<u>Referee Comments (RC1):</u>

Hasan and Su tried to get the permeability of deep hard rock by a geophysical approach. They used the CSAMT to get the resistivity of the subsurface for several 2D profiles and then built an empirical equation to describe the relationship between permeability and resistivity using 37 permeabilities from boreholes. Then they applied the equation to all 2D profiles and finally extrapolated 2D profiles to a 3D field. They argued that the advantage of their approach is that it is able to get the information of the deep subsurface to 1 km depth. They also said their approach is low-cost than borehole drilling. I am sorry I am not that encouraging to this work. I don't think this work is novel enough for publication in HESS, a top journal in hydrology and water resources. I suggest rejecting it for publication in other journals of geology. Following are my reasons:

Response:

Dear Anonymous Referee,

Thank you for your detailed and thoughtful review of our manuscript. We sincerely appreciate the time and effort you dedicated to evaluating our work and providing constructive feedback. Extensive revisions have been made throughout the manuscript, especially in the Introduction, Methods, and Discussion sections, to enhance clarity, address reviewer feedback, and better highlight the study's contributions. **All suggested changes have been clearly marked and are provided in the track-changes file for ease of review.**

We fully acknowledge the prestige of *Hydrology and Earth System Sciences (HESS)* as a leading journal in the field, and we believe our study contributes meaningfully to its scope by addressing a critical gap in deep groundwater assessment using a novel geophysical approach. While traditional borehole-based approaches remain central to permeability estimation, they are often logistically constrained, cost-intensive, and spatially limited, particularly in geologically complex hard-rock terrains.

This work builds on our extensive experience in geophysical research applied to both hydrogeological and geotechnical challenges, with several peer-reviewed publications in the top journals. The novelty of this study lies not in the use of CSAMT alone, but in its comprehensive and site-specific application, demonstrated for the first time, to generate high-resolution 2D and 3D permeability models for deep groundwater exploration at depths exceeding 1 km in highly heterogeneous hard-rock settings, a capability not previously reported in the literature.

We appreciate your comments and acknowledge that some of your critiques are constructive and valuable. Specifically, we have addressed the unit inconsistency for permeability (corrected from m/d to mD), incorporated your suggestions to expand and clarify our dataset, and discussed theoretical underpinnings such as the Archie and Kozeny–Carman equations in the revised manuscript, and so on.

However, we also respectfully feel that the overall novelty and relevance of our study may have been underappreciated in your evaluation. In contrast, the editor, other reviewers, and members of the research community have recognized the novel contributions of this work and deemed it suitable for publication in *HESS*, recommending only minor revisions. We believe that, in its thoroughly revised form, the manuscript now clearly communicates its innovations, even to readers without a background in hydrogeophysics. Below, we clarify several key innovations and contributions of our work that differentiate it from prior research:

1. **First-time measurement of permeability (k) at depths exceeding 1 km** in a hard-rock environment.
2. **Generation of 2D and 3D k models**, to our knowledge, the first of their kind for deep groundwater assessments using any geophysical method.
3. **Innovative use of CSAMT** to derive volumetric estimations of hydraulic parameters such as permeability, which has not been attempted previously.
4. **Application in a highly heterogeneous lithological context** involving sandstone, granite, and hornstone, where such estimation of k had never been conducted before.
5. **Efficient integration of sparse borehole data** to produce high-resolution subsurface hydrogeological models over a large hard-rock terrain, demonstrating a practical alternative to intensive drilling.
6. **Significant reduction in the need for costly deep boreholes**, which would otherwise be required in the hundreds to achieve a similar level of spatial resolution.

These contributions have been highlighted in the revised **Introduction (Page 12/13, Lines 267–277)** section of the manuscript:

"This study introduces several important advancements in the assessment of deep groundwater resources. It is the first to estimate permeability beyond depths of 1,000 m within a hard-rock environment and to develop detailed two and three dimensional permeability models through geophysical techniques. The innovative use of CSAMT for volumetric hydraulic parameter estimation represents a notable methodological breakthrough. Carried out in a geologically

intricate setting dominated by sandstone, granite, and hornstone, where such deep assessments were previously unattempted, this work also highlights the effective integration of limited borehole data to generate high-resolution hydrogeological models. This strategy offers a practical and cost-efficient alternative to widespread deep drilling, significantly decreasing the number of boreholes required to achieve similar spatial detail in permeability mapping."

And **Discussion section (Page 58/59, Lines 1069–1074)** of the manuscript:

"While the methodology is rooted in established geophysical principles, the innovation of this study lies in its comprehensive, site-specific implementation, combining deep permeability modeling, field-based verification, and empirical calibration specifically tailored to the local geological context. Overall, the results underscore the considerable potential of geophysical techniques, particularly CSAMT, in supporting sustainable groundwater exploration and management at significant depths."

