

Global crustal groundwater volumes larger than previous estimates

Grant Ferguson^{1,2,3,4}, Jennifer C. McIntosh^{1,3}, Oliver Warr⁵, Barbara Sherwood Lollar⁵, Christopher J. Ballantine⁶, James S. Famiglietti^{2,4}, Ji-Hyun Kim³, Joe Michalski⁷, John F. Mustard⁸, Jesse Tarnas⁹, Jeffrey J. McDonnell^{2,4,10,11}

1. Department of Civil, Geological and Environmental Engineering, University of Saskatchewan
2. Global Institute for Water Security, University of Saskatchewan
3. Hydrology and Atmospheric Sciences, University of Arizona
4. School of Environment and Sustainability, University of Saskatchewan
5. Earth Sciences, University of Toronto
6. Department of Earth Sciences, University of Oxford
7. Division of Earth and Planetary Science, University of Hong Kong, Hong Kong.
8. Department of Earth Environmental and Planetary Sciences, Brown University
9. Jet Propulsion Laboratory, California Institute of Technology
10. School of Resources and Environmental Engineering, Ludong University, Yantai, China.
11. School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK.

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 cratonic 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 2-10 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.

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.**

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 km³ of groundwater was present in the upper 2 km of the Earth's crust (Table 1; 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). Active 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) and seismicity (Townend & Zoback, 2000). Warr et al (2018) estimated a groundwater volume of 8.5 million km³ in Precambrian cratons between 2 to 10 km deep 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 deep in sedimentary basins and Phanerozoic crystalline rocks has not yet been quantified.

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. In carbonate rocks, porosity varies from less than 1% to over 28% and in clastic rocks porosity varies between at least 7% to 31% (Ehrenberg & Nadeau, 2005). Despite this variability, 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.

$$\eta = \eta_0 e^{-\beta z} \quad [1]$$

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 basin 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 implied by 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 cratons 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 cratonic rock supports the approach of using a constant porosity with depth to estimate pore volumes in deep cratons.

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 >40,000 porosity values from depths of 0 to 5.5 (Ehrenberg & Nadeau, 2005) and the CRUST1.0 database (G Laske et al., 2013) (see Methods) to determine the volume of groundwater in deep sedimentary and cratonic rocks with uncertainty bounds.

3 Methods

Estimates of the thickness of sedimentary cover from the CRUST1.0 database (G 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 >40,000 porosity values from depths of 0 to 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 $1.5 \times 10^{-4} \text{ m}^{-1}$ 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 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).

For cratonic 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 [1] we used the following equation (Bethke, 1985) for the case where porosity decreases with depth:

$$\eta = \frac{\eta_0 - za^{-1}}{100} \quad [2]$$

Where a is a fitting coefficient. Following Sherwood Lollar et al (2014), we used $\eta_0 = 1.6\%$ and $a = 2.1 \times 10^{-4} \text{ m}^{-1}$ 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 dataset 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), along with 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 26.5 million and 71.0 million km³ (see Figure S1). Using the same approach, our estimate for the amount of groundwater in the upper 2 km is 23.6 million km³ (1.8 million km³ in cratons and 21.8 million km³ in sediments) – a value quite similar to the estimate of 22.6 million km³ 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, et al., 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. We estimate that there are 15.9 million km³ of groundwater in that zone, while the remaining 28.3 million km³ 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 km³) is similar to the amount found in cratons (11.9 km³) despite the much larger volume of cratonic rocks globally (Figure 2). While there is considerable uncertainty with these estimates, even increasing the porosity of cratonic rocks to 2% would still result in fluid volumes in sedimentary and cratonic 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 cratonic rocks between 2 and 10 km would only be 6.6 million km³ (Figure S1). In the deepest crustal sediments and crystalline rocks between 8 and 10 km, there is approximately 22.2 million km³ of groundwater, dominated by high salinities (Stotler et al., 2012). The inclusion of sediments and Phanerozoic crystalline rocks below 2 km adds 13.7 million km³ to the 8.5 million km³ 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 $\frac{1}{3}$ 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 km³ (Eakins & Sharman, 2010), the volume of water in the upper 10 km of continental crust (43.9 km³) estimated here is greater than the amount of water held in ice sheets in Antarctica (27 million km³) (Fretwell et al., 2013) and Greenland (3 million km³) (Lee et al., 2015) and glaciers (158 thousand km³) (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 km³ 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 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; O 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 is 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 analysed for only major ion chemistry, without information on fluid residence times (Blondes et al., 2016). Data is more limited from cratons, 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 (O Warr et al., 2018). The limited data available suggests 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, et al., 2018), suggesting that the volume of fresh groundwater available for human use may actually be less than previously estimated.

