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Discussions

Interactive comment on "Storage and routing of water in the deep critical zone of a snow dominated volcanic catchment" *by* Alissa White et al.

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Distinct stores and routing of water in the deep critical zone of a snow dominated volcanic catchment by Alissa White et al. Authors' reply to Anonymous Referee #2

General Comments

This manuscript presents various data to show how critical zone "structure" influences hydrologic "function" by comparing two sites with distinct lithologies and positions within the Jemez River Basin Critical Zone Observatory. Supported by geochemical / isotopic tracers and hydrologic data, the authors found that the site with highly fractured tuff had

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fast responses to precipitation and contributed most of the streamflow water from its deep groundwater stores, while the site with collapse breccia included disconnected perched water table aquifer that contributed little to the stream. This study presents an impressive amount of data and analysis. However, as the manuscript is currently written, it is easy for the reader to feel a bit lost about what to focus on. I provide the following suggestions for what to clarify and potentially reorganize.

We appreciate the referee's thoughtful comments and helpful suggestions. We have addressed their specific comments by clarifying text and addressing specific questions they brought up. We have also addressed their broader comments by explicitly defining structure and function, reorganizing our results and discussion, and adding a paragraph to our concluding remarks that stresses the implications, general utility, and potential application of our findings to other studies in mountain systems. Detailed responses to each of the referee's comments are provided below each comment.

Major Comments

1. Clarify what is referred to as critical zone "structure" and what aspect of "structure" is the focus of the study. The abstract states the main goal of the study to be to show how critical zone "structure" controls hydrologic response, but a specific definition is not provided until Research Question 2 at the end of the Introduction – it should be stated earlier. Also, the authors alternate between "structure" and "architecture" but do not explain if these refer to the same thing or not. Finally, I am guessing that "structure" and "architecture" refer to physical properties. In the definition of "structure" in Research Question 2, the authors include "mineralogy", but I don't see any argument for how mineral composition affects physical flow – only how it affects water chemistry, which is used as a tracer for flow.

A definition of CZ structure, as well as clarification of the use of structure and architecture interchangeably was added to the introduction in lines 64-66. We agree with the reviewer's point about the use of mineralogy and have removed mineralogy as one of the examples listed in Research Question 2. Herein, we use the term subsurface structure or architecture to refer to physical properties of the subsurface such as lithology, fracture density, and location and extent of geologic heterogeneities that may impact movement of water through the subsurface.

2. Clarify what hydrologic "functions" are the focus of the study. The authors do a good job of listing functions in their abstract (water routing, storage, mean water residence times, and hydrologic response), and these correspond to some of the subsection titles of the Results and Discussions sections. However, the research questions only seem to list the two functions of "hydrologic response" and "groundwater contributions to streams", and not all of the subsection titles of the Results and Discussion correspond to the 4 functions listed in the abstract. One especially confusing aspect is that "storage" is highlighted in the manuscript title, but results mostly focus on different categories of groundwater stores, but not on any storage quantification.

The paper's title was modified from "Storage and routing of water in the deep critical zone of a snow dominated volcanic catchment" to "Distinct stores and routing of water in the deep critical zone of a snow dominated volcanic catchment" because without more extensive geophysics or drilling we are unable to estimate the lateral extent of the aquifers and; therefore, cannot quantify storage.

Research Question 2 was modified to include water routing, mean residence times, and seasonal contribution of distinct groundwater stores to streams. The hydrologic functions outlined in the abstract, research questions, and discussion section titles now match and help to clarify which hydrologic functions are investigated in this paper.

RQ2: How does CZ architecture, such as fracture density, lithology, and subsurface heterogeneities, influence water routing, mean residence times, and the seasonal contribution of distinct groundwater stores to streams?

3. Explain the broader implications of this work. The conclusions are very specific about what is occurring at JRB-CZO, and it would be good if the authors can comment

on whether this understanding corroborates, challenges, or adds to what is already known about catchment behavior. One particular question I have is about the importance of the conclusions. Was it not to be expected that the fractured site would have faster response times? However, I do find it interesting that the perched water table aquifer is mostly disconnected to the stream – how commonly is this seen? What about the "structure" makes this disconnection happen?