We would also like to underscore that this work builds upon our previously applied geophysical approaches, for the first time, to predict key geomechanical parameters, such as Rock Quality Designation (RQD), Rock Mass Integrity Coefficient (Kv), and Rock Core Index (RCI), which have been successfully applied in the 2D/3D evaluation of rock mass quality for the construction of major national infrastructure projects in China. Some of these (published in top journals) include:

- **Rock Mass Integrity Coefficient (Kv)** — *Engineering Geology* (DOI: 10.1016/j.enggeo.2022.106560), *JRMGE* (DOI: 10.1016/j.jrmge.2022.07.008)

- **Rock Quality Designation (RQD)** — *RMRE* (DOI: 10.1007/s00603-021-02766-8), *Scientific Reports* (DOI: 10.1038/s41598-025-85626-7)
- **Rock Core Indices (RCI)** — *IJRMMS* (DOI: 10.1016/j.ijrmms.2024.105816)

These published results were used in the design and safety evaluation of large-scale underground (well-known) facilities such as the High Intensity Accelerator Facility (HIAF), Accelerator Driven System (ADS), and the Jiangmen Underground Neutrino Observatory (JUNO), the latter being located near our current study area at ~700 m depth.

We have also cited this past work in the **Study Area and Hydrogeological Settings** section **(Page 15, Lines 314–321)**:

"This study is part of a broader suite of major national-level initiatives in South Guangdong of China, each targeting distinct aspects of deep subsurface exploration. These include both the investigation of deep groundwater resources, as undertaken in this study, and the development of deep-underground engineering infrastructure, such as the Jiangmen Underground Neutrino Observatory (JUNO), China's next-generation neutrino detector (Hasan et al., 2025). While each project addresses distinct hydrogeological and geotechnical challenges, they are collectively aligned with China's broader strategic agenda for deep subsurface resource development and sustainable utilization."

And we further elaborated on its methodological relevance in the **Discussion (Page 54/55, Lines 975–985)**:

"Building on this foundation, our previous research (Hasan and Shang, 2022; Hasan et al., 2025) applied similar geophysical strategies in geotechnical engineering, where 2D and 3D

modeling of Rock Quality Designation (RQD) and rock mass integrity coefficient (Kv), two key geomechanical parameters, was conducted using empirical correlations between borehole core data and resistivity derived from ERT/CSAMT. These methods were instrumental in site evaluations for major national infrastructure projects, including the Accelerator Driven System (ADS) in Huizhou and the Jiangmen Underground Neutrino Observatory (JUNO), located approximately 700 m below ground in South Guangdong, adjacent to the present study area. The successful deployment of this geophysical approach in both hydrogeological and geotechnical domains underscores its reliability, scalability, and interdisciplinary value for large-scale subsurface characterization."

This novel approach bridges hydrogeology and geotechnical engineering, reaffirming its interdisciplinary significance and scalability.

We deeply value your critique and hope that the revisions and clarifications provided here and in the revised manuscript highlight the novelty, rigor, and importance of our work. We remain confident that this contribution aligns with the scientific objectives of *HESS* and will be of interest to its readership, particularly in the context of sustainable groundwater management in deep and data-scarce settings.

Thank you once again for your review and the opportunity to improve our manuscript.

Comment 1:

Either component of this work is very old. The CSAMT can date back to 1970s. The relationship between the permeability and resistivity has also been largely studied so far. The inversion of permeability/hydraulic conductivity using geophysical approaches is so well-known.

Response 1:

We thank the reviewer for this important comment.

We agree that both CSAMT and the general concept of relating resistivity to permeability have a long history in geophysical and hydrogeological research. However, the key contribution of our study lies not in the introduction of entirely new methods, but in the **novel integration and application** of established techniques to a unique and challenging geological context, resulting in unprecedented outcomes.

Specifically, while CSAMT has traditionally been used for deep geophysical investigations, its application in **hydrogeology for constructing 2D and 3D models of permeability (k) at depths exceeding 1 km**, especially in a **highly heterogeneous hard-rock setting** comprising sandstone, granite, and hornstone, has **not been demonstrated in any previous work**, to the best of our knowledge.

In fact, no past studies have reported the generation of **volumetric (2D and 3D) models of k or any hydraulic parameter** using either direct (drilling-based) or indirect (geophysical, etc) methods at such depths and across such varied lithologies. In our earlier work, we demonstrated for the first time the use of **ERT** to generate shallow-depth models of hydraulic conductivity in a tuff rock environment. Building on that, this study extends the concept both **methodologically**

and spatially by using CSAMT to model permeability at much greater depths and over geologically complex terrain.

