Reply to review

Thank you for this complete review. Both reviewers took the time to provide detailed comments that are considerably improving the quality of this manuscript, especially the figures. We followed those advises and updated the document consequently. Please find attached the revised manuscript with track changes as well as the reply to the detailed comments, directly in purple.

Reviewer 1:

The authors present an interesting case study integrating geophysical, geological and hydrochemical data to map potential pathways for water and gases across complex sedimentary formations in the Northern Territories, in Australia. The approach used by the authors is innovative and allows to elaborate several hypotheses regarding the occurrence and movement of both paleo and more recent fluids. Results appear to be sound and supported by the illustrations. Figures, however, need to be significantly improved for the final manuscript (see detailed comments below). Overall, the implications of this study are important not only for industrial purposes (reservoir exploration and operation) but also for our basic understanding of subsurface flow processes over geological timescales. This study should therefore gather significant interest and is worthy of a prompt publication.

Figures.

- Figure 1: Are colors in Figure 1 A related to the hydrostratigraphy or depicting topography? If the latter applies, make sure to provide a scale. The colour refer to the SEEBASE depth to basement, the legend has been added
- Figure 2: The left spine (or border) does not appear on the pdf reviewed. This figure could be improved by adding shaded satellite image to help the reader compare the mapped drainage systems (which were automatically mapped) and fault traces/lineaments with the real features observed. Thanks, the figure have been entirely revisited and divided into four subfigures.
- Figure 3: The text (lines 258-259) mentions magnetic lineaments as prominent features, which can be caused by faulting. Such features are hard to visualize. It would certainly help if they were highlighted directly on the figure. The figure has been redrawn and the magnetic lineaments indicated
- Figure 4: This figure could go in the appendix. It is good to let the reader know that not all seismic surveys provided the same quality, but this is more a technical point. Thank you. We hesitated on this point but decided to keep the figure in as the quality of the seismic in the shallow level is really crucial to the discussion. We need to know if the interpretation is reliable, especially in this shallow zone that is not well imaged by this type of data. A misinterpretation can led to the targeting of circulation pathways that are in fact only artefacts.
- Figure 6: Put the title of each subfigure above the plot. It doesn't read well otherwise.done
- Figure 7: What is special about the locations highlighted by the markers (crosses on Figure 7B and square markers on Figure 7C). At this scale, the reader can't see much detail. We removed the seismic interpretation of figure 7G (cross) that were misleading the reader and add the interpretation of the fluid leakage features on the images
- Figure 9: Remove 's' from <10 yearss. Also, increase the thickness of the fault lines to make them more obvious.done, we also totally revisited this figure as to have a cleared output

Text.

- Lines 271-272: Why is the signal quality so variable, and how were the categories (excellent, average and poor) defined? We added :

‘this is due to the different seismic acquisition technics and processing applied in each survey as well as the fact that our interval of interest is shallow and not fitting with the interval of interest the companies tried to best image with those datasets”

- Lines 323-324: The authors should explain why low magnitude local seismic signals can be believed to represent permeable pathways promoting water or gas migration. We added “as the presence of fluid or gas can locally alter the seismic signal”
- Lines 339-357/Section 4.3: The map shown on Figure 9 that provides the location where groundwater and springs were sampled could be referred to. done
- Line 360: Here and throughout the text, the word ‘recent’ is used to describe some tectonic activity. It would be good define what recent means in the context of this study. An indication is provided in the Discussion (Line 414), but it would go to state this value upfront in the text. We added: “We define as recent tectonic activity the events that are recorded at the surface and can alter the surface with active tectonic features, such as modifications of the drainage system”
- Discussion: One general comment, could the use of other tracers (radon, of stable isotopes of water) yield also insight on the origin of the fluids sampled in this study?

  Radon cannot give this information since with the short half-live of 3.8days it's signal comes only from the direct vicinity of the sampled location. Stable isotopes of water could in principle do this if there is a geothermal signature on them (such as plotting far left to the meteoric water line - see inset in Figure 1 of McIntosh and Ferguson, 2020 – Geophysical research Letter) - but we have not seen such a signature. We may mention that in the text - but for such a signature to be discernible the bulk of the water needs to be geothermal, and what we see is only a small admixture.

Reviewer 2:

Summary of content: The study investigates potential connections between unconventional petroleum plays and water assets in the Beetaloo Sub-basin in the Northern Territory, Australia.

Magnetic data and 2D seismic reflection profiles were used to image structural features, and fluid/gas leakage pathways. Helium content of the aquifer systems was sampled and measured. Recent fault activity was identified using a combination of sub-surface imaging and comparison of fault orientations and surface drainage networks.

The study concludes that there the shallow aquifers are connected to deep-seated gas source along faults, some of which show evidence of recent movement. Helium isotope data do not provide an unequivocal answer to whether the gas originates from the unconventional plays or a deeper source.

Although the authors point out that more data is needed to identify the source of the gas, the observations made in this study confirm the presence of fault-controlled fluid flow pathways connecting the stratigraphic levels where the unconventional plays are located with shallower aquifers the Beetaloo basin.

