

Dear Dr. Kei Ogata, Dr. Stephen Laubach, Dr. Giacomo Medici and reviewers:

Thank you very much for your constructive advices on my manuscript **egosphere-2025-2749 (Geological factors and fracture distribution in deep and ultra-deep sandstones in Kuqa Depression, Tarim Basin, China)** submitted to your journal “Solid Earth”.

We have carefully revised the manuscript considering the remarks made by the two reviewers and the editors, and would like to re-submit it for your consideration. We have addressed the comments raised by the reviewers, and the amendments are highlighted in red or blue in the revised manuscript. We are indebted to you and the two anonymous reviewers for your constructive comments, which improve the manuscript significantly.

We also download some papers recently published in **Solid Earth**, and revised the references format carefully. Further some papers published recently in your journal have been cited in the revised manuscript (highlighted in blue in the references lists).

The point by point responses to the two reviewers’ and Editor’s comments are listed below.

Below, the original comments are in black, and our responses are in blue.

Comments of Editor

Dear Authors,

When posting your author comments (ACs), you can choose between new comments or co-listing of existing ones. Please also consider replying to community comments (CCs) from the scientific community.

Reply:

Thank you for your valuable feedback.

We have provided detailed responses to all comments from the three reviewers and have revised the manuscript accordingly. We appreciate your handling of our manuscript and your dedicated efforts throughout the process.

1. Reviewer #1, Dr. Laubach

Dr. Laubach had the following comments and suggestions:

Fractures in ultra-deep sandstones are of considerable scientific and practical interest.

The Introduction needs to be modified to more clearly state the claims of the work. This element should come near the end of the Introduction. See comment under line 70.

Reply:

Dear Dr. Laubach,

Thank you for your constructive comments.

We have carefully revised the Introduction to address the comment. As requested,

we have added a succinct paragraph near the conclusion of the Introduction (Section 1, final paragraph in line 71) to explicitly outline the core claims of our study. This addition concisely synthesizes the key relationships and novel findings investigated in our work, directly addressing the scientific and practical significance of fractures in ultra-deep sandstones.

The added text in line 72: Here we show the relationships between geological factors and fracture distribution in deep and ultra-deep reservoirs in Kuqa Depression. Our analysis establishes that high-angle fractures represent the dominant fracture type in ultra-deep (>6000 m) tight sandstones of the Bozi-Dabei block, with the highest fracture density observed in fine-grained sandstones. An inverse relationship is delineated between sandbody thickness and fracture density, with fracture networks preferentially developed in thin sandstones interbedded with mudstone layers. A positive correlation is quantitatively established between maximum paleostress magnitude and fracture density. Earth stress may influence fracture characteristics, where an increase in the horizontal stress difference leads to a decrease in fracture parameter magnitude. While in situ stress modulates apertures, cementation may counteract closure for some fractures oriented at a high angle to S_{Hmax} where mineral bridges develop due to rapid diagenesis in Kuqa Depression (eg., Laubach et al., 2004; Olson et al., 2007; Laubach et al., 2019). Fracture density is maximized in anticlinal hinges compared to limbs, elevated in upper formations along longitudinal axes, and significantly amplified near faults due to stress field perturbations. Critically, we demonstrate that fracture density directly and quantitatively enhances hydrocarbon

productivity, with higher fracture densities correlating with elevated oil production rates. The results show that the fundamental geological controls on fracture distributions in ultra-deep foreland basin reservoirs and provide a predictive framework for targeting high-productivity zones.

Thank you again for your constructive comments.

The citations to the literature cover important references, but the precision of the citing is lacking in some instances. The authors should consider working to tailor the citations more specifically to the points being made. And in many cases adding ‘e.g.’ would be useful, to indicate that these are just some examples from the literature, because in some instances they are neither the earliest examples nor the most recent reviews.

Reply:

Dear Dr. Laubach,

Thank you for your constructive comments.

We sincerely appreciate the reviewer's insightful feedback regarding citation precision. We fully agree that citations should be meticulously tailored to support specific technical claims and that contextual indicators like e.g. enhance scholarly rigor. Each citation will be explicitly linked to the precise concept/mechanism it validates. The reference to Barton et al. (1995) now directly follows the Coulomb failure criterion equation within the sentence: The differential stress ratio (S_{Hmax}/S_{Hmin}) and pore pressure control fracture shear reactivation and dilation (Barton et al., 1995). Similarly, discussions on lithology and earth stress effects on fracture distribution are now

precisely anchored to dedicated references. Key works by Laubach et al. (2004), Laubach et al. (2023), Zoback (2007), Zhang and Ma (2021), Yu et al. (2023) and Mercuri et al. (2020) have been cited in Line 60 to support these specific points.

Thank you again for your constructive comments.

The title says deep and ultradeep, but how deep is not sufficiently emphasized. I don't think you mention actual depths at all in the Introduction. For the international reader this will be an interesting aspect of this paper and it needs to be underlined. Tell the reader what constitutes deep and ultra-deep. And make it clear what depths your samples are from. For example figure 8 is a spectacular illustration of image log fracture intensity variations with rock type but it just has a simple, cryptic label and there is no emphasis that the observations are from 6778 to 6801 meters.

