimated. Beyond these depths, a vast body of largely saline and non-potable groundwater exists down to at least 10 km—a volume that has not yet been quantified reliably at the global scale. Here, we estimate the amount of groundwater present in the upper 10 km of the Earth's continental crust by examining the distribution of sedimentary and crystalline rocks with depth and applying porosity-depth relationships. We demonstrate that groundwater in the 2–10 km zone (what we call "deep groundwater") has a volume comparable to that of groundwater in the upper 2 km of the Earth's crust. These new estimates make groundwater the largest continental reservoir of water, ahead of ice sheets, provide a basis to quantify geochemical cycles, and constrain the potential for large-scale isolation of waste fluids.

Plain Language Summary Global groundwater volumes in the upper 2 km of the Earth's continental crust, which include important potable water supplies, are well estimated. At greater depths, a vast body of largely saline water exists down to at least 10 km and this volume that has not yet been quantified reliably at the global scale. Here, we estimate the amount of groundwater present in the upper 10 km of the Earth's continental crust. We demonstrate that groundwater between 2 and 10 km deep has a volume comparable to that of groundwater in the upper 2 km of the Earth's crust. These new estimates make groundwater the largest continental reservoir of water, ahead of ice sheets. This large volume of fluid, which is thought to be largely disconnected from the rest of the hydrologic cycle, is largely uncharacterized.

1. Introduction

Groundwater is known to be much larger than any other terrestrial reservoir of liquid water (Shiklomanov, 1993), but previous estimates of the volume of groundwater have varied considerably in their computed volumes and approach. Studies with a focus on groundwater in a water resource context have typically used a 1 or 2 km lower boundary for groundwater (Gleeson et al., 2016; Nace, 1969; Richey et al., 2015) because the bulk of water beneath this depth is too saline to be potable or is assumed to be not part of the active hydrologic cycle. Gleeson et al. (2016) estimated that 22.6 million km^3 of groundwater was present in the upper 2 km of the Earth's crust (Table1; Figure 1). Although the volume of groundwater above the 2 km boundary includes most potable groundwater resources, the circulation of meteoric water can extend well beyond this depth (McIntosh & Ferguson, 2021). Groundwater flow is known to occur to a depth of at least 10 km based on evidence from geological processes, such as metamorphism (Ingebritsen & Manning, 1999), hydrothermal activity (Ingebritsen et al., 1992), and seismicity (Townend & Zoback, 2000).

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Table 1
Previous and Revised Groundwater Volume Estimates for the Crust and Relative Percentages in Each Reservoir

Lithology	Previous est. (10^6 km^3)	%	Revised est. (10^6 km^3)	%
Sediments (0–2 km)	21.2[a]	70	21.8	50
Sediments (2–10 km)	n.a.	n.a.	8.4	19
Crystalline (0–2 km)	1.4[a]	4	1.8	4
Crystalline (2–10 km)	8.5[b]	26	11.9	27
Total	32.5		43.9	

Note. "n.a." indicates not previously estimated for sediments deeper than 2 km. In the top 2 km revised groundwater estimates for sediments and crystalline rock are comparable to previous published values. Between 2 and 10 km revised crystalline rock groundwater volume estimates are higher due to increasing proportion of crystalline rocks with depth and inclusion of all crystalline rock (Figure 3). The revised crystalline groundwater estimate coupled with new estimates for deep sediments increase the groundwater volume estimate by 11.4 million km^3.

[a]Previous estimates are taken from Gleeson et al. (2016). [b]Previous estimates are taken from Warr et al. (2018).

Warr et al. (2018) estimated a groundwater volume of 8.5 million km^3 in Precambrian cratons between 2 to 10 km depth by considering the 72% of the Earth's surface area beneath previously mapped Precambrian rocks (Goodwin, 1996; Sherwood Lollar et al., 2014) (Figure 1). The amount of groundwater between 2 and 10 km depth in sedimentary basins and Phanerozoic crystalline rocks has not yet been quantified.

Constraining the volume of deep groundwater has implications to our understanding of global hydrological and biogeochemical cycles over a range of temporal and spatial scales (Beinlich et al., 2020; Ingebritsen et al., 2006; Person & Baumgartner, 1995; Sherwood Lollar et al., 2014). Studies have previously revealed how fluid residence times in the deep crust may be millions to in excess of a billion years and, as a result, may potentially provide key insights into processes and events occurring over deep geologic time (e.g., Holland et al., 2013; Warr et al., 2018, 2021). Groundwater up to at least 4 km depth is thought to be habitable for microbes (Bar-On et al., 2018; Magnabosco et al., 2018), suggesting that deep groundwater may host a considerable amount of biomass. Here, we estimate the volume of water in both sediments and crystalline rock to a depth of 10 km for the first time and revise previous estimates for global groundwater volumes to incorporate this significant groundwater component associated with the remaining ~28% of crust between 2 and 10 km depth. The revised estimates presented here can be used to better refine and constrain estimates of subsurface biomass and hydrologic and geochemical budgets.