Review summary

Scientific aims clearly stated.

The text is well organized and well written.

Methods are sound and clearly described,

There are some shortcomings in documentation and presentation of results, which weaken the link between observations and conclusion. Development of the petroleum resources in this region is

controversial and faces opposition from Traditional Owners as well as climate scientists, and environmentalists. One of the key issues in the Beetaloo Sub-basin, the risk of groundwater contamination from fracking-based production of the unconventional plays. The present paper is thus part of an ongoing debate and the findings presented here are likely to influence discussions and decisions by stakeholders. This fact stresses the need for clarity when presenting data and results. Improving the design of the figures and adding links/references to primary data sources would go a long way towards addressing this.

Conclusions appear supported by the observations made in this study, but presentation of results needs to be improved.

Detailed comments

Aeromagnetic survey data acquired over the last 50+ years were employed for mapping structural and lithological features.

Although the aeromagnetic data is said to be employed for structural interpretation, details somewhat sketchy. Reference is made to "…prominent […] magnetic lineaments which can be caused by faulting", and "…several circular low magnetization anomalies, approximately two kilometers in diameter, aligned with northwest trending lineaments". It would be nice to include a map with these features and lineaments interpreted from the aeromagnetic datasets. This would also tie the observations based on this dataset closer to the seismic interpretation (see below).

The revisited figure 43 is now providing this information

Seismic reflection 2D lines (1989-2015). 8500 km. Interpretation of shallow horizons and faults using all publicly available geological and geophysical data of the Beetaloo region. Fault polygons defined for five horizons. Depth conversion using check-shot velocities from 26 wells.

See comments to Figure 4. The depth maps provided in Figure 5 should be supplemented by isochore maps for the rock volumes between pairs of mapped reflectors. See also comments to Figure 7.

Thank you, the details comments on those figures have been followed and new figures are provided

Helium measurements from groundwater samples. With respect to the helium measurements, no detailed documentation of where these samples were collected is provided beyond referring to Geological and Bioregional Assessment Program (2021a) Fact sheet 12, and Geological and Bioregional Assessment Program (2021b) Regional tracer results from the Cambrian Limestone Aquifer. These are both summary documents. Please provide a reference to the primary documentation.

There is no other reference to date to the "primary documentation" but the link to the data (they should now be online) which are in the fact sheets.

Fault and surface drainage network mapping (tectonic geomorphology). The drainage network was extracted automatically. It is not clear if the "simplified" drainage network shown in Figure 2 was also extracted automatically.

The data is summarized in Figure 8 (see also comments to Figure 8 below). It is not clear if the surface drainage network line dataset is based on the "unfiltered" or "simplified" data shown in Figure 2. Since n=130, one can assume the latter. It is however not made clear how this "simplified" network was generated, but there appear to be a substantial number of instances where the "simplification" provides apparent mismatches with the original data (see examples included in comments to Figure 2 below). The accuracy of the resulting plot can therefore be questioned. If the "simplified" network was generated automatically, I encourage the authors to do a manual QC of the results.

We have redone the figure 2 and added explanations on the process (see reply to comments on figure 2). Figure 8 should now be easier to read

The surface drainage network line dataset was indeed based on the simplified (n=130) network following the following approach: *Small segments with less than 10 nodes were automatically removed in SKUA (Paradigm/Emerson Trademark) and one iteration of smoothing was applied that further removed small irregularities without changing the overall orientation of major drainage lines. This output was then overlayed upon satellite and magnetic images where lineaments are evident for checking and quality control. In this process, minor mismatches of the automated simplified lines were removed and small drainage segments were connected along major lineaments for further simplification and reduction of the dataset.*

-Line 303: "We reviewed the seismic data in detail at the intersections with north-northwest trending lineaments observed on the magnetic dataset (Figure 4)." No such lineaments are shown in Figure 4.There is indeed an error on the figure referencing, we modified to Figure 3B where the lineaments are now clearly indicated.

-Line352: "However, the elevated helium concentrations show no systematic pattern of increase with flow distance (as expected for in-situ production along the flow path) but a rather patchy regional pattern (Figure 8)." This should refer to Figure 9.done

-Line 582. Link for supplementary materials does not work. We indeed need to add this link- we will put a link in place upon acceptance of the paper

Figures

Figure 1A.

-Add scale.done

-Add colour scale for map (depth).done

-Well- and fault-labels largely illegible. Consider removing labels not referred to in the text. done

-Poor visual discretization of main surface fault traces and Post Wilton geophysical faults (maybe use different colour for the two?) done, we also modified the fault legend to add clarity

- Replace white labels with black lettering with no labels and white lettering. done

Figure 1B

-Consider adding a small inset table or schematic to showing the Cambrian Limestone Aquifer stratigraphy in the Georgina, Daly and Wiso basin. Although this is described in the caption, it is not easy to grasp for someone not familiar with the stratigraphy in the area without spending time some time with paper and pencil.