Based on circulation depths of meteoric water (McIntosh & Ferguson, 2021), salinity distributions (Ferguson, McIntosh, Grasby, et al., 2018; Ferguson, McIntosh, Perrone, et al., 2018; Fritz & Frape, 1982; Stanton et al., 2017) and groundwater residence times ranging from 10s of thousands (Jasechko et al., 2017) to over a billion years (Holland et al., 2013; O Warr et al., 2018), the ~20 million km³ of water beneath 1 to 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 $> 10^{-17} \text{ m}^2$ over

most of the upper 10 km of the upper crust, a value which would allow for advection-dominated transport (Manning & Ingebritsen, 1999). The lack of documented advection 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; O 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). 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; O 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; O 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), CO₂ sequestration (Benson & Cole, 2008) and protection of strategic water resources (Ferguson, McIntosh, Perrone, et al., 2018; Perrone & Jasechko, 2019).

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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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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
Cratons (0-2 km)	1.4 ^a	4	1.8	4
Cratons (2-10 km)	8.5 ^b	26	11.9	24
Total	32.5		43.9	

Table 1: Previous and revised groundwater volume estimates for the crust and relative percentages in each reservoir. Previous estimates are taken from a) Gleeson et al., 2016(Gleeson et al., 2016) and b) Warr et al., 2018(O Warr et al., 2018). 'n.a.' indicates not previously estimated for sediments deeper than 2 km. In the top 2 km revised groundwater estimates for sediments and cratons are comparable to previous published values. Between 2-10 km revised cratonic groundwater volume estimates are higher due to increasing proportion of cratonic rocks with depth and inclusion of Phanerozoic rock (Fig. 3). The revised cratonic groundwater estimate coupled with new estimates for deep sediments increase the groundwater volume estimate by 11.4 million km³.