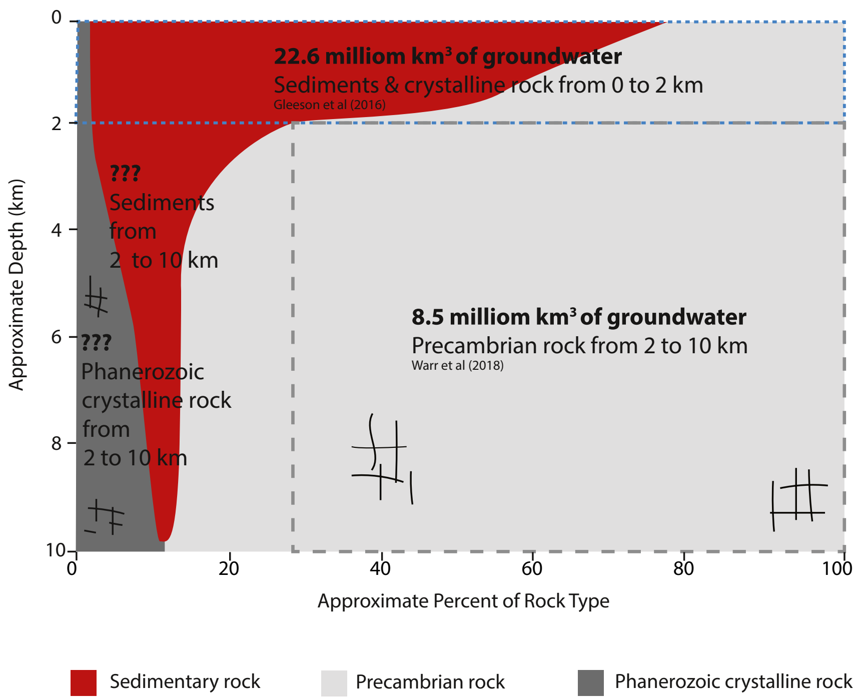

Figure 1. Estimates of groundwater volumes from previous studies of the upper 2 km and for Precambrian rocks between 2 and 10 km depth[23]. Volumes between 2 and 10 km depth in sedimentary basins and Phanerozoic crystalline rock have not yet been considered in recent studies estimating groundwater volumes at the global scale.

2. Distribution of Porosity in the Earth's Crust

The porosity of sedimentary rocks has been studied extensively to depths of approximately 5 km (Bjørlykke, 2014; Ehrenberg & Nadeau, 2005), primarily because of its importance to the oil and gas industry. Ehrenberg and Nadeau (2005) found that in carbonate rocks porosity varies from less than 1% to over 28% and in clastic rocks porosity varies between at least 7%–31%. The data from that study was derived largely from higher permeability reservoir rocks and the clastic rocks were likely dominated by sandstones. However, a synthesis of models describing the variation of porosity in shale with depth by Magara (1980) found porosities that ranged from approximately 40% at shallow depths to approximately 10% at a depth of 6 km, which is similar to that for clastics provided in Ehrenberg and Nadeau (2005). Despite this variability within individual lithologies, a consistent relationship between porosity and depth in sedimentary rocks has been recognized. Athy (1930) proposed a decay curve to describe the distribution of porosity with depth.

$$\eta = \eta_0 e^{-\beta z} \tag{1}$$

Where η is porosity, η_0 is porosity at the ground surface, β is a fitting parameter and z is depth in m below ground surface. This relationship was originally attributed to compaction (Athy, 1930; Rubey & King Hubbert, 1959) and β has been defined as compressibility (Gleeson et al., 2016). However, best-fit values of β from porosity-depth profiles are often much greater than those derived from a geomechanical treatment of compaction (Ingebritsen et al., 2006). Other studies have demonstrated that observed decreases in porosity with depth can arise due to diagenesis and that temperature and fluid chemistry may exert primary controls on the degree of porosity reduction with depth (Bjørlykke & Høeg, 1997; Bjørlykke & Jahren, 2012; Ehrenberg & Nadeau, 2005; Magara, 1980). Regardless of the mechanism, observations from a range of sedimentary environments show an exponential decrease in porosity with depth and models such as those above are reasonably successful for describing porosity versus depth on a regional or basinal scale (Ehrenberg & Nadeau, 2005; Goldhammer, 1997; Schmoker & Halley, 1982).

Porosity in crystalline rocks has received comparatively less attention than in sedimentary rocks, and measurements remain sparse especially below 1 km depth. Based on limited sampling from a small number of locations, porosity has been shown to range from ∼0.1% to 2.3% at depths >1 km but with no obvious trend with depth (Morrow & Lockner, 1994; Stober & Bucher, 2007) (Figure S1). It has been hypothesized that porosity will decrease with depth in cratons (Sherwood Lollar et al., 2014) and this can be inferred from permeability models (Achtziger-Zupančič et al., 2017; Ingebritsen & Manning, 1999); however, it has not been confirmed by measurements. The deepest known direct measurement of porosity, from a depth >11 km at Kola, Russia, is 0.6% (Morrow & Lockner, 1994). Warr et al. (2018) applied a porosity of 1%, invariant with depth, for estimation of groundwater volumes in Precambrian rocks at depths between 2 and 10 km, the same approach Gleeson et al. (2016) used for the upper 2 km. Detailed studies of fractures at a number of locations in crystalline bedrock at depths between 0.2 and 3.45 km have not found a significant correlation between either fracture spacing or aperture with depth (Barton & Zoback, 1992; Seeburger & Zoback, 1982). This suggests that fracture porosity does not have a simple relationship with depth in crystalline bedrock. Reductions in porosity with depth in crystalline rock are likely less pronounced than they are in sedimentary environments due to the lower porosity values to begin with, lower compressibilities of igneous and metamorphic rocks (Ingebritsen et al., 2006) and the role of diagenetic processes in sedimentary environments (Ehrenberg & Nadeau, 2005). This lack of evidence for a reduction in porosity with depth in crystalline rock supports the approach of using a constant porosity with depth to estimate pore volumes in deep crystalline rock.

Relationships between porosity and depth have previously been used to estimate groundwater volumes in specific environments but have not been applied to the entire upper 10 km of the Earth's continental crust. Here we use >40,0000 porosity values from depths of 0–5.5 (Ehrenberg & Nadeau, 2005) and the CRUST1.0 database (Laske et al., 2013) (see Section 3) to determine the volume of groundwater in deep sedimentary and crystalline rocks with uncertainty bounds.