Reply:

Dear Dr. Laubach,

Thank you for your thoughtful review and constructive suggestions. We sincerely appreciate your insightful feedback regarding the need to emphasize depth ranges in our manuscript. Please find below our point-by-point revisions addressing your concerns:

Explicitly defined “deep” (>4500 m) and “ultra-deep” (>6500 m) in the west basin in the opening paragraph using standard petroleum industry thresholds in line 35. Specified study depths as “ultra-deep (>6500 m)” when introducing the Kuqa Depression.

Explicit Sample Depths Highlighted in Materials and methods section. we have added a sentence in line 136: All analyzed cores and image logs were obtained from depths of 4500-7200 m, with fracture characterization focusing in Cretaceous Bashijiqike Formation where fracture networks are most extensively developed.

The caption of Figure 9 (original Figure 8) is revised. The revised version: Figure 8: Fracture characteristics in sandbodies of the BZ 104 interval (6778-6801 m). Sandbodies with constant thickness show increased fracture potential where the adjacent mudstone is thinner.

We sincerely appreciate this suggestion, which significantly strengthens the manuscript's impact by contextualizing our findings within globally relevant ultra-deep reservoir challenges. Thank you for your valuable guidance.

I'm not necessarily recommending you cite this work, but Laubach et al. 2023 might be a good guide for how to add emphasis on the deep observations you have to offer. This is part of what makes your study interesting so make this aspect more obvious to the reader. (Laubach, S.E., Zeng, L., Hooker, J.N., Wang, Q., Zhang, R.H., Wang., J., Ren, B., 2023. Deep and ultra-deep basin brittle deformation with focus on China. Journal of Structural Geology 175, 104938)

Reply:

Dear Dr. Laubach,

Thank you for your constructive comments.

We deeply appreciate you highlighting Laubach et al. (2023) as a conceptual

guide-the work expertly frames the significance of deep and ultra-deep brittle deformation. We already cited this work at the introduction. Crucially, we have incorporated a citation to Laubach et al. (2023) (Journal of Structural Geology, 175, 104938) in Section (Introduction) and Section 5.2 (Line 324) to explain the effect of diagenetic processes on fractures.

Thank you again for your constructive comments.

Some of the figure captions are too short and cryptic. Figure 8, for example. Explain what is in the figures and draw attention to key points. These need to be more than mere labels. (On the figures, the rose diagrams should show $n =$ for how many readings and say if these are equal area plots).

Reply:

Dear Dr. Laubach,

Thank you for your constructive comments.

We have comprehensively revised this caption per your recommendation. The caption now explicitly highlights how geological factors control fracture distribution. Similar enhancements have been applied to some figures. The revised version as follow:

Figure 2: The core depth has been included in the caption of Figure 2.

Figure 4: The well log response of fracture in well logs including conventional well logs, image logs, and array acoustic logging in Well DB 302

Track 1: Elemental Capture Spectroscopy (ECS)

Track 3: Compressional wave slowness, Compensated neutron and density logging

Track 4, 5: Fracture parameters including fracture aperture, porosity, density and length

Track 6: Stoneley wave attenuation from array acoustic logging

Track 7: FMI image showing filled fractures (blue) and conductive fractures (yellow)

Track 8: Core photos

Figure 5: Figure 5 has been updated to include the ultra depth. Additionally, detailed fracture characteristics across distinct sandstone lithologies interbedded with mudstone layers of varying thicknesses have been added.

Figure 7 in original paper Figure 6: Lithology-controlled fracture characteristics revealed by FMI logs in Bozi-Dabei block, Kuqa Depression

(a) Long, well-connected fracture in thick sandstone interbedded with thin mudstone (6147.5 m)

(b) Restricted fracture propagation in thin sandstone interbedded with thick mudstone (6152 m)

(c) Restricted fracture in thin sandstone interbedded with thick mudstone (6153 m)

Figure 9 in original paper Figure 8: Fracture characteristics in sandbodies of the BZ 104 interval (6,78-6801 m). Sandbodies with constant thickness show increased fracture potential where adjacent mudstone is thinner.

Figure 11 in original paper Figure 10: In situ stress magnitude and fracture parameters including fracture porosity and fracture aperture in Well BZ 17. The fracture aperture is higher at the lower $\Delta\sigma/S_{hmin}$ (A, B). The fracture aperture is lower at the higher

$\Delta\sigma/S_{hmin}$ (C).

Figure 15: The fracture characteristic in different structure position in anticline located at the DB 9 wellblock. Schematic cross-section illustrating three mechanical zones defined by folding: Extensional Area (above the incremental neutral line), Transitional Area (between neutral lines), and Shortening Area (below the finite neutral line) (modified after Frehner, 2011; Li et al., 2018). Summary of fracture characteristics observed in two key wells (DB 902 and DB 9) located in the transitional and extensional hinge areas, respectively.

The rose diagram n-values were added in Fig. 6, Fig. 11, Fig. 12.

Thank you very much for your constructive comments.

There are a few sections in the Results that should be moved to the Discussion. I've marked some of these below, but the entire text should be checked. Much of the section around line 256 on in situ stress belongs in the Discussion (where a more nuanced appreciation is needed). See comments below.

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We have carefully implemented your suggestions regarding restructuring content between the Results and Discussion sections. The in-situ stress analysis (original Section 4.4, lines 256-289) has been moved to Section 5.2.2 (In situ stress magnitude and fracture distribution) in the Discussion.