The unexpected finding is that deep groundwater from the fractured site was connected to streamflow year round while the perched aquifer does not contribute significantly to streamflow, although the perched aquifer was expected to be connected to the stream, and this had previously been suggested to be the case. Transmission of perched aquifers to streams has been previously documented, as described in the introduction and conceptual models typically generalize to show contributions to streams from multiple sources and depths of groundwater. The differences in lithology (including presence of confining layer) and subsequent differences in fracture density between tuff (site 1 wells) and collapse breccia deposits (site 2 wells, specifically perched aquifer) that are scattered throughout the JRB-CZO controls the connection or lack of connection between groundwater stores and streamflow.

Added to conclusions to expand implications: Surprisingly, deep groundwater from site 1 wells appear to be more chemically-representative of waters that contribute to La Jara stream and more representative of the structure (geology, fractured aquifer, and greater depth to water table) and function (hydrologic response, solute fluxes, and water routing) of the CZ in the greater La Jara catchment, suggesting that deep groundwater from the fractured aquifer, rather than shallow subsurface flow from the perched aquifer, sustains stream baseflow. Further, we suggest that the deep subsurface flow paths observed in the JRB-CZO are likely a signature of snow dominated volcanic catchments transferable to other deeply fractured extrusive bedrock systems. The dominant contribution of deep groundwater to surface flows and the hydraulic connection between the fractured bedrock aquifer and streamflow may suggest that deep groundwater stores in fractured bedrock aquifers are sensitive to changes in climatic drivers of streamflow like shifts in precipitation magnitude and timing, as predicted in the southwestern United States. We assert that this study emphasizes the utility of interdisciplinary research to discern the distribution of groundwater stores, their connection to streamflow, and the underlying impact of CZ architecture on hydrologic response to climatic drivers. Furthermore, we propose that it highlights the need to better characterize the deep subsurface of mountain systems by transferring this approach to other complex settings that challenge and advance the current understanding of subsurface hydrologic systems around the world. We hope that this study provides an example of how to bring together multiple lines of evidence to simultaneously examine both, CZ architecture and hydrology, through hydrometric, geophysical, geochemical, and residence time analyses.

4. I suggest that the authors either combine their Results and Discussions sections, or they reorganize them so that they are more distinct. Right now, with identical subsection titles, there is much repetition in places, and the reader has to keep flipping back and forth to match up results and discussion. Also, there are a lot of laborious details in the Results section – the authors could simply point to the figures (for example, no need to point out all the specific dates and discharge values in Section 3.1).

We followed the reviewer's suggestion to reorganize the results and discussion sections to make them more distinct rather than combine them entirely. The results section titles have been changed to focus more on the type of analysis performed rather than the finding as the discussion section titles do. Many of the laborious specifics from the results section were pulled from the text. Instead, the authors point the reader to the figures and tables where those details can be found.

Minor comments

P4 L104-105: I'm confused. By definition, aren't springs comprised of groundwater? If it is not groundwater, then what is the water source? Also, how is this relevant to the

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following Research Questions.

While it is true that springs are comprised of groundwater by definition (i.e., saturated zone intersection with the soil surface), the composition of that water source may be quite distinct from the composition of the groundwater sampled, e.g., as from groundwater monitoring wells, because by transport through the near surface soil media, the groundwater composition may be altered relative to its composition at depth. Therefore, Frisbee et al., (2013) found that springs integrated multiple water sources like groundwater, soil water, unsaturated flow, and precipitation. These details of integrated water sources in springs were added to the text. This point about springs is meant to highlight how the analysis of groundwater in this paper enhances previous research that used springs as proxies for groundwater at this intensively studied observatory.

P5, L136: Define VCNP. Fig 1 and throughout text: I suggest naming your wells in a way so that it is easier to keep track of where they are. For example, “Well 1” could be “Well T” for Tuff, and “Well 2” could be “Well B” for Breccia. We defined the abbreviation VCNP as Valles Caldera National Preserve. We intended the distinctions in rock type highlighted in Figures 1 and 2 to help readers keep track of the locations of each well.

Fig 1A: Improve resolution of text. Text resolution was fixed.

Fig 1B: Change the color of stream line. It is not visible with the current color and transparency. Stream line was changed to darker blue.