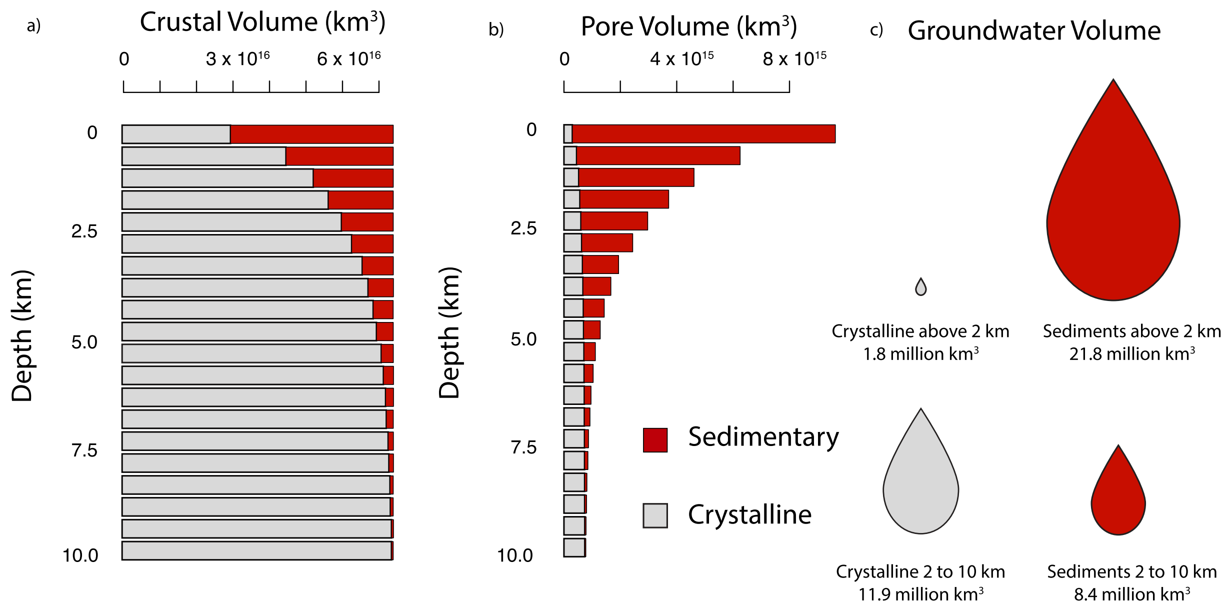

Figure 2. Global volumes of (a) sediments and crystalline rock from the CRUST 1.0 database (Laske et al., 2013) in 500 m intervals, (b) pore volumes calculated using those rock volumes along with a depth decaying porosity for sediments using Equation 2 and regressed constants from Ehrenberg and Nadeau (2005) and a constant porosity of 1% for crystalline rock, and (c) volumes of water in crystalline rocks and sediments in the upper 2 km and between 2 and 10 km depth (width of drops proportional to volumes).

3. Methods

Estimates of the thickness of sedimentary cover from the CRUST1.0 database (Laske et al., 2013, p. 0) (Figure S3) were used to determine the volumes of sedimentary rock at 0.5 km intervals in the Earth's crust down to a depth of 10 km (Figure 2). The 10 km depth was chosen because it is often considered the limit of groundwater due to its approximate coincidence with the brittle-ductile transition in the Earth's crust (Ingebritsen & Manning, 1999). Groundwater volumes were then estimated by multiplying the rock volumes by estimated porosities. This approach neglects the unsaturated zone, which is less than 20 m thick over most of the Earth's surface (Fan et al., 2013). This approach also assumes that volumes of other fluids, such as oil, are negligible at the global scale.

Porosities for sedimentary rock at each 0.5 km interval were estimated using Equation 1 and linear regression with the >40,0000 porosity values from depths of 0–5.5 km compiled by Ehrenberg and Nadeau (2005). Values for η_0 were 0.16 and 0.25 for carbonate and siliciclastic sediments, respectively; values for β were 1.7×10^{-4} and 1.5×10^{-4} m^{-1} for those rock types (Figure S1). We also examined the fits to the 10th and 90th percentiles of the same datasets to allow for a measure of uncertainty present in our estimates (Figure S2). We assumed that the volumetric proportion of sedimentary rocks for the entire thickness of the sedimentary sequence followed the same ratio of 23% carbonate rock and 68% siliciclastic that Gleeson et al. (2016) used. Also following Gleeson et al. (2016), we assigned 9% of the sedimentary cover as volcanic rock with porosity of 9 (±9)% given the CRUST1.0 classification maps the bulk of these rocks as sediments at the earth's surface (Gleeson et al., 2016; Hartmann & Moosdorf, 2012). While porosity of volcanic rocks can vary substantially, there is little evidence of correlation between porosity and depth for volcanic rocks (Gleeson et al., 2016 and references therein).

For crystalline rock, we assumed a depth-invariant porosity of 1% and used values of 0.5% and 2% to examine the uncertainty in these estimates. We also explored the implications of exponentially decreasing porosity with depth. Rather than using Equation 1 we used the following equation (Bethke, 1985) for the case where porosity decreases with depth:

$$\eta = \frac{\eta_0^{-za^{-1}}}{100} \quad (2)$$

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Where a is a fitting coefficient. Following Sherwood Lollar et al. (2014), we used $\eta_0 = 1.6\%$ and $a = 2.1 \times 10^{-4}$ m^{-1} to examine the implications of assuming an exponential decay of porosity with depth on pore volumes in deep crystalline rock.