Thank you very much for your constructive comments.

Although reasonably clearly written, the text could use additional polishing for concision.

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. Throughout the manuscript, we have implemented rigorous text polishing to enhance precision and eliminate redundancy.

Thank you very much for your constructive comments.

Comments keyed to lines in the text

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We have meticulously addressed all reviewer comments. Modifications are directly referenced to manuscript line numbers, with all edits highlighted in the modified file.

Thank you very much for your constructive comments.

39 Check for typo

Reply:

Dear Dr. Laubach,

We apologize for the typo errors. The typos have already been revised.

Thank you very much for your constructive comments.

47 'makes it'

Replies:

Dear Dr. Laubach,

Thank you very much for your constructive comments. We have revised the sentences in line 50.

Thank you very much for your constructive comments.

70 Near the end of the Introduction you need to state the claims of your paper. You have a list of what you did and topics you cover but not statement of claims. You really need these to draw in the reader. Consider adding a paragraph that starts with the phrase 'here we show that...' and then say what you show: your claims. Some of the extant text can be readily altered for this purpose. For example, in line 69 instead of saying "The results will provide new insights into geological..." say "The results show that [and then fill in what the insight is]"

Replies:

Dear Dr. Laubach,

Thank you very much for your constructive comments.

Thank you for your insightful feedback on our manuscript. We have carefully revised the Introduction to explicitly state our paper's claims as suggested. The paragraph has already been added in line 72:

Here we show the relationships between geological factors and fracture distribution in deep and ultra-deep reservoirs in Kuqa Depression. Our analysis establishes that high-angle fractures represent the dominant fracture type in ultra-deep (>6000 m) tight sandstones of the Bozi-Dabei block, with the highest fracture density observed in fine-grained sandstones. An inverse relationship is delineated between sandbody thickness and fracture density, with fracture networks preferentially developed in thin sandstones interbedded with mudstone layers. A positive correlation is quantitatively established between maximum paleostress magnitude and fracture density. In stress has a significant influence on fracture aperture and porosity, where an increase in the horizontal stress difference leads to a decrease in fracture parameter magnitude. While in situ stress modulates apertures, cementation may counteract closure for some fractures oriented at a high angle to S_{Hmax} where mineral bridges develop due to rapid diagenesis in Kuqa Depression (eg., Laubach et al., 2004; Olson et al., 2007; Laubach et al., 2019). Fracture density is maximized in anticlinal hinges compared to limbs, elevated in upper formations along longitudinal axes, and significantly amplified near faults due to stress field perturbations. Critically, we demonstrate that fracture density directly and quantitatively enhances hydrocarbon productivity, with higher fracture densities correlating with elevated oil production rates. The results show that the fundamental geological controls on fracture distributions in ultra-deep foreland basin reservoirs and provide a predictive framework for targeting high-productivity zones.

Thank you again for your valuable critique.

111 What is the depth range of the samples?

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. The depth range of the samples has already been added into section 3 (Materials and methods) in line 135. All analyzed cores and image logs were obtained from depths of 4500-7200 m, with fracture characterization focusing in the Cretaceous Bashijiqike Formation where fracture networks are most extensively developed.

Thank you again for your constructive comments.

143 From the images, it looks as though most of the fractures are opening-mode fractures rather than faults. Why not use this terminology?

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. To improve terminological precision, we now consistently use “opening-mode fractures” instead of “fractures” where appropriate in section 4.1 in line 193.

Thank you again for your constructive comments.

149-150 There is a problem with this sentence, since open fractures by definition can't be filled with calcite. Maybe you mean that some opening-mode fractures are open or are only partly filled with mineral deposits like calcite, and some are filled with calcite.

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We are sorry for our misunderstanding. We acknowledge the terminological inconsistency in our original description. As correctly noted, we revised the description for partly-filled fracture in line 198.

Thank you again for your constructive comments.

150 (figure) why not mention sample depths in the figure caption?

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We have revised the caption of Figure 2 in line 194-202. All samples have already been mentioned sample depths.

Thank you again for your constructive comments.

173 (figure) The open, irregular pore space in these fractures is not necessarily due to dissolution. This kind of texture can arise from incomplete infill of fractures (see Lander and Laubach 2015, GSA Bulletin). In any case, in your description you should describe what you see in terms that do not imply a mechanism, otherwise you have a circular argument (And you also have to explain how you get dissolution in these siliciclastic rocks). If you use descriptive terms in the Results you can use arguments in the Discussion to make the case for how you think those textures arose. In other words,

the Discussion is where you say ‘we interpret the irregular, partly open fractures to be the result of dissolution because ...’

Reply:

Dear Dr. Laubach,

Thank you for your insightful critique regarding fracture description in our Results section. We have implemented your suggestions as follows:

We have removed interpretive mechanisms. All references to “dissolution” and “tectonic compression” have been removed from the Results section. The descriptive terminology was adopted in line 216. All figure 3 captions now use purely descriptive language. Furthermore, we have downloaded the seminal study to learn about this knowledge by Lander and Laubach (2015, GSA Bulletin).

Fracture distribution in this study was analyzed using well logging data. Microfractures cannot be detected by well logging tools due to resolution limitations. Consequently, the Discussion section does not address microfracture characterization.