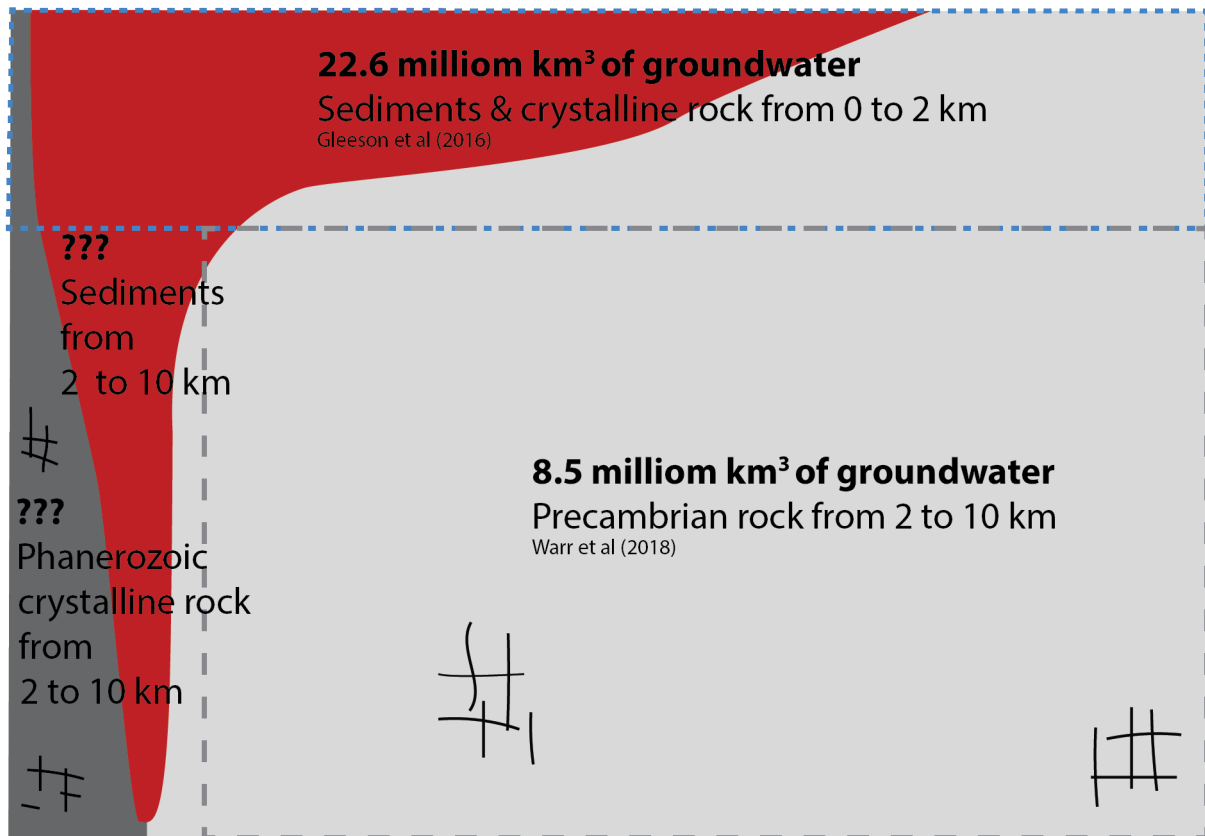


Figure 1: Estimates of groundwater volumes from previous studies of the upper 2 km³ and for Precambrian rocks between 2 and 10 km depth²³. Volumes between 2 and 10 km in sedimentary basins and Phanerozoic crystalline rock have not yet been considered in recent studies estimating groundwater volumes at the global scale. Red shading (sediments); dark grey (Phanerozoic crystalline rock); light grey (Precambrian crystalline rock).

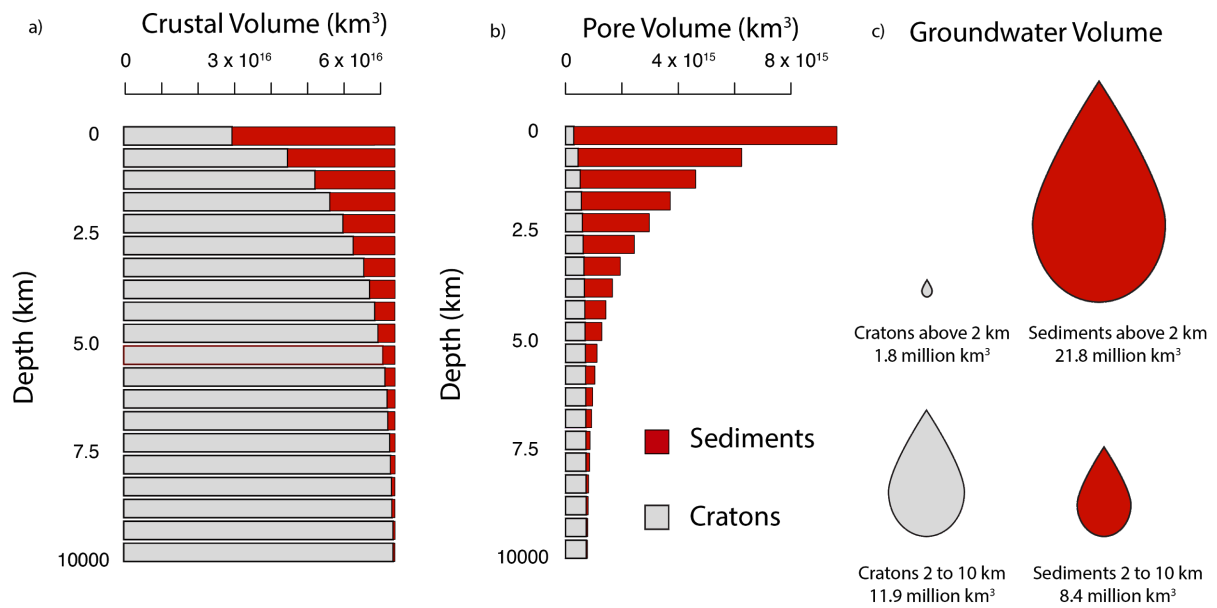


Figure 2: Global volumes of a) sediments and cratonic rock in from the CRUST 1.0 database (G Laske et al., 2013) in 500 m intervals, b) pore volumes calculated using those rock volumes along with a depth decaying porosity for sediments using equation [2] and regressed constants from Ehrenberg and Nadeau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