4. Results

Our analysis, using the CRUST1.0 database to examine rock volumes in 500 m intervals, shows that beneath the Earth's continents, 12% of the upper 10 km is sedimentary rock and 88% is crystalline rock. Applying the porosity-depth relationship derived from fitting Equation 1 to the data set of Ehrenberg and Nadeau (2005) for this volume of sedimentary rock along with a uniform porosity of 1% for crystalline rock, we estimate that there is 43.9 million km^3 of groundwater in the upper 10 km of the Earth's crust (Table 1; Figure 2). To assess the uncertainty in this estimate, we use the 10th and 90th percentiles of porosities for sediments from Ehrenberg and Nadeau (2005), porosities of 0% and 18% for volcanics (Gleeson et al., 2016), and porosities of 0.5% and 2.0% for crystalline rock, which covers the bulk of the observed range for deep crystalline rocks (Stober & Bucher, 2007). This produces a range of estimated groundwater volumes between 25.0 million and 72.5 million km^3 (see Figure S1). The uncertainty in the relative amounts of clastic and carbonate sediments was of lesser importance than the porosities of these rock types. Reversing the percentages of these rock types (i.e., 68% carbonates and 23% clastics) results in an estimated groundwater volume of 38.0 million km^3.

Our estimate for the amount of groundwater in the upper 2 km is 23.6 million km^3 (1.8 million km^3 in crystalline rock and 21.8 million km^3 in sediments)—a value quite similar to the estimate of 22.6 million km^3 from Gleeson et al. (2016), which used slightly different values of porosity based on fits to the upper 2 km of available data along with the coarser resolution CRUST2.0 (Laske & Masters, 1997) database. Based on previous summaries of groundwater salinity distributions with depth (Ferguson, McIntosh, Perrone, & Jasechko, 2018; Fritz & Frape, 1982; Stanton et al., 2017; Stotler et al., 2012), it is likely that only the upper 1 km of groundwater is fresh (TDS <1,000 mg/L; Hem, 1985). We estimate that there is 15.9 million km^3 of groundwater in that zone, while the remaining 28.3 million km^3 between 1 and 10 km deep is likely brackish to saline in many locations.

It is notable that the amount of water beneath 2 km in deep sedimentary basins (8.4 million km^3) is similar to the amount found in crystalline rock (11.9 million km^3) despite the much larger volume of crystalline rocks globally (Figure 2). While there is considerable uncertainty with these estimates, even increasing the porosity of crystalline rocks to 2% would still result in fluid volumes in sedimentary and crystalline rock between 2 and 10 km that are similar in magnitude. However, if porosity decreases with depth following Equation 2, the amount of water in crystalline rocks between 2 and 10 km would only be 6.6 million km^3 (Figure S1). In the deepest crustal sediments and crystalline rocks between 8 and 10 km, there is approximately 22.2 million km^3 of groundwater, dominated by high salinities (Stotler et al., 2012). The inclusion of sediments and all crystalline rocks below 2 km adds 13.7 million km^3 to the 8.5 million km^3 of groundwater in Precambrian cratons previously estimated by Warr et al. (2018).

5. Discussion & Conclusions

We have identified a previously unmapped volume of groundwater that represents approximately ⅓ of the Earth's groundwater to a depth of 10 km. While the global oceans remain the planet's largest reservoir of water at 1.3 billion km^3 (Eakins & Sharman, 2010), the volume of water in the upper 10 km of continental crust (43.9 million km^3) estimated here is greater than the amount of water held in ice sheets in Antarctica (27 million km^3) (Fretwell et al., 2013) and Greenland (3 million km^3) (Lee et al., 2015) and glaciers (158 thousand km^3) (Farinotti et al., 2019), making groundwater now the largest reservoir of water globally other than the oceans (Figure 3). Even where porosity estimates at the lower end of observed values are used, the 26.5 million km^3 of groundwater we estimate is similar to that of the Antarctic Ice Sheet.

We recognize and acknowledge that there is considerable uncertainty in the estimated volumes of groundwater due to difficulties in estimating porosity distributions (Ehrenberg & Nadeau, 2005; Gleeson et al., 2016; Richey et al., 2015). The challenge of assigning lithologies at depth creates additional uncertainty. Our

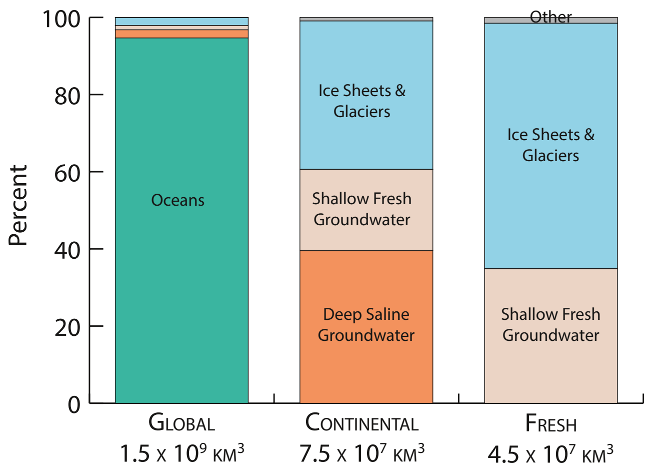

Figure 3. Relative sizes of water stores compared to overall storage of waters globally, on the continents and as a portion of total global freshwater storage. The bulk of continental water storage is likely groundwater, rather than ice sheets as previously thought (i.e., Shiklomanov, 1993).

results were calculated using the CRUST1.0 model that classified 88% of the upper 10 km of the crust as crystalline bedrock based on seismic measurements. Other studies have used a figure of 72%–75% for Precambrian crust, including both exposed crust and that under sedimentary cover (Sherwood Lollar et al., 2014; Warr et al., 2018), that encompasses the bulk of the Earth's crystalline crust. At 2.0 km depth, the CRUST1.0 model estimates that 75% of the Earth's surface area is covered by crystalline rock, which is similar to the value from Goodwin (1996) but would also include younger crystalline rock. Given the increase in the areal coverage of crystalline rocks with depth, Precambrian crust may occupy a slightly greater volume than previously thought. Additionally, it is unclear whether the assumption that the distribution of sediment types remains constant with depth (Gleeson et al., 2016) is valid. While the use of the CRUST1.0 model provides a first-order attempt at estimating the distribution of porosity in three dimensions, reconciling geophysical models with geological mapping efforts is required to improve estimates.