We sincerely appreciate your guidance in strengthening the distinction between observation and interpretation. These revisions have significantly improved our manuscript’s scientific rigor by eliminating circular reasoning.

Thank you again for your constructive comments.

175 ‘Formation’ needs to be capitalized for formal units.

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We have revised the mistakes.

Thank you again for your constructive comments.

187 'often' is a time term; 'commonly' is better

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We have revised the mistakes in line 232.

Thank you again for your constructive comments.

198-199 This line about fluid flow belongs in the Discussion

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We have deleted this sentence in line 202.

Thank you again for your constructive comments.

200-202 These acoustic effects can be interfered with by rugose borehole. How smooth is your wellbore?

Reply:

Dear Dr. Laubach,

We appreciate your keen observation regarding borehole artifacts. Per your recommendation, Figure 4 has been superseded by new Figure, which eliminates rugosity interference through clear visualization of the wellbore profile (see Section 4.3, Lines 247). The boreshape in track 2 showing borehole breakout intervals where hole diameter exceeds bit size.

Thank you again for your constructive comments.

226-230 Some of this material is fine, but it is out of place. Here in the Results describe what you found. Move the text about what you expect given the fractured layer thickness to the Discussion.

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript.

We agree that the discussion regarding expectations of fracture distribution relative to layer thickness is more appropriately positioned within the Discussion section. Accordingly, we have relocated this text (originally in Results, Lines 217-248) to Section 5.1 of the Discussion (now Lines 284-297).

Thank you again for your constructive comments.

228-230 This seems to contradict what you said in the Abstract, where I read “Fracture density increases as sandbody thickness increases” which would indeed be a surprising result. Check.

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We sincerely thank the reviewer for identifying this critical inconsistency. We have made the following corrections. In abstract, the sentence has revised. In line 23, the sentence has changed into “Fracture density exhibits an inverse relationship with sandbody thickness”.

Thank you again for your constructive comments.

242 (figure 8) this is a nice, interesting illustration.

Reply:

Dear Dr. Laubach,

We sincerely appreciate the reviewer’s recognition of Figure 8 as an interesting illustration. Your recognition of our results has been incredibly encouraging and motivating.

Thank you again for your constructive comments.

245-253 This material belongs in the Discussion.

256 (section) this interpretation of the effects of stress belongs in the Discussion. In the Results you could provide evidence of what the state of stress is in these sandstones. It is an interpretation that stress contrasts might have the effects that you describe but the rocks here are in all around compression and the difference between SHmax and Shmin is probably small (in the Results you can say what this is). But just because this effect might be important does not mean that it is important, so saying

“Therefore, in situ stress has a significant influence on the fracture aperture and porosity” is not warranted unless you have observations that you have not presented on changes with stress in in situ aperture or pore space. In many deeply buried sandstones natural fracture aperture are quite sensitive to in situ stress changes going back to experiments on core by Warpinski in the late 1980s; in many moderately to deeply buried sandstones open fractures exist at a wide range of angles (including at right angles) to SHmax (Laubach et al., 2004, EPSL) a circumstance that can be explained by the precipitation of cement in the stressed host rock (Olson et al., 2007) or to partial mineral bridges like some of the ones visible in your images (Laubach et al., 2004). Olson et al. show that if host rock diagenesis is happening during fracture, the expected stiffening effect of host rock cements means that an unacceptably high stress would be needed to close the fractures. See figure 15 in Laubach et al. (2019) to see what the magnitude of modulus increase likely is in a sandstone like the ones you describe. There are several papers on diagenesis of sandstone in basins near yours that show that such cement accumulations were likely happening rapidly in these deeply buried and hot settings.

My suggestion: here focus on what you can observe about the stress state in your rocks; in the Discussion, where most of this text belongs, mention these alternative interpretations.

Laubach, S.E., Olson, J.E., and Gale, J.F.W., 2004, Are open fractures necessarily aligned with maximum horizontal stress? *Earth & Planetary Science Letters*, 222/1, 191-195.

Olson, J. E., Laubach, S. E., and Lander, R. L., 2007, Combining diagenesis and mechanics to quantify fracture aperture distributions and fracture pattern permeability: In Lonergan, L., Jolley, R.J., Sanderson, D.J., Rawnsley, K., eds., *Fractured Reservoirs*, Geological Society of London Special Publication 270, 97-112.

Laubach, S.E., Lander, R.H., Criscenti, L.J., et al., 2019. The role of chemistry in fracture pattern development and opportunities to advance interpretations of geological materials. *Reviews of Geophysics*, 57 (3), 1065-1111. doi:10.1029/2019RG000671

Reply:

Dear Dr. Laubach,

We sincerely appreciate the reviewer's insightful guidance on properly contextualizing stress effects. We have restructured this section as follows to address your concerns:

We removed all interpretive statements regarding stress effects on fracture aperture and added quantitative stress characterization in section 4.5:

In situ stress affects the late modification of natural fractures (Rajabi et al., 2010; Lai et al., 2019). The one-dimensional earth stress model is utilized to calculate the in-situ stress (Lai et al., 2022). The maximum principal horizontal stress (S_{Hmax}) magnitude, the minimum principal horizontal stress (S_{Hmin}) magnitude, and vertical principal stress (S_v) magnitude can be calculated using Eq. 1-Eq. 4. The vertical stress was calculated using an overburden gradient of 25.28 MPa/km. Maximum (S_{Hmax}) and minimum (S_{Hmin}) horizontal stresses were continuously estimated by well logs using Eq.