A detailed discussion of the novel application of CSAMT in this study has been incorporated at various points in the revised manuscript, most notably in the **Discussion section (Page 55, Lines 986–996)**, where we elaborate on its advantages for deep permeability estimation in geologically complex hard-rock terrains:

"CSAMT, introduced in the 1970s, remains uniquely valuable for deep subsurface exploration, particularly in resistive, hard rock environments. Unlike conventional geophysical techniques, CSAMT excels at delineating lithological boundaries and fluid-bearing zones. Recent advances in instrumentation and inversion techniques have significantly enhanced its resolution and depth penetration, enabling applications such as ours that extend its use beyond historical limits. The novelty of this study lies not in the use of CSAMT or resistivity–permeability relationships themselves, both of which are well-established, but in their integrated, site-specific application to a geologically complex and deeply fractured hard rock environment This is the first study to successfully model permeability at depths of up to 1300 m in granite, sandstone, and hornstone using a data-driven approach validated by high-resolution borehole data."

Although the novelty of this study and the resistivity–permeability relationship has been discussed throughout the manuscript, it is more clearly articulated in the **Introduction section (Pages 10–11, Lines 224–245)**:

"Numerous studies have investigated empirical and semi-empirical correlations between these two parameters, with the objective of utilizing resistivity as a proxy for estimating hydraulic conductivity or permeability in regions with limited data (De Lima and Niwas, 2000; Hubbard

and Rubin, 2002; Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Jardani et al., 2007; Sinha et al., 2009; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). Niwas and De Lima (2003) developed an analytical model linking formation resistivity to transmissivity in porous media. Similarly, Jardani et al. (2007) demonstrated the feasibility of employing geophysical inversions to infer permeability distributions in heterogeneous aquifers. Recent studies have applied these approaches to fractured and hard-rock environments; however, such correlations are less common and frequently constrained by site-specific geological variability (Soupios et al., 2007; Hasan et al., 2021; Asfahani, 2023). Despite recent advancements, the development of robust, high-resolution 2D and 3D permeability models from resistivity data, particularly in geologically complex environments at significant depths, remains a major challenge. To date, no previous studies have successfully achieved this, underscoring the critical need for improved integration of geophysical measurements with sparse borehole data. The relationship between resistivity measurements and borehole-derived data provides an efficient and cost-effective method for estimating aquifer properties over extensive spatial areas and varied depth profiles. This study, for the first time, demonstrates a novel application of the CSAMT technique to create high-resolution two and three dimensional permeability models reaching depths of around 1300 m in a geologically complex and heterogeneous environment characterized by sandstone, granite, and hornstone."

Furthermore, we have now included **a more detailed discussion in the revised manuscript** regarding the relationship between resistivity and permeability (e.g., using the Archie and Kozeny-Carman equations), along with how our approach advances existing methodologies, i.e., **2.3.2 Permeability-resistivity relationship (Archie and Kozeny-Carman equation) (Page 27-29, Lines 559-592).**

We hope this clarification better highlights the **novelty, scale, and practical significance** of our work within the context of existing literature.

Comment 2:

Authors even didn’t well discuss the previous studies of relationship between permeability and resistivity, such as the Archie equation and Kozeny-Carman equation.

Response 2:

We thank the reviewer for this insightful comment. In response, we have included a detailed discussion in the revised manuscript regarding previous studies on the relationship between resistivity and permeability, specifically addressing the Archie equation and the Kozeny-Carman equation. These models are fundamental in petrophysical and hydrogeophysical studies and serve as a theoretical basis for linking electrical resistivity measurements to hydraulic properties. Their relevance, limitations in heterogeneous geological settings, and how our approach builds upon these foundations are now clearly articulated in the revised version of the manuscript.

A brief discussion is given in the revised manuscript **(Page 27-29, Lines 559-592):**

“2.3.2 Permeability-resistivity relationship (Archie and Kozeny-Carman equation)

Several foundational studies have established empirical and theoretical relationships between electrical resistivity and hydraulic properties such as permeability. The Archie equation, introduced by Archie (1942), is widely used in clean, saturated sedimentary formations. It relates formation resistivity to porosity and water saturation but assumes the absence of clay minerals *and thus has limitations in more complex lithologies (Waxman & Smits, 1968; Glover, 2015). The Kozeny-Carman equation is another widely accepted model that links permeability to porosity and specific surface area (Bear, 1972; Carman, 1956). While it does not directly involve resistivity, it is often used alongside petrophysical models to interpret hydrogeological characteristics based on geophysical data (Paterson & Wong, 2005; Clennell, 1997).*

Archie's law (Archie, 1942) relates the bulk electrical resistivity of a fully saturated porous medium to its porosity and fluid resistivity. It is commonly expressed as:

$$\rho b = a \cdot \rho f \cdot \phi^{-m} \qquad (2)$$

where, ρb is the bulk resistivity, ρf is the fluid resistivity, ϕ is the porosity, a and m are empirical constants. Although Archie's law does not directly estimate permeability, porosity is often used as a proxy because of its influence on fluid flow. The resistivity-porosity relationship can be indirectly extended to infer permeability, especially when combined with other petrophysical models (Binley et al., 2005; Revil & Cathles, 1999).