Sedimentary environments have been characterized by the oil and gas industry but groundwater data are limited in deeper sedimentary environments beyond 5 km. The deepest water sample available in the USGS Produced Water Database is 8,595 m. There are only 346 samples from below 5 km and the vast majority of those samples have been analyzed for only major ion chemistry, without information on fluid residence times (Blondes et al., 2016). Data are more limited from crystalline rocks, where spatially disparate mines are commonly used as windows into the subsurface. The deepest samples from those environments are from mines in the Witwatersrand, South Africa at 3.3 km (Lippmann et al., 2003) and Kidd Creek, Canada at 2.9 km (Warr et al., 2018). The limited data available suggest that the vast majority of water below 2 km is highly saline and unpotable. The extent of potable groundwater is variable but less than 1 km in most regions (Ferguson, McIntosh, Perrone, & Jasechko, 2018), suggesting that the volume of fresh groundwater available for human use may actually be less than previously estimated (e.g., Gleeson et al., 2016).

Based on circulation depths of meteoric water (McIntosh & Ferguson, 2021), salinity distributions (Ferguson, McIntosh, Grasby, et al., 2018; Ferguson, McIntosh, Perrone, & Jasechko, 2018; Fritz & Frape, 1982; Stanton et al., 2017) and groundwater residence times ranging from tens of thousands (Jasechko et al., 2017) to over a billion years (Holland et al., 2013; Warr et al., 2018), the ~20 million km^3 of water beneath 1–2 km in both sedimentary and crystalline rock is only weakly connected to the rest of the hydrologic cycle. There is little evidence of water with these chemistries discharging to surface environments. Most waters within shallow groundwater systems with elevated salinity tend to have high Cl:Br and water isotopes that plot near the GMWL and have been attributed to dissolution of evaporites by meteoric water (Grasby & Chen, 2005; McIntosh et al., 2012; Reitman et al., 2014). This disconnection occurs despite the presence of bulk crustal permeabilities $>10^{-17}$ m^2 over most of the upper 10 km of the upper crust, a value which would allow for advection-dominated transport (Manning & Ingebritsen, 1999). Although advective transport of both heat and solutes at depths exceeding a few kilometers is evident in geothermal systems (Ingebritsen et al., 1992), areas of dolomitization (Jones et al., 2004), and during the formation of ore deposits (Garven et al., 1993; Ingebritsen & Appold, 2012), this does not appear to be a globally prevalent process. Instead, the dearth of documented meteoric water circulation at regional scales in deeper groundwater systems suggests compartmentalization and isolation occurs due to a combination of negative buoyancy (Ferguson, McIntosh, Grasby, et al., 2018), low permeability aquitards (Neuzil, 1994), and isolated fracture networks (Holland et al., 2013; Warr et al., 2018). Considerable uncertainty remains around effective permeabilities and drivers of fluid flow in these deeper environments and their linkages to the rest of the hydrologic cycle. Connection of deep and shallow groundwater has been linked to geological events such as erosion and uplift (Yager et al., 2017) or continental glaciations (McIntosh et al., 2012; Person et al., 2007). Mixing of shallow and deep groundwater during these events may have important implications to biogeochemical cycles and subsurface life (Head et al., 2003; Martini et al., 2003; Wilhelms et al., 2001).

Finally, despite potentially being the largest continental store of water, groundwater generally receives less attention than other parts of the hydrologic cycle (Famiglietti, 2014). This is especially true of deep groundwater, which is hitherto largely uncharacterized (McIntosh & Ferguson, 2021; Stober & Bucher, 2007; Warr et al., 2018, 2021). Our knowledge of the deep hydrogeosphere is limited to a few deep drilling projects and windows provided by the oil and gas industry and deep mines. Increased efforts are required in this frontier area of hydrology to understand hydrologic (Ferguson, McIntosh, Grasby, et al., 2018; McIntosh & Ferguson, 2021; Warr et al., 2018) and geochemical cycles (Li et al., 2016; Sherwood Lollar et al., 2014) and the distribution of life in the subsurface (Bar-On et al., 2018; Lollar et al., 2019; Magnabosco et al., 2018). This will require consideration of modern hydrogeological conditions as well as those over geological time as far back as the oldest crustal rocks (Precambrian Era in some cases). Considerations of such long time periods may also provide important insights into how the legacy of the Anthropocene might be preserved over deep time in the subsurface. These efforts are also urgently needed in the short term in the race for porosity between both conventional and emerging energy projects in the subsurface (Ferguson, 2013; McIntosh & Ferguson, 2019; Vengosh et al., 2014), waste isolation (Benson & Cole, 2008; Cherry et al., 2014), CO_2 sequestration (Benson & Cole, 2008), and protection of strategic water resources (Ferguson, McIntosh, Perrone, & Jasechko, 2018; Perrone & Jasechko, 2019).

Data Availability Statement

Datasets for this research are available in these in-text data citation references: Laske et al. (2013), Ehrenberg and Nadeau (2005).