3-4. While vertical stress (S_v) increases linearly with depth, horizontal stresses exhibit significant fluctuations. Fluid overpressures are prevalent (overpressure coefficient = 1.6-2.2), exemplified at 6,440 m depth where horizontal stresses range between 110-200 MPa (Fig.6). The in-situ stress regime corresponds to strike-slip faulting ($S_{Hmax} > S_v > S_{Hmin}$) (Fig.6). The induced fractures are aligned with the direction of S_{Hmax} , and the Breakouts are perpendicular to the direction of S_{Hmax} . Fracture image-log observations reveal that the S_{Hmax} direction trends close to north-south and S_{Hmin} direction trends close to west-east (Fig.6).

We have significantly rewritten Section 5.2.2 (In situ stress magnitude and fracture distribution). As suggested, we have incorporated the discussion on the competition between in-situ stress and chemical diagenesis. We cited the recommended literature (Laubach et al., 2004; Olson et al., 2009; Laubach et al., 2019) to explain that while stress modulates aperture, chemical processes specifically the formation of mineral bridges and the stiffening of the host rock due to quartz cementation play a critical role in preserving open fractures in these deep, hot sandstones, even when oriented at high angles to S_{Hmax} . The effect of diagenesis of sandstone on fractures was mentioned in line 335 and the sections 4.4, 4.5, 4.6 of the original paper were removed to Discussion 5.1-5.2. While discussing the potential influence of in situ stress on fractures, it is essential to acknowledge the inherent uncertainties in such interpretations. We modified the saying “Therefore, in situ stress has a significant influence on the fracture aperture and porosity” into

“The inverse correlation observed between fracture parameters (aperture and

porosity) and the differential stress ratio ($\Delta\sigma/S_{hmin}$) (Fig. 11) indicates that in situ stress conditions may influence fracture characteristics in these sandstones. Lower horizontal stress differences ($\Delta\sigma = S_{Hmax} - S_{hmin}$) appear to correlate with better-preserved fracture apertures. Higher fracture parameters (fracture aperture and porosity) correspond to the lower $\Delta\sigma/S_{hmin}$ ($\Delta\sigma/S_{hmin}=(S_{Hmax}-S_{hmin})/S_{hmin}$) (Fig.11A, Fig.11B).”

Meanwhile, key references have been incorporated in line 342-347.

“While stress state modulates fracture apertures (e.g., Warpinski, 1987), the preservation of open fractures at high angles to S_{Hmax} suggests additional controls. Mineral bridges (Laubach et al., 2004) and synkinematic cementation (Olson et al., 2009) likely reduced fracture compressibility. Host-rock diagenesis, which evidenced by quartz overgrowths increased matrix modulus (Laubach et al., 2019, Fig. 15), further inhibiting fracture closure. Rapid cementation in high-temperature settings in the Kuqa Depression could sustain fracture porosity despite burial stresses (Wang et al., 2020; Laubach et al., 2023).”

We modified the conclusive statement in Conclusion, and the sentences are added in line 423:

“In situ stress affects the late modification of natural fractures. An increase in the horizontal stress difference, reflecting a greater disparity between the horizontal principal stresses, leads to a decrease in fracture parameter magnitude. Although stress state influences fracture apertures, the preservation of open fractures at high angles to S_{Hmax} indicates additional controlling factors. Consequently, in-situ stress likely

interacts with fracture-filling cements to jointly regulate aperture maintenance, rather than serving as the primary control.”

Thank you again for your constructive comments.

275 type amone>among

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. The misspelled word amone has been corrected to among in the sentence.

Thank you again for your constructive comments.

296 ‘three wells’ (small number rule)

Reply:

Dear Dr. Laubach,

Thank you for your insightful feedback on our manuscript. We thank the reviewer for highlighting this stylistic oversight. Following standard English writing conventions for small cardinal numbers. We revised this mistake in line 335.

Thank you again for your constructive comments.

2. Reviewer #2

The Reviewer #2 had the following comments and suggestions:

This manuscript presents a comprehensive, multi-method investigation of fracture

distribution and its controlling factors in deep to ultra-deep sandstones within the Kuqa Depression. The study integrates core, thin-section, acoustic emission, and a suite of geophysical logs to address an important topic in reservoir characterization and hydrocarbon exploration. The work is generally well-structured, data-rich, and relevant to the field. I can recommend acceptance after the following minor revisions

Reply:

Thank you for your thorough review and constructive comments. We appreciate your positive assessment and have carefully addressed each of your suggestions. The revisions have strengthened the clarity, precision, and scholarly rigor of the manuscript. We found the comments to be highly constructive and believe they have significantly improved the quality and clarity of our work. We have carefully addressed all the comments. Below is a point-by-point response detailing how each issue was resolved.

The introduction adequately contextualizes the importance of fractures in deep reservoirs. You should add some related references.

Reply:

We thank the reviewer for this suggestion. We have added two recent and relevant references on fracture characterization in sandstone reservoirs to the Introduction section, which provide valuable insights into multi-scale fracture controls that are analogous to our sandstone study.