The Kozeny–Carman equation establishes a theoretical relationship between permeability (k) and porosity (ϕ), expressed as follows:

$$k = \frac{C \cdot \phi^3}{(1-\phi)^2 . S^2} \qquad (3)$$

In this equation, k *denotes permeability,* ϕ *represents porosity,* S *is the specific surface area, and* C *is a structural constant reflecting pore geometry and tortuosity. The application of this equation alongside Archie's law facilitates the development of empirical or semi-empirical* *models that connect electrical resistivity to permeability (Jiang et al., 2014; Jardani et al., 2007).*

Although these formulations offer a robust theoretical foundation, their direct application in complex geological contexts, particularly in heterogeneous hard rock such as granite, sandstone, and hornstone, is frequently limited. This results mainly from differences in mineral composition, pore connectivity, and structural anisotropy (Roa-García et al., 2010; Singh et al., 2020). Our present study establishes a localized empirical relationship between resistivity and permeability through co-located measurements obtained from deep boreholes and CSAMT profiles to address these challenges. Such correlation facilitates the development of high-resolution 2D and 3D permeability models in the Jinji area (study area), thereby improving the comprehension of subsurface hydrogeology in contexts where traditional methods fall short."

Comment 3:

A perfect equation (Fig. 3) was built using only 37 known permeabilities. It is hard to convince me the number of k values is enough to build an equation for a domain of 1.8 km*1.8 km*1km of high heterogeneity. It is hard to say this equation is still available for other positions and depths in the domain. As the authors also mentioned, the resistivity is determined by many other factors, not only the permeability.

Response 3:

We thank the reviewer for this important comment regarding the validity and representativeness of the empirical relationship established in old Fig. 3 (new Fig. 4 and 5). We fully agree that both resistivity and permeability (k) are influenced by multiple geological and physical factors, such as lithology, degree of weathering, fluid content, porosity, fracturing, saturation, and jointing, among others (Also mentioned in Lines 216-219 of the revised manuscript). This complexity underscores the need for careful calibration of any empirical relationship.

As mentioned in the original manuscript, the initial empirical equation ($k = 15.345(e)^{-0.002(\rho)}$, $R^2 = 0.97$) was built using 37 carefully (best fit) selected borehole-derived k values. These were not arbitrarily chosen; rather, they were distributed across all three major rock types in the area, sandstone, granite, and hornstone, and covered the full observed range of resistivity (72–4765 Ωm) and permeability (0.01–19.8 mD). Our intention was to ensure the equation's applicability across the domain by capturing the full variability of both geological conditions and resistivity-permeability values within the study area (as demonstrated in our previous published research mentioned above, where we successfully predicted geomechanical parameters from resistivity data through similar empirical correlations).

To further address the concern about sample size and enhance the robustness of our model, **we have now expanded the dataset by adding 79 new data points, bringing the total to 116**. This expanded dataset includes wider spatial coverage and continues to represent all three lithologies. The updated empirical equation based on 116 data points has a slightly adjusted but still strong correlation ($k = 15.373(e)^{-0.002(\rho)}$, $R^2 = 0.96$), confirming the reliability of the established relationship. The new data spans a resistivity range of **35–4765 Ωm** and a permeability range of **0.01–19.9 mD**, reflecting a comprehensive coverage of the variability in the study domain (1.8 × 1.8 × 1.0 km).

The drilling locations were strategically selected to capture both spatial and geological heterogeneities, ensuring that the derived empirical model can be confidently applied to the entire domain, even at locations and depths where no direct permeability measurements were available. This approach significantly enhances the feasibility of deep permeability modeling in data-scarce regions and reduces the need for excessive drilling, which is costly and often impractical in hard rock terrains.