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References

Achtziger-Zupančič, P., Loew, S., & Mariethoz, G. (2017). A new global database to improve predictions of permeability distribution in crystalline rocks at site scale. *Journal of Geophysical Research*, *122*(5), 3513–3539. https://doi.org/10.1002/2017JB014106

Athy, L. F. (1930). Density, porosity, and compaction of sedimentary rocks. *AAPG Bulletin*, *14*(1), 1–24. https://doi.org/10.1306/3d93289e-16b1-11d7-8645000102c1865d

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences*, *115*(25), 6506–6511. https://doi.org/10.1073/pnas.1711842115

Barton, C. A., & Zoback, M. D. (1992). Self-similar distribution and properties of macroscopic fractures at depth in crystalline rock in the Cajon Pass Scientific Drill Hole. *Journal of Geophysical Research*, *97*(B4), 5181–5200. https://doi.org/10.1029/91jb01674

Beinlich, A., John, T., Vrijmoed, J. C., Tominaga, M., Magna, T., & Podladchikov, Y. Y. (2020). Instantaneous rock transformations in the deep crust driven by reactive fluid flow. *Nature Geoscience*, *13*(4), 307–311. https://doi.org/10.1038/s41561-020-0554-9

Benson, S. M., & Cole, D. R. (2008). CO_2 sequestration in deep sedimentary formations. *Elements*, *4*(5), 325–331. https://doi.org/10.2113/gselements.4.5.325

Bethke, C. M. (1985). A numerical model of compaction-driven groundwater flow and heat transfer and its application to the paleohydrology of intracratonic sedimentary basins. *Journal of Geophysical Research*, *90*(B8), 6817–6828. https://doi.org/10.1029/jb090ib08p06817

Bjørlykke, K. (2014). Relationships between depositional environments, burial history and rock properties. Some principal aspects of diagenetic process in sedimentary basins. *Sedimentary Geology*, *301*, 1–14.

Bjørlykke, K., & Høeg, K. (1997). Effects of burial diagenesis on stresses, compaction and fluid flow in sedimentary basins. *Marine and Petroleum Geology*, *14*(3), 267–276.

Bjørlykke, K., & Jahren, J. (2012). Open or closed geochemical systems during diagenesis in sedimentary basins: Constraints on mass transfer during diagenesis and the prediction of porosity in sandstone and carbonate reservoirs. *AAPG Bulletin*, *96*(12), 2193–2214.

Blondes, M. S., Gans, K. D., Thordsen, J. J., Reidy, M. E., Thomas, B., Engle, M. A., et al. (2016). *US Geological Survey National produced waters geochemical database v2. 3 (PROVISIONAL)*. United States Geological Survey.

Cherry, J. A., Alley, W. M., & Parker, B. L. (2014). Geologic disposal of spent nuclear fuel. *The Bridge on Emerging Issues in Earth Resources Engineering*, *44*(1), 51–59.

Eakins, B. W., & Sharman, G. F. (2010). Volumes of the world's oceans from ETOPO1 (Vol. 7). NOAA National Geophysical Data Center.

Ehrenberg, S. N., & Nadeau, P. H. (2005). Sandstone vs. carbonate petroleum reservoirs: A global perspective on porosity-depth and porosity-permeability relationships. *AAPG Bulletin*, *89*(4), 435–445. https://doi.org/10.1306/11230404071

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945–948. https://doi.org/10.1038/nclimate2425

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of groundwater table depth. *Science*, *339*(6122), 940–943. https://doi.org/10.1126/science.1229881

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., & Pandit, A. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience*, *12*(3), 168–173. https://doi.org/10.1038/s41561-019-0300-3

Ferguson,G.(2013).Subsurfaceenergyfootprints.*EnvironmentalResearchLetters*,*8*(1),014037.https://doi.org/10.1088/1748-9326/8/1/014037

Ferguson, G., McIntosh, J. C., Grasby, S. E., Hendry, M. J., Jasechko, S., Lindsay, M. B. J., & Luijendijk, E. (2018). The persistence of brines in sedimentary basins. *Geophysical Research Letters*, *45*(10), 4851–4858. https://doi.org/10.1029/2018gl078409

Ferguson, G., McIntosh, J. C., Perrone, D., & Jasechko, S. (2018). Competition for shrinking window of low salinity groundwater. *Environmental Research Letters*, *13*, 114013. https://doi.org/10.1088/1748-9326/aae6d8

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., et al. (2013). Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, *7*(1), 375–393. https://doi.org/10.5194/tc-7-375-2013

Fritz, P., & Frape, S. K. (1982). Saline groundwaters in the Canadian Shield—A first overview. *Chemical Geology*, *36*(1), 179–190. https://doi.org/10.1016/0009-2541(82)90045-6

Garven, G., Ge, S., Person, M. A., & Sverjensky, D. A. (1993). Genesis of stratabound ore deposits in the Midcontinent basins of North America; 1, The role of regional groundwater flow. *American Journal of Science*, *293*(6), 497–568. https://doi.org/10.2475/ajs.293.6.497

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, M. B. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience*, *9*(2), 161–167. https://doi.org/10.1038/ngeo2590

Goldhammer, R. K. (1997). Compaction and decompaction algorithms for sedimentary carbonates. *Journal of Sedimentary Research*, *67*(1), 26–35. https://doi.org/10.1306/d42684e1-2b26-11d7-8648000102c1865d

Goodwin, A. M. (1996). *Principles of precambrian geology*. Elsevier.