Laubach, S.E., Zeng, L., Hooker, J.N., Wang, Q., Zhang, R.H., Wang, J., Ren, B.,

2023. Deep and ultra-deep basin brittle deformation with focus on China. *Journal of Structural Geology* 175, 104938

Lander, R. H., Laubach, S. E. 2015. Insights into rates of fracture growth and sealing from a model for quartz cementation in fractured sandstones. *GSA Bulletin*, 127(3-4), 516-538.

Zhang, S., Ma, X. 2021. How does in situ stress rotate within a fault zone? Insights from explicit modeling of the frictional, fractured rock mass. *Journal of Geophysical Research: Solid Earth*, 126(11), e2021JB022348.

Yu, G., Liu, K., Xi, K., Yang, X., Yuan, J., Xu, Z., Zhou, L., Hou, S. 2023. Variations and causes of in-situ stress orientations in the Dibei-Tuziluoke gas field in the Kuqa foreland basin, western China. *Marine and Petroleum Geology*, 158, 106528.

These additions enrich the literature background and connect our work to contemporary research on fracture systems.

The description of methods is detailed but occasionally disjointed. For example, the stress calculation equations (Eq. 1-4) are introduced without sufficient explanation of the parameters (ν , B , C , a). Please define each variable and briefly justify the chosen model.

Reply:

We sincerely thank the reviewer for their thoughtful feedback regarding the clarity of our methodological description. In response, we have comprehensively revised this section to include a detailed explanation of the methodology for calculating in situ stress.

We have revised this section to provide a comprehensive explanation as follows:

“Among various approaches for in-situ stress calculation, One-dimensional Mechanical Earth Models (1-D MEMs) have emerged as the preferred methodology owing to its performance advantages over conventional techniques (Barton et al., 1988; Zoback et al., 2003; Zoback et al., 2007; Tingay et al., 2009). The model effectively represents geological formations as anisotropic media, and incorporates the coupled influence of both Young’s modulus and Poisson’s ratio in stress calculation (Barton et al., 1988; Zoback et al., 2003; Zoback et al., 2007; Tingay et al., 2009). These features make it especially suitable for complex geological environments, as evidenced by its successful application in the Tarim Basin, where it has consistently demonstrated superior predictive capability compared to traditional stress models (Ju and Wang, 2018; Lai et al., 2019).

One-dimensional Mechanical Earth Models (1-D MEMs) enable the determination of in-situ stress magnitudes ($S_{H_{max}}$, $S_{h_{min}}$, S_v). Vertical stress (S_v) is calculated by bulk density integration from surface to target depth (Eq.1), with standard gradients at 23 MPa/km (2.3 g/cm³ average density). In the Kuqa Depression, acoustic emission experiments established a gradient of 25.28 MPa/km (2.528 g/cm³), yielding $S_v=173.79$ MPa at 6,873.38 m. Pore pressure (P_p) is determined using Eaton’s sonic transit time method (Eq.2), where deviations from normal compaction trends ($\Delta t_n/\Delta t$) indicate overpressure. Drilling-induced fractures indicate $S_{H_{max}}$ direction while breakouts define $S_{h_{min}}$ orientation using image logs. Log-derived stress calculations incorporate $S_{H_{max}}$ and

S_{hmin} , with dip corrections applied in steep structures using a modified Anderson model accounting for stratigraphic geometry (Eq.3-4).

$$S_v = \int_0^H \rho g dz \quad (1)$$

$$P_p = P_0 - (P_0 - P_w)(\Delta t_n / \Delta t)^c \quad (2)$$

$$Sh_{min} = \left(\frac{\nu}{1-\nu} + A - C\right)(Sv - \alpha P_p) + \alpha P_p \quad (3)$$

$$SH_{max} = \left(\frac{\nu}{1-\nu} + B - C\right)(Sv - \alpha P_p) + \alpha P_p \quad (4)$$

Here, S_v is the vertical stress (MPa); H is the burial depth, m; ρ is the bulk density obtained from density (DEN) logs, kg/m³ and g is the gravitational acceleration (m/s²). P_p represents the formation pressure, while P_0 denotes the overburden pressure; P_w corresponds to the hydrostatic pore pressure. The measured sonic transit time in shale, obtained from well logs, is given by Δt , and Δt_n refers to the normal-compaction sonic transit time in shale, derived from the normal trend line. The exponent c is an empirical constant. ν is Poisson's ratio, calculated using compressional wave velocity (V_p), shear wave velocity (V_s), and bulk density logs. The tectonic stress coefficients A and B are set as 0.405 and 0.891, respectively. C is the coefficient of stratigraphy dip.”

Thank you again for your comments.

Some terms such as “earth stress” and “in-situ stress” are occasionally used interchangeably in the text. To improve clarity and precision, it is recommended that a single, consistent term be adopted throughout the manuscript.

Reply:

We thank the reviewer for this insightful comment. For clarity, we use “earth stress”

as a broad term encompassing both paleostress (historical stress) and present-day in-situ stress. In the revised manuscript, we have consistently used “in-situ stress” when referring to the current stress field, and “paleostress” when discussing past stress conditions. This distinction ensures greater precision and consistency throughout the text.

Thank you again for your comments.

The captions for some figures could be more descriptive. Enhancing them would help readers better understand the context of each figure.