Explained (with **new Fig. 4 and 5**) in the revised section **2.3.3 Spatial permeability modeling from CSAMT data (Page 29-34, Lines 593-675)**

Also explained in the **Discussion section (Page 55/56, Lines 997-1019)**:

"In this study, we established an empirical relationship between resistivity and permeability using 116 co-located data pairs across the three dominant lithologies in the study area: 62 for granite, 31 for sandstone, and 23 for hornstone. The dataset spans a resistivity range of 35 to 4,765 Ωm and a permeability range of 0.01 to 19.9 mD, and is evenly distributed across the geological formations, thereby minimizing lithological bias and ensuring robust calibration. The derived correlation yielded a high coefficient of determination (R^2 = 0.96), indicating strong predictive capability. The lithological classification emerging from this resistivity–permeability relationship is both geologically consistent and empirically validated by field observations and borehole data: low-permeability granite (>700 Ωm; k = 0–5 mD), moderate-permeability hornstone (350–700 Ωm; k = 5–10 mD), and high-permeability sandstone (<350 Ωm; k = 10–20 mD). These ranges reflect the distinct hydrogeological behavior of each unit under site-specific geological conditions. We emphasize, however, that these resistivity–k associations are localized and must be recalibrated for application in other regions with different geological

settings. The strength of our approach lies in its ability to significantly reduce the reliance on extensive borehole drilling and direct permeability measurements, which are both cost-prohibitive and operationally challenging, particularly in deep or structurally complex terrains. By using a limited number of boreholes for calibration, our method enables the construction of high-resolution 2D and 3D permeability models over large areas using CSAMT-derived resistivity. If extensive borehole data were readily available or required, the added value of our geophysical integration would diminish, along with its cost-effectiveness and broader applicability. Thus, the novelty and practical relevance of our approach stem from its ability to enhance subsurface characterization in data-scarce environments while minimizing invasive testing."

Comment 4:

The fitted line is too perfect to believe. I always saw the fitting as follows (very noisy):

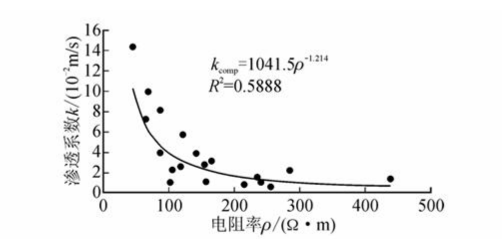
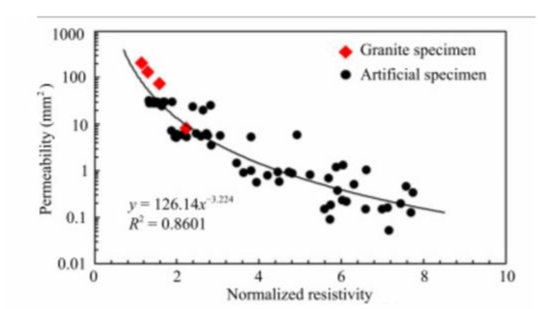


图 1　经验公式法求解的渗透系数与电阻率的关系
Fig. 1　Relationship between hydraulic conductivity and resistivity calculated by empirical formula method



Response 4:

We appreciate the reviewer’s observation and understand the concern regarding the quality of the curve fitting. However, the smoothness or “perfection” of a fitted relationship between resistivity and permeability (k) is highly dependent on a number of factors that vary significantly across different studies. These factors include the geological setting, the distribution and range of data points, the lithology, the degree of heterogeneity, and the accuracy of both resistivity and k measurements.

In our study, the resistivity values span a wide range (approximately 35 to 4765 Ω·m), and the permeability values range from 0.01 to 19.9 mD. This wide dynamic range helps to better resolve trends, especially in high-resistivity rocks such as granite, where permeability remains very low and changes minimally. In such cases, large differences in resistivity correspond to small variations in permeability, naturally resulting in a smoother inverse curve.

We agree that in many past studies, **the relationship appears noisy, often because the resistivity data is concentrated in a narrower range (e.g., 50–300 Ωm as shown in the figs provided by the reviewer)**, and the variations in k may be more influenced by local heterogeneities. In contrast, the broader data spread in our study, combined with careful selection of measurement locations to capture the variability of all three dominant lithologies (sandstone, granite, and hornstone), contributes to a more stable empirical trend.

In the revised manuscript, we have increased the number of data points from 37 to 116, yet the curve still maintains a high degree of correlation ($R^2 = 0.96$), suggesting the robustness of the relationship rather than overfitting. The updated Fig. 4 and 5 show the expanded dataset and reaffirm this trend.

Additionally, we have emphasized in the manuscript that both resistivity and k are influenced by a range of factors, such as porosity, saturation, fluid content, fractures, and lithology, which are inherently linked in this geological context. While some scatter exists, particularly at lower resistivity values (<1500 Ωm) and higher k values (>1 mD), the overall trend aligns well with the theoretical and empirical basis established in previous research showing an inverse relationship between resistivity and permeability.