Grasby, S. E., & Chen, Z. (2005). Subglacial recharge into the Western Canada Sedimentary Basin—Impact of Pleistocene glaciation on basin hydrodynamics. *The Geological Society of America Bulletin*, *117*(3–4), 500–514. https://doi.org/10.1130/b25571.1

Hartmann, J., & Moosdorf, N. (2012). The new global lithological map database GLiM: A representation of rock properties at the Earth surface. *Geochemistry, Geophysics, Geosystems*, *13*(12). https://doi.org/10.1029/2012gc004370

Head, I. M., Jones, D. M., & Larter, S. R. (2003). Biological activity in the deep subsurface and the origin of heavy oil. *Nature*, *426*(6964), 344–352. https://doi.org/10.1038/nature02134

Hem, J. D. (1985). *Study and interpretation of the chemical characteristics of natural water* (USGS Water Supply Paper 2254). USGS.

Holland, G., Sherwood Lollar, B., Li, L., Lacrampe-Couloume, G., Slater, G., & Ballentine, C. (2013). Deep fracture fluids isolated in the crust since the Precambrian era. *Nature*, *497*(7449), 357. https://doi.org/10.1038/nature12127

Ingebritsen, S. E., & Appold, M. S. (2012). The physical hydrogeology of ore deposits. *Economic Geology*, *107*(4), 559–584. https://doi.org/10.2113/econgeo.107.4.559

Ingebritsen, S. E., & Manning, C. E. (1999). Geological implications of a permeability-depth curve for the continental crust. *Geology*, *27*(12), 1107–1110. https://doi.org/10.1130/0091-7613(1999)027<1107:gioapd>2.3.co;2

Ingebritsen, S. E., Sanford, W. E., & Neuzil, C. (2006). *Groundwater in geologic processes*. Cambridge University Press.

Ingebritsen, S. E., Sherrod, D. R., & Mariner, R. H. (1992). Rates and patterns of groundwater flow in the Cascade Range volcanic arc, and the effect on subsurface temperatures. *Journal of Geophysical Research*, *97*(B4), 4599–4627. https://doi.org/10.1029/91jb03064

Jasechko, S., Perrone, D., Befus, K. M., Cardenas, M. B., Ferguson, G., Gleeson, T., et al. (2017). Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. *Nature Geoscience*, *10*(6), 425–429. https://doi.org/10.1038/ngeo2943

Jones, G. D., Whitaker, F. F., Smart, P. L., & Sanford, W. E. (2004). Numerical analysis of seawater circulation in carbonate platforms: II. The dynamic interaction between geothermal and brine reflux circulation. *American Journal of Science*, *304*(3), 250–284. https://doi.org/10.2475/ajs.304.3.250

Laske, G., & Masters, G. (1997). A global digital map of sediment thickness (Vol. 78). EOS Trans. AGU. https://doi.org/10.1002/eost.v78.46

Laske, G., Masters, G., Ma, Z., & Pasyanos, M. (2013). Update on CRUST1. 0—A 1-degree global model of Earth's crust. *Geophysical Research Abstracts*, *15*.

Lee, V., Cornford, S. L., & Payne, A. J. (2015). Initialization of an ice-sheet model for present-day Greenland. *Annals of Glaciology*, *56*(70), 129–140. https://doi.org/10.3189/2015aog70a121

Li, L., Wing, B. A., Bui, T. H., McDermott, J. M., Slater, G. F., Wei, S., et al. (2016). Sulfur mass-independent fractionation in subsurface fracture waters indicates a long-standing sulfur cycle in Precambrian rocks. *Nature Communications*, *7*(1), 1–9. https://doi.org/10.1038/ncomms13252

Lippmann, J., Stute, M., Torgersen, T., Moser, D. P., Hall, J. A., Lin, L., et al. (2003). Dating ultra-deep mine waters with noble gases and ^{36}Cl, Witwatersrand Basin, South Africa. *Geochimica et Cosmochimica Acta*, *67*(23), 4597–4619. https://doi.org/10.1016/s0016-7037(03)00414-9

Lollar, G. S., Warr, O., Telling, J., Osburn, M. R., & Sherwood Lollar, B. (2019). 'Follow the Water': Hydrogeochemical constraints on microbial investigations 2.4 km below surface at the kidd creek deep fluid and deep life observatory. *Geomicrobiology Journal*, *36*, 1–14.

Magara, K. (1980). Comparison of porosity-depth relationships of shale and sandstone. *Journal of Petroleum Geology*, *3*(2), 175–185. https://doi.org/10.1111/j.1747-5457.1980.tb00981.x

Magnabosco, C., Lin, L.-H., Dong, H., Bomberg, M., Ghiorse, W., Stan-Lotter, H., et al. (2018). The biomass and biodiversity of the continental subsurface. *Nature Geoscience*, *11*(10), 707. https://doi.org/10.1038/s41561-018-0221-6

Manning, C., & Ingebritsen, S. (1999). Permeability of the continental crust: Implications of geothermal data and metamorphic systems. *Reviews of Geophysics*, *37*(1), 127–150. https://doi.org/10.1029/1998rg900002

Martini, A. M., Walter, L. M., Ku, T. C., Budai, J. M., McIntosh, J. C., & Schoell, M. (2003). Microbial production and modification of gases in sedimentary basins: A geochemical case study from a Devonian shale gas play, Michigan basin. *AAPG Bulletin*, *87*(8), 1355–1375. https://doi.org/10.1306/031903200184

McIntosh, J. C., & Ferguson, G. (2019). Conventional Oil—The Forgotten Part of the Water-Energy Nexus. *Groundwater*, *57*(5), 669–677. https://doi.org/10.1111/gwat.12917

McIntosh, J. C., & Ferguson, G. (2021). Deep Meteoric water circulation in Earth's crust. *Geophysical Research Letters*, *48*(5), e2020GL090461. https://doi.org/10.1029/2020gl090461

McIntosh, J. C., Schlegel, M., & Person, M. (2012). Glacial impacts on hydrologic processes in sedimentary basins: Evidence from natural tracer studies. *Geofluids*, *12*(1), 7–21. https://doi.org/10.1111/j.1468-8123.2011.00344.x

Morrow, C., & Lockner, D. (1994). Permeability differences between surface-derived and deep drillhole core samples. *Geophysical Research Letters*, *21*(19), 2151–2154. https://doi.org/10.1029/94gl01936

Nace, R. L. (1969). World water inventory and control. In R. J. Chorley (Ed.), *Water, earth, and man* (pp. 31–42). Methuen.