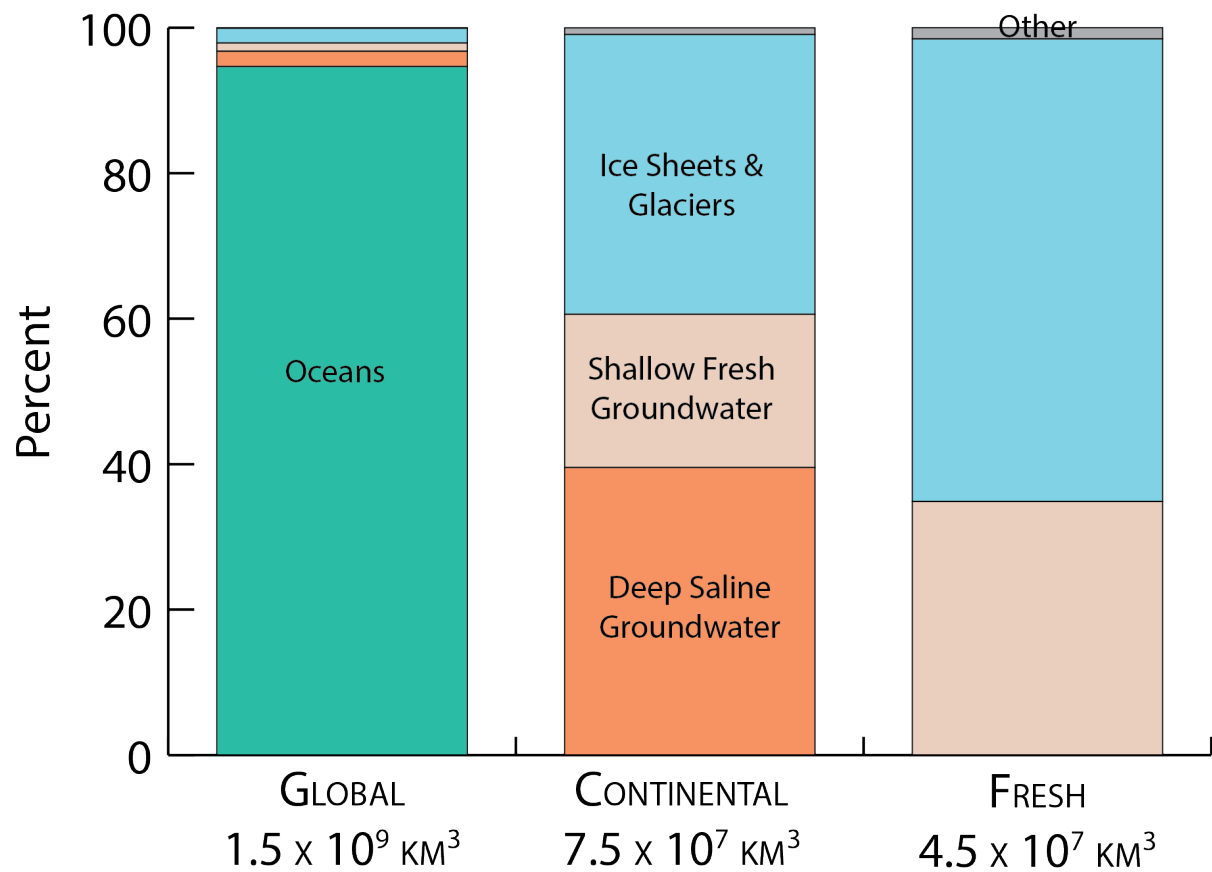


Figure 3: Relative sizes of water stores compared to overall storage of waters globally, on the continents and as a portion of total global freshwater storage. The bulk of continental water storage is likely groundwater, rather than ice sheets as previously thought (i.e. Shimanov, 1993).