P6, L176-177: Why were different pumping methods used at the different wells? Text was added to clarify the different diameter casing of wells 1 and 2 and readers were directed to Supplemental Table 4.

P6, L194: For “not shown here” - either entirely omit mention of it from the paper if it does not affect your conclusions, or put in supplementary info. Those items were pulled.

P7, L223-224: how were the uncertainties associated with the background TU concentration and measured TU in samples estimated? These details were added to the methods section.

P8, L260: If only showing data for 2 sites, is it necessary to mention the other ones? This also applies to P9, L307. The first sentence (Line 260) was moved from the main text to the figure caption of Supplemental Figure 1 and Supplemental Figure 1 was referenced in the previous mention of vibrating wire piezometers. We maintain that it is important to explain the monitoring well and transducer details of all wells as this is the first paper to describe their construction and installation process so we want to keep those details in supplemental. The second sentence (Line 307) was removed from the text entirely.

P9, L281: Seems like Figure 4 reference precedes Figure 3 in the text. That reference was premature in the description of methods; therefore, the reference was changed to direct readers to the location of the pedons (Figure 1) rather than to the results from them.

P9, L309: What is the "node file"? The detailed reference to a node file (file that saves locations of fractures from Adobe Illustrator) was pulled and reworded to clarify.

P10, L331: Even though the water level in well 1A raises less in 2nd snowmelt event than the 1st one, and in well 2D it increases with a lower rate than the 1st snowmelt event, the discharge goes higher in La Jara stream on 4/18 relative to 3/22. Could you explain that?

The second snowmelt peak in La Jara streamflow exceeded the first snowmelt peak because a considerable depth of snow (approximately 500 mm; Olshansky et al., 2018) remained on the ground in La Jara catchment when temperatures dropped below freezing again in March, adding to La Jara streamflow that remained much greater than baseflow between peaks. This explanation was added to the text.

Fig 3 and 4: Show the NAM time period in Figure 3 in the same way as in figure

4. Change the x-axis label to monthly intervals. Use the same scale and width for the x- axes in these two figures for easier comparison. We added the shaded NAM time period to Figure 3 and adjusted the figures' scales for easier comparison between Figures 3 and 4. However, we think that changing labels from every 3 months to every month would make figures too crowded, especially in Figure 3 where specific dates are highlighted on the figure.

Fig4 , pedon 3: VWC at 65cm depth is hard to see. This adjustment was made.

P11, L361: Explain why changes in VWC are more pronounced in deeper parts. Why is the response for pedon 5 different than for pedons 1 and 6, even though they seem to have the same geology based on their locations on fig 1? Pedon 5, while located in the same tuff rock type as pedons 1 and 6, is situated in the convergent zone of the ZOB and therefore receives lateral subsidies of moisture from upslope, and retains more moisture than pedons 1 and 6 located upslope of the convergent zone. Text highlighting this distinction was added to the text. Changes in VWC are likely most pronounced in deeper parts of the soil pedons because of subsurface lateral flow. Neutron probe profiles show evidence of subsurface lateral flow at approximately 12 mbgs at site 2, but were unable to confidently capture those changes less than 1 mbgs because of escape of neutrons through the surface. Previous work (Liu et al., 2008; McIntosh et al., 2017; Olshansky et al., 2018) also found minimal overland flow and suggested the presence of subsurface lateral flowpaths in the JRB-CZO. This text was added to section 3.1.

P13, L420: Could you explain why major ion concentrations are so different in wells 2A and 2B relative to 2C and 2D? If 2D is a perched aquifer with vertical connection to the wells beneath as the author mentioned in P8, L629, the temporal changes in the major ion concentrations should follow the same trend, but that is not seen in the figure. Differences in mineralogy, specifically the presence of calcite within the top 15 mbgs at site 2 wells, create differences in major ion concentrations – generally higher Ca^{2+} and DIC in wells 2D and 2C and higher Mg^{2+}, Na^{+}, and K^{+} in wells 2A and 2B where

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there are greater percentages of feldspars at depth. Unfortunately, there are far fewer samples from the deeper site 2 wells (2A and 2B) and the geochemical time series of those wells begins in October 2017 because of issues developing those deepest wells. These differences in sampling frequency prevent the comparison of temporal changes across depth in site 2 wells. We do, however, see that the concentration of major ions in wells 2D and 2C change simultaneously.