In addition to the explanation provided in our **Response 3**, this point is further addressed in the **Discussion section (Pages 56–57, Lines 1020–1032)**, where we elaborate on the variability of the resistivity–permeability relationship across different lithologies and the implications of data distribution on the stability of the empirical trend:

"The fitted relationship between resistivity and permeability (k) in our study (shown in Fig. 5) is inherently influenced by several factors, including the geological setting, lithological variability, data distribution, and the accuracy of both resistivity and permeability measurements. The broad dynamic range observed in our dataset, resistivity values from 35 to 4,765 Ωm and permeability values from 0.01 to 19.9 mD, provides a solid foundation for resolving trends across all three dominant lithologies: sandstone, granite, and hornstone. This wide spread is particularly beneficial for characterizing high-resistivity rocks such as granite, where permeability remains consistently low and varies only slightly. In such cases, even large differences in resistivity correspond to minor changes in k, resulting in a smoother inverse trend. Conversely, in the lower resistivity range (e.g., <1500 Ωm) where permeability exceeds 1 mD, small changes in resistivity correspond to larger variations in k, resulting in a more scattered and nonlinear trend in the correlation. This behavior is expected and reflects real geological variability."

We hope this clarifies the rationale behind the nature of the fitted curve and addresses the reviewer's concern.

Comment 5:

I am not sure the resolution of the resistivity obtained by CSAMT and the permeability obtained by pumping test. Do the scales match well? i.e., what's the size of the pixel in the maps in Fig. 4? The k obtained by pumping test always represents the average hydraulic conductivity of an area, so do this range and your pixel size match?

Response 5:

Thank you for raising this important point regarding the consistency between the resolution of resistivity measurements from CSAMT and the permeability (k) values derived from borehole tests.

The accuracy of the estimated k values from our empirical relationship is primarily dependent on the quality of the input data: (1) the resistivity values derived from CSAMT and (2) the k values obtained from boreholes. In our study, we ensured a high-quality CSAMT dataset through optimized survey design, careful data acquisition, and advanced processing and inversion techniques. The resulting models achieved a root mean square (RMS) misfit of less than 5%, ensuring reliable subsurface resistivity measurements. Additional details on data acquisition and processing are provided in the revised manuscript.

Regarding k measurements, we acknowledge that **pumping tests yield average hydraulic conductivity over relatively large volumes**, which are suitable for 1D correlation with averaged geophysical data. However, our objective in this study was to construct **high-resolution 2D and 3D permeability models**, which require point-based permeability measurements that are more compatible with the spatial resolution of CSAMT-derived resistivity data **(a similar geophysical approach was employed in our previously cited publications, where geomechanical parameters such as Rock Quality Designation (RQD), Rock Core Index (RCI), and rock mass integrity coefficient (Kv), obtained from rock core samples, were empirically correlated with geophysical data, just as permeability (k) is correlated in this study)**. To achieve this, we relied on **rock core tests** rather than pumping tests. Rock core analysis allows for permeability measurements at specific depths and locations, enabling a more precise match with the local resistivity values at those points.

As for the model resolution, each pixel in the 2D maps represents an area of approximately **50 m × 50 m** in the horizontal direction, which directly corresponds to the CSAMT station spacing. The **vertical resolution** varies with depth but generally falls within **tens of meters** across the total investigated depth of **approximately 1300 m**, depending on signal penetration and inversion sensitivity. This level of resolution is well-suited for resolving key subsurface features and provides a robust basis for the reliability of the derived permeability models.

Therefore, both the k values and resistivity measurements were acquired and processed at compatible spatial scales, ensuring that the empirical relationship and resulting 2D/3D k models are internally consistent and scientifically robust.

Detailed information on the resolution and quality of both resistivity and permeability (k) data is provided in the Methodology section, specifically in Section **2.2: CSAMT Survey (Pages 17–24, Lines 367–500)**, and Section **2.3: Permeability Estimation Framework (Pages 25–34, Lines 505–675)**.

Also some explanation has been provided in the **discussion section (Page 57, Lines 1033-1041)**:

"To ensure accuracy and reduce uncertainty, we implemented a robust workflow across all stages of data acquisition, processing, inversion, and modeling. For CSAMT, we employed careful survey design, optimized electrode configurations, and applied advanced filtering and static shift corrections. Inversion incorporated multidimensional modeling with borehole-constrained a priori information to improve resolution and reduce non-uniqueness. The permeability data from borehole cores were collected under controlled conditions, using high-quality, undisturbed samples from six boreholes, thereby reducing lab-to-field scale discrepancies. These efforts, combined with integrated lithological data, yielded a reliable permeability model capable of informing groundwater assessments across the study domain."

Also in the **Discussion section (Page 58, Lines 1049-1063)**:

"While pumping tests provide average hydraulic conductivity over large volumes of subsurface material, making them suitable for establishing 1D correlation with spatially averaged geophysical data, they are less appropriate for high-resolution 2D or 3D modeling. In contrast, our objective was to develop detailed 2D and 3D permeability models that reflect the spatial heterogeneity of the subsurface. Achieving this level of resolution requires point-specific permeability measurements at varying depths, which align more precisely with the localized nature of resistivity values derived from CSAMT data. To meet this requirement, we employed rock core analysis rather than traditional pumping tests. Rock core testing offers the advantage of extracting permeability data at discrete depths and locations, providing a direct and fine-scale match with CSAMT-derived resistivity. This approach enhances the accuracy of the resistivity–permeability relationship and allows for more reliable permeability modeling in complex

geological settings. Scale compatibility between CSAMT-derived resistivity and borehole-derived permeability (k) values was carefully addressed. The typical lateral resolution of CSAMT (~50 × 50 meters) closely matches the spatial scale of the core-based permeability data used in this study."

Comment 6:

Table 2, the same problem, even for the pumping test itself, the k values obtained are with large uncertainties, the deviations of one order of magnitude is not surprising. However, the differences of k values between the CSAMT and borehole drilling are less than 1 or 0.1, which is unbelievable.

Response 6:

Thank you for this valuable observation. Details regarding the high-quality resistivity–permeability (k) dataset, including its resolution and reliability, have been provided in our **Response 5**. We would like to clarify that the **old Table 2 presents a comparison between the predicted and measured *k* values for only 12 selected data points**. These points were chosen to highlight instances of close agreement; however, they do not represent the full variability in the dataset.

The reviewer noted that "the differences of *k* values between the CSAMT and borehole drilling are less than 1 or 0.1," but this is **not consistently true**, even within the **previously selected 12 data points**. For instance, a difference of **3.6 mD** and **2.7 mD** was observed between predicted and measured *k* values for sounding number **P6-1** and well **4** at depths of **10 m** and **45 m**, respectively.

Furthermore, several data points within the (new) full dataset of 116 borehole locations exhibit notable differences between predicted and measured permeability (k) values. To more accurately represent this natural variability and the inherent uncertainties in both field measurements and model predictions, we have expanded Table 2 in the revised manuscript to include a broader selection of 18 representative datasets. These additions provide a clearer picture of the model's performance across diverse geological conditions. For example, significant differences between predicted (k′) and measured (k) values were observed in several cases: a discrepancy of **7.1 mD** for P3-21 vs. BH-6 at 45 m depth, **6.0 mD** for P6-1 vs. BH-4 at 15 m depth, and **3.2 mD** for P1-5 vs. BH-1 at 40 m depth. These examples highlight the complexities involved in permeability prediction and emphasize the importance of site-specific calibration and geologic heterogeneity considerations.

Explained in **3.5 Validation of predicted vs. measured permeability (Page 48-51, Lines 848-897)**

Further explained in the **Discussion section (page 57, Lines 1042-1048):**

"Matching between measured and predicted permeability (k vs. k') was also rigorously validated (Table 2). Among 18 selected points from boreholes, 10 showed a difference of less than 1 mD, with only two exceeding 4 mD. Despite minor deviations, all points were accurately classified by lithology. This confirms the empirical model's reliability and its utility for regional-scale k prediction, even in areas lacking direct measurements. The geophysical model effectively

compensates for sparse drilling data, offering a scalable and cost-effective tool for hydrogeological evaluation in hard rock terrains."

Comment 7:

I am not sure why very deep k is necessary. A latest study found that groundwater deep than 500 m is not an active component in terrestrial hydrologic cycle and the water there might be brine. You may say your work found there are a lot of sandy rocks in depth. However, given the large uncertainties of your approach, did you compare the findings with the results of local or national geologic survey? DOI:10.1038/s43247-023-00697-6

Response 7:

Thank you for this insightful comment and for highlighting the referenced study.

While it is true that deep groundwater (below 500 m) is often less connected to the active terrestrial hydrologic cycle and may contain brine, the necessity for deep groundwater exploration in our study area arises from several critical and site-specific factors:

1. **Surface water resources in the study area are limited and unreliable**, making deep groundwater a potentially vital alternative water source.
2. **Shallow zones are predominantly composed of fresh granite**, which typically has low permeability and limited groundwater potential. In contrast, **fractured granite, sandstone, and hornstone formations that can host significant groundwater resources are found at greater depths**.