Reply:

We appreciate the reviewer’s suggestion to make the figure captions more concise. We have revised all figure captions to include more detailed descriptions of the geological context, lithology, depth, and fracture types shown. For example, the caption for Figure 2 now specifies each fracture type, well name, depth, and filling material. Similar enhancements have been made to Figures 4-15.

Thank you again for your comments.

Some recently published articles offer valuable insights into fracture formation mechanisms, and it would be beneficial to consider citing them. Distribution and Development of Faults and Fractures in Shales. *Minerals*, 2025,15(11): 1154. Multi-scale characterization and control factors of bedding-parallel fractures in continental shale reservoirs: Insights from the Qingshankou Formation, Songliao Basin, China.

Marine and Petroleum Geology, 2025, 182: 107580.

Reply:

Thank you for your valuable time and insightful feedback on our manuscript. We have incorporated both suggested references into the Introduction and Discussion sections where appropriate, acknowledging their relevance to multi-scale fracture characterization and control factors.

Thank you again for your comments.

Some sentences are overly long or passive (Fractures are prevalent in deep...). Consider revising for conciseness

Reply:

Thank you for your valuable time and insightful feedback on our manuscript. We have reviewed the entire manuscript and revised overly long or passive sentences for clarity and conciseness. Shorter sentence structures are now used where possible, improving readability without sacrificing technical accuracy.

Thank you again for your comments.

3. Commenter #1, Dr. Medici

Dr. Medici had the following comments and suggestions:

You have very deep (>6 km) data. I think it's the deepest investigation for a sandstone open to public, it's a novelty. Please, follow my suggestions to fix minor issues to your good research.

Reply:

Dear Dr. Medici,

We are profoundly grateful for your recognition of the novelty in our ultra-deep sandstone reservoir investigation (>6000 m). Thank you for acknowledging the significance of this unique dimension of our research. We have meticulously implemented all your technical suggestions point-by-point in the revised manuscript (detailed in responses below), and welcome further guidance to ensure our work meets the highest standards. Your expertise has been invaluable in strengthening this contribution to deep reservoir characterization.

Thank you again for your constructive comments.

Lines 10-30. Quantify how much deep or ultradeep the sandstones are in terms of meters in the abstract.

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. We have explicitly quantified the depth range in Line 11 of the Abstract to define deep and ultra-deep reservoirs. Additionally, Section 3 (Materials and Methods) now specifies the exact sampling depths across all wells in this research.

Thank you again for your constructive comments.

Line 36. "Fractures play a crucial role in environmental and energy resource issues". Please, insert a recent publication that discusses the role of fracture connectivity in the geo-energy field:

- Romano, V., Proietti, G., Pawar, R.J., Bigi, S., 2025. Evaluation of fracture network efficiency to CO₂ storage with a DFN approach. International Journal of Greenhouse Gas Control, 141, p.104317.

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. We have added this cite in Line 36. This revision makes the manuscript more solid by supporting its main claims with the latest practical research.

Thank you again for your constructive comments.

Line 40-41. “Geophysical well logs including conventional well logs, image logs, and array acoustic logs provide crucial insights into the rock’s physical properties, compositional variations, and structural discontinuities”. Insert recent publication on the use of wireline and acoustic image logs to detect the rock’s physical properties and structural heterogeneities:

- Medici, G., Munn, J.D. and Parker, B.L., 2024. Delineating aquitard characteristics within a Silurian dolostone aquifer using high-density hydraulic head and fracture datasets. Hydrogeology Journal, 32(6), pp.1663-1691.

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. We have added this

cite in Line 40-41. This revision makes the manuscript more solid by supporting its main claims with the latest practical research.

Thank you again for your constructive comments.

Line 71. Clearly mention the 3 to 4 specific objectives of your research by using numbers (e.g., i, ii, and iii).

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. We have restructured the research objectives for enhanced clarity in the Introduction. The content was added in line 65: Here we show that the relationships between geological factors and fracture distribution in deep and ultra-deep reservoirs in Kuqa Depression. Our analysis establishes that high-angle fractures represent the dominant fracture type in ultra-deep (>6,000 m) tight sandstones of the Bozi-Dabei block, with the highest fracture density observed in fine-grained sandstones. An inverse relationship is delineated between sandbody thickness and fracture density, with fracture networks preferentially developed in thin sandstones interbedded with mudstone layers. A positive correlation is quantitatively established between maximum paleostress magnitude and fracture density. An increase in the horizontal stress difference, reflecting a greater disparity between the horizontal principal stresses, leads to a decrease in fracture parameter magnitude. Fracture density is maximized in anticlinal hinges compared to limbs, elevated in upper formations along longitudinal axes, and significantly amplified near faults due to stress field perturbations. Critically, we demonstrate that fracture density

directly and quantitatively enhances hydrocarbon productivity, with higher fracture densities correlating with elevated oil production rates.

Thank you again for your constructive comments.

Lines 73-104. Be more specific on the type of faults (thrusts, normal faults, strike-slip?).

Reply:

Dear Dr. Medici,

Thank you for your valuable feedback on our manuscript. In response to your suggestion, we have clarified that the structural architecture of the Kuqa Depression is characterized by southwest-vergent thrust fault systems, with secondary strike-slip fault components, which developed during the peak compressional phase of the Late Himalayan orogeny (Fig. 1) (Lu et al., 1994; Ju et al., 2014; Lai et al., 2019) in line 91.