Fig 7: It is difficult to see the trend with lines with markers. Removing markers could make it easier to read. We think that the markers will be necessary to distinguish between sites for readers that print in black and white. We also think that the markers are helpful to highlight the differences in sampling frequency across time and between sites. We tried adjusting the size and shape of markers, but ultimately felt that the markers are best as they are.

P13, L433: Briefly explain why Na+ concentration increases in well 1A around June 2017 (again it would be helpful if the x-axis labels are at monthly intervals). Increased Na+ concentrations are likely the result of the weathering of feldspars, like albite, which were observed in quantitative mineralogic analysis of cores (Moravec et al., 2018). We hypothesize that site 1 Na+ concentrations increase following spring snowmelt on 5/27 as the well 1A water table slowly recedes allowing greater contact time for weathering of feldspars at approximately 37 mbgs. This explanation was added to the text.

P14, L454: Provide discussion about the enrichment. Discussion of the enrichment of ïĄd'18O and ïĄd'2H is provided in the discussion in lines 674 to 684.

P14, L479-482: This sentence should be reworked. It currently implies that understanding the geochemistry is the end-goal, but actually, the geochemistry is the means for understanding the impacts of the structure and architecture. The logic in the current wording seems backwards. We agree and this sentence was reworked.

P14, L497 paragraph: Is there a way to back out K values that are more relevant for the spatial scale of interest, which should be higher in tuff than breccia? For example, using the discharge rates and hydraulic gradients? Would the backed out K values be more consistent with literature values for high vs. less dense fractures than the slug test K results? While we appreciate the suggestion and agree that it would be great to have effective K values for a larger scale, we do not think this calculation can be made with the current dataset. Because it is unclear where the perched aquifer drains and there is only one monitoring well accessing this aquifer, it is not possible to measure the hydraulic gradient or discharge needed for calculation of K in the breccia. We would need more geophysical data to discern the spatial extent of both aquifers and question the validity of the assumption that all La Jara creek discharge would be attributed solely to groundwater contribution from the fractured tuff aquifer.

P15, L518: Typo: sentence ends with “and” Typo corrected.

P16, L539: Maybe “in contrast to” instead of “however”? Change made.

P16, L546: Isn’t lesser water table response to summer rains typically due to higher ET, which prevents wetting fronts to descend below the root zone? We agree that lesser water table response to summer rains is a function of increased ET, which works to produce drier antecedent soil moisture like that referred to in Figure 4 and highlighted in the text. Text was added to clarify this point.

P17, L569: delete comma after “both” Change made.

P17, L583: Seems like the correspondence of gravel and wetting patterns is major part of the paper’s findings about the relationship between structure and hydrologic function. As such, the gravel data should be presented more prominently. At the very least, state what depth corresponds to the gravel-like layer. I would suggest to even further show graphically where the gravel is – either superimposed on Figure 6 or on a separate dedicated figure with similar y-axis scale. The depth of the gravel-like layer was added to the text and the layer is now highlighted in Figure 6.

P19, L642 paragraph: Seems out of sequence. Shouldn’t this summary conceptual model come AFTER the subsequent section and old and young water? We agree and that paragraph has been moved.

Figure 9: The ellipses for the Summer Precip and Snow seem very approximate. Is there a more specific range? These ranges are volume weighted means from previous studies in the JRB-CZO. The range of d18O and d2H for snow were taken directly from Gustafson, 2008 and those of summer precipitation were taken from Zapata Rios et al. (2015b). The ellipses were fit directly over that data. These specific details were more added to the methods section 2.3 and to Figure 9 caption.

P19, L665: Figure 10 is referenced, but it seems like a figure showing tritium results should be referenced instead. Is there supposed to be a figure showing tritium measurements? A reference to Table 3, which provides details of the tritium measurements was added.

P20, L703-704: parenthetical for “structure” includes “deep groundwater” and “longer mean residence time”, but neither of those are properties of the physical porous media. I assumed “structure” to refer to the physical porous media. “Longer mean residence time” was removed and “deep groundwater” was changed to greater depth to water table.

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