3. In China, recent national groundwater resource assessment initiatives have prioritized **deep earth exploration** in areas with potential for deep aquifers, to support sustainable development and ensure long-term water security, especially in regions experiencing severe water stress.
4. Deep groundwater investigations are essential for:
    - Identifying **hidden but critical water sources**.
    - **Characterizing deep aquifers** and understanding their storage and recharge potential.
    - Supporting **strategic water resource planning** in response to increasing demand and climate variability.

To address concerns regarding uncertainty:

- We employed a **robust CSAMT survey design**, followed by **accurate resistivity inversion and low-RMS models**.
- **Rock core testing** was used to measure *k* values at multiple depths with high confidence.
- An **empirical equation based on a representative and extensive dataset (116 points)** was used to derive 2D and 3D *k* models.

Furthermore, we **compared our findings with existing geological information from both local and national geological surveys**, and found our results to be consistent with the known stratigraphy and hydrogeological features of the region.

Explanation on importance of deep groundwater exploration is given in many parts of the manuscript, such as in the **Abstract (Page 2, Lines 24-27)**:

"Deep groundwater exploration in hard rock terrains is essential in regions with the potential for deep aquifers, especially where water scarcity threatens sustainable development and long-term water security. However, such exploration remains a global challenge due to the geological complexity and the limitations of traditional investigation methods."

Further explanation (above reference was also cited) in the **Introduction section (Page 4/5, Lines 73-92)**:

"Groundwater at depths greater than 500 m is typically less affected by surface hydrological processes and frequently contains brackish or saline water (Gleeson et al., 2016; Margat and van der Gun, 2013; Ferguson et al., 2023). Its exploration is increasingly recognized as strategically important in certain geological and environmental contexts. In the Jinji region (study area), various site-specific factors require a targeted examination of these deeper reserves. First, surface water availability is both scarce and unreliable, increasing the importance of deep aquifers as a potential supplementary source of freshwater. Second, the shallow subsurface is largely composed of fresh granite, a rock type known for its inherently low porosity and permeability, thus offering limited groundwater potential (Dewandel et al., 2006; Lachassagne et al., 2021). In contrast, favorable water-bearing zones such as fractured granite, sandstone, and hornstone are typically found at much greater depths. Third, recent national water initiatives in China have underscored the need for deep subsurface exploration, especially in structurally complex terrains, to uncover underutilized aquifers that could contribute to more resilient water supply systems in the face of increasing demand and climatic uncertainties (MOHURD, 2021; Qian et al., 2024). Comprehensive assessments of deep groundwater are therefore essential for identifying these hidden but strategically valuable water sources,

evaluating their recharge characteristics, and integrating them into sustainable long-term management plans (Courtois et al., 2010; Refsgaard et al., 2012). As pressures on surface and shallow subsurface water sources intensify, deeper aquifer systems may serve as a critical buffer, ensuring more reliable water access amid growing environmental and socio-economic challenges."

Information on comparing the findings with the results of local or national geologic survey, given in the **Discussion section (Page 58, Lines 1064-1068)**:

"Furthermore, our findings were cross-validated against existing geological data from both local and national surveys, revealing strong alignment with the established stratigraphy and hydrogeological characteristics of the region. This consistency reinforces the validity of our integrated geophysical–borehole approach, which offers a scientifically robust and practically scalable framework for estimating permeability in structurally complex and data-scarce terrains."

The accuracy of our approach fundamentally relies on three key components: high-quality geophysical data, reliable permeability (k) measurements from rock core samples, and a well-constrained empirical resistivity–k relationship. Detailed explanations of the steps taken to ensure data quality and minimize uncertainty, both in resistivity and permeability measurements, as well as in the derivation of the empirical equation, are provided in the Methodology section. Specifically, **Section 2.2: *CSAMT Survey* (Pages 17–24, Lines 367–500)** outlines the acquisition, processing, and resolution of the resistivity data, **while Section 2.3: *Permeability Estimation Framework* (Pages 25–34, Lines 505–675)** discusses the procedures for permeability measurement, data validation, and formulation of the empirical correlation. These sections collectively demonstrate the rigor applied to ensure the robustness and reliability of the integrated geophysical–hydrogeological modeling framework.

We believe that, despite the challenges, this deep groundwater investigation provides valuable insights and practical relevance, especially in arid and semi-arid regions where shallow resources are scarce or overexploited.

Comment 8:

I found a work of the authors just published in scientific reports https://www.nature.com/articles/s41598-025-85626-7 It is exactly the same workflow with this one. Many sentences are the same. I am not supportive for research of such a style in the community.

Response 8:

We sincerely thank the reviewer for the thoughtful observation and appreciate the opportunity to clarify the distinction between our current study and our previously published work.

As stated at the outset of our responses, our research group