We appreciate your thoughtful input and hope this revision addresses your concern.

Lines 73-104. Provide sedimentological detail for your sandstones

Reply:

Dear Dr. Medici,

Thank you for this constructive suggestion on our manuscript. The following sedimentological details have been added to Section 2 (Geological settings) to characterize the sedimentological detail in Kuqa depression comprehensively:

Sedimentary Architecture is added in this section in line 115: Comprising braided river delta front deposits, the K_1b_{s2} unit contrasts with the fan delta front deposits of

the K_{1bs3} . Laterally, these sand bodies exhibit considerable thickness, extensive lateral continuity, and broad distribution (Lai et al., 2019; Xu et al., 2025).

Permeability characteristics reveal a significant contrast: Comparison reveals that while matrix sandstone permeability is primarily 0.001-0.1 mD, that of fractured sandstone ranges from 1 to 10 mD, differing by 1-3 orders of magnitude (Du et al., 2025).

The sedimentary facies of K_{1bs2} and K_{1bs3} unit: Comprising braided river delta front deposits, the K_{1bs2} unit contrasts with the fan delta front deposits of the K_{1bs3} . Laterally, these sand bodies exhibit considerable thickness, extensive lateral continuity, and broad distribution (Lai et al., 2019; Xu et al., 2025).

Lines 111-140. You have described very well the materials, but you need to add description of the type of analysis (the methodology).

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. We appreciate the reviewer's constructive feedback. A comprehensive methodology section has been added in Section 3. The revised manuscript now incorporates SonicScanner workflow, anisotropy Analysis, stress magnitude workflow.

The text was added in line 168: Processing involves waveform semblance correction, shear wave splitting quantification to derive fracture density and orientation from fast-shear azimuth (FSA), with Stoneley reflectivity modeling estimating fracture

apertures, validated through integration with image logs and anisotropy tensor decomposition.

One-dimensional Mechanical Earth Models (1-D MEMs) enable determination of in-situ stress magnitudes ($S_{H_{max}}$, $S_{H_{min}}$, S_v). Vertical stress (S_v) is calculated via bulk density integration from surface to target depth (Eq.1), with standard gradients at 23 MPa/km (2.3 g/cm³ average density). In the Kuqa Depression, acoustic emission experiments established a gradient of 25.28 MPa/km (2.528 g/cm³), yielding $S_v=173.79$ MPa at 6,873.38 m. Pore pressure (P_p) is determined using Eaton's sonic transit time method (Eq.2), where deviations from normal compaction trends ($\Delta t_n/\Delta t$) indicate overpressure. Drilling-induced fractures indicate $S_{H_{max}}$ direction while breakouts define $S_{H_{min}}$ orientation using image logs. Stress magnitudes leverage multi-method calibration: $S_{H_{min}}$ from leak-off tests or micro-fracturing, and $S_{H_{max}}$ via breakout width analysis or frictional limits. Log-derived stress calculations incorporate $S_{H_{max}}$ and $S_{H_{min}}$, with dip corrections applied in steep structures using a modified Anderson model accounting for stratigraphic geometry (Eq.3-4).

Thank you again for your constructive comments.

Lines 145-340. Research built on a robust dataset. Very good point.

Reply:

Dear Dr. Medici,

We sincerely appreciate the reviewer's positive assessment of the dataset and analyses presented in Lines 145-340. Your recognition of our results has been incredibly

encouraging and motivating.

Figures and tables

Figure 1. It would be good to have a geological cross-section.

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. As the studied wells are geospatially discontinuous, a unified geological cross-section could not be incorporated into Figure 1. However, representative geological cross-sections for individual well blocks (BZ-3, DB-9, BZ-12) are presented in Figures 11, 12, and 14 respectively.

Thank you again for your constructive comments.

Figure 5. Core photos too dark. Possible to improve?

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. We appreciate the reviewer's comment on the core photo quality. Unfortunately, the samples are no longer accessible for rephotography, and original high-resolution files are unavailable for enhancement. We apologize for this constraint but confirm the key geological features including fracture characteristics remain identifiable in the present figures. We will prioritize optimal imaging protocols in subsequent work.

Thank you again for your constructive comments.

Figure 7. “Sandstone thickness” in the caption. Thickness of? Beds? Please, clarify this point.

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. I apologize for using inappropriate wording, which has led to ambiguity. We confirm that Sandstone thickness represents fractured layer thickness. We already modified the Figure 8 (original Figure 7).

Thank you again for your constructive comments.

Figure 9. “Fracture density”. Is it a P10?

Reply:

Dear Dr. Medici,

Thank you for your insightful feedback on our manuscript. I apologize for using inappropriate wording, which has led to ambiguity. Thank you for your meticulous attention to detail. We confirm that fracture density represents Lineal fracture frequency (P10), expressed as the number of fractures per unit length.

Thank you again for your constructive comments.

Once again, thank you very much for your comments and suggestions.

Above are the point by point responses to the comments of the anonymous reviewers and you. Thank you for your checking.

Once again, thank you very much for your comments and suggestions.

We hope that the revised version of the manuscript is now acceptable for publication in your journal. We appreciate for Editors/Reviewers' warm work earnestly, and hope that the corrections will meet with approval.

We look forward to your information about my revised papers and thank you for your good comments.

With best wishes,

Yours sincerely,

All the authors

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