We separated the legends from figures 1A and 1B as to add clarity. This article is focused on the Beetaloo subbasin and we use the direct input for Geoscience Australia in this stratigraphic column. We are not willing to add complexity by presenting in detail the Basins that are covering the Beetaloo Sub-Basin. We removed from the legend the details on the different basins as we understand that it is

leading the reviewer in directions we are not exploring on the CLA stratigraphy- we do not refer this complexity in the results and discussion.

Figure 2

-Poor quality figure (low resolution) in the version available to the reviewer. Quality improved

- Very, very overloaded figure, screen-dump from a mapping programme? Thanks, the figure have been entirely revisited and divided into four subfigures as advised below

-Consider splitting into several maps, e.g. one showing unfiltered + simplified drainage network, and one showing faults).done

-How the authors arrive at the simplified drainage network is not very clear

The adopted approach was:

Small segments with less than 10 nodes were automatically removed in SKUA (Paradigm/Emerson Trademark) and one iteration of smoothing was applied that further removed small irregularities without changing the overall orientation of major drainage lines. This output was then overlayed upon satellite and magnetic images where lineaments are evident for checking and quality control. In this process, minor mismatches of the automated simplified lines were removed and small drainage segments were connected along major lineaments for further simplification and reduction of the dataset.

We added this description of the adopted approach in the legend

Figure 3

-Very small/illegible typeface on map coordinates – consider simplifying scales and use larger typeface. done

-Replace the white label with black typeface with plain white typeface. done

Figure 4

-Poor quality figure (low resolution) in the version available to the reviewer. figure redrawn

- Replace white labels with black typeface with white typeface. done

-Many well-name labels are hard difficult to read/illegible. Consider replacing well names on the map with numbers at the well position (white circles, black typeface) and add a table in the legend listing number and corresponding name of the well. Well label typos modified

-Thin grey seismic lines are not explained in the legend or caption. Why are these not classified in terms of signal quality? Legend added for those lines

-The outline of the Eastern and Western Beetaloo Basin in Figure 3 and 4 should be kept identical in order to position Figure 6 A, B and C in relation to the seismic lines shown in Figure 4. Alternatively the position of Figure 6 A, B and C should be indicated in Figure 4 as well as Figure 3.done

Figure 5. Consider adding isochore maps for intervals between interpreted reflectors. These often highlight tectonic accommodation space creation better than maps. isochores added as supplementary material

Figure 6 Add scale(s).done

Figure 7. Very poorly designed map (screen-dump?). Reviewer copy is also poor resolution.

Clean up the legend:

1. a) Remove underscores,done
2. b) Correct use of small caps, large caps in labels.done
3. c) Correct spelling (e.g. frameworkboundaries to framework boundaries; populated places to Populated places/(Settlements?); PossibleFluidEscapeFeatures to Possible fluid-escape features etc.).done, legend cleared from information not represented
4. d) Explain/improve labels (what do you mean by “ntspr_2M_gw”? “Coast_10million”? “frameworkboundaries”? “State_Borders_10million”. Amend labels or explain in caption. done, legend cleared from information not represented
5. e) Several items in the legend appear to have the same or very similar signatures. checked and clarified

Clean up map:

1. Not possible to differentiate post-Wilton fault types properly in the figure. Clearly identified in the legend and representation
2. Could not find “Coast_10million”, “frameworkboundaries” or “State_Borders_10million” on the map. If these items are present, please use a more contrasting signatures to make it more visible. If they are not present on the map, remove these items from the legend. removed
3. Consider replacing the purple outline of the eastern and western sub-basin with light grey shading. Outline size modified and homogenised with other figures
4. Consider using the most prominent colour (red) for the possible fluid escape features as this is the key element of the map. Bright green might also bee an option. Red selected
5. Not possible to differentiate “ntspr_2M_gw” (whatever that is) and “PossibleFluidEscapeStructures” (same colour). modified

The link between interpreted faults and fluid or gas escape features is a key feature of this figure. The map differentiates between “BaseCambrian seismic faults”, Post-Wilton “Strike-slip” and “Reverse” faults, and “FAULTS”. The categorization is not adequately explained (e.g. what differentiates “FAULT” from a “BaseCambrianSeismic fault”?). modified accordingly

Consider adding a simple conceptual sketch highlighting the stratigraphic position of the different faults (and possible fluid escape structures– this would also help visualizing which stratigraphic intervals the potential fluid escapes originate from and which stratigraphic intervals are potentially

connected along potential fault-related fluid flow pathways. With the new classification the reader should be able to better read the paper and can now directly refer to the stratigraphic table

Figure 8. Please provide a more informative caption to what these plots show. What is included in the “Drainage and structural lineament analysis” plot? Done, figure clarified as well

Figure 9. Poor resolution in the copy provided for the review. Consider using higher contrast colours or thicker lines to highlight different faults on the map. done, we also totally revisited this figure as to have a cleared output

I hope you will find these comments useful when revising the manuscript and look forward to seeing the paper published in *Geoscience*. Thank you, we truly appreciated the time took by the reviewer to provide detail guidance to improve the manuscript and the figures