Neuzil, C. (1994). How permeable are clays and shales? *Water Resources Research*, *30*(2), 145–150. https://doi.org/10.1029/93wr02930

Perrone, D., & Jasechko, S. (2019). Deeper well drilling an unsustainable stopgap to groundwater depletion. *Nature Sustainability*, *2*(8), 773–782. https://doi.org/10.1038/s41893-019-0325-z

Person, M., & Baumgartner, L. (1995). New evidence for long-distance fluid migration within the Earth's crust. *Reviews of Geophysics*, *33*(S2), 1083–1091. https://doi.org/10.1029/95rg00254

Person, M., McIntosh, J., Bense, V., & Remenda, V. H. (2007). Pleistocene hydrology of North America: The role of ice sheets in reorganizing groundwater flow systems. *Reviews of Geophysics*, *45*(3). https://doi.org/10.1029/2006rg000206

Reitman, N. G., Ge, S., & Mueller, K. (2014). Groundwater flow and its effect on salt dissolution in Gypsum Canyon watershed, Paradox Basin, southeast Utah, USA. *Hydrogeology Journal*, *22*(6), 1403–1419. https://doi.org/10.1007/s10040-014-1126-0

Richey, A. S., Thomas, B. F., Lo, M., Famiglietti, J. S., Swenson, S., & Rodell, M. (2015). Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. *Water Resources Research*, *51*(7), 5198–5216. https://doi.org/10.1002/2015WR017351

Rubey, W. W., & King Hubbert, M. (1959). Role of fluid pressure in mechanics of overthrust faulting: II. Overthrust belt in geosynclinal area of western Wyoming in light of fluid-pressure hypothesis. *The Geological Society of America Bulletin*, *70*(2), 167–206. https://doi.org/10.1130/0016-7606(1959)70[167:rofpim]2.0.co;2

Schmoker, J. W., & Halley, R. B. (1982). Carbonate porosity versus depth: A predictable relation for south Florida. *AAPG Bulletin*, *66*(12), 2561–2570. https://doi.org/10.1306/03b5ac73-16d1-11d7-8645000102c1865d

Seeburger, D. A., & Zoback, M. D. (1982). The distribution of natural fractures and joints at depth in crystalline rock. *Journal of Geophysical Research*, *87*(B7), 5517–5534. https://doi.org/10.1029/jb087ib07p05517

Sherwood Lollar, B., Onstott, T. C., Lacrampe-Couloume, G., & Ballentine, C. (2014). The contribution of the Precambrian continental lithosphere to global H_2 production. *Nature*, *516*(7531), 379–382. https://doi.org/10.1038/nature14017

Shiklomanov, I. (1993). In P. H. Gleick (Ed.), *Water in crisis: A guide to the world's fresh water resources*. Oxford University Press.

Stanton, J. S., Anning, D. W., Brown, C. J., Moore, R. B., McGuire, V. L., Qi, S. L., et al. (2017). *Brackish groundwater in the United States*. US Geological Survey. https://doi.org/10.3133/pp1833

Stober, I., & Bucher, K. (2007). Hydraulic properties of the crystalline basement. *Hydrogeology Journal*, *15*(2), 213–224. https://doi.org/10.1007/s10040-006-0094-4

Stotler, R., Frape, S., Ruskeeniemi, T., Pitkänen, P., & Blowes, D. (2012). The interglacial–glacial cycle and geochemical evolution of Canadian and Fennoscandian Shield groundwaters. *Geochimica et Cosmochimica Acta*, *76*, 45–67. https://doi.org/10.1016/j.gca.2011.10.006

Townend, J., & Zoback, M. D. (2000). How faulting keeps the crust strong. *Geology*, *28*(5), 399–402. https://doi.org/10.1130/0091-7613(2000)028<0399:hfktcs>2.3.co;2

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology*, *48*(15), 8334–8348. https://doi.org/10.1021/es405118y

Warr, O., Giunta, T., Onstott, T. C., Kieft, T. L., Harris, R. L., Nisson, D. M., & Sherwood Lollar, B. (2021). The role of low-temperature ^{18}O exchange in the isotopic evolution of deep subsurface fluids. *Chemical Geology*, *561*, 120027. https://doi.org/10.1016/j.chemgeo.2020.120027

Warr, O., Sherwood Lollar, B., Fellowes, J., Sutcliffe, C. N., McDermott, J. M., Holland, G., et al. (2018). Tracing ancient hydrogeological fracture network age and compartmentalisation using noble gases. *Geochimica et Cosmochimica Acta*, *222*, 340–362. https://doi.org/10.1016/j.gca.2017.10.022

Wilhelms, A., Larter, S. R., Head, I., Farrimond, P., di-Primio, R., & Zwach, C. (2001). Biodegradation of oil in uplifted basins prevented by deep-burial sterilization. *Nature*, *411*(6841), 1034–1037. https://doi.org/10.1038/35082535

Yager, R. M., McCoy, K. J., Voss, C. I., Sanford, W. E., & Winston, R. B. (2017). The role of uplift and erosion in the persistence of saline groundwater in the shallow subsurface. *Geophysical Research Letters*, *44*(8), 3672–3681. https://doi.org/10.1002/2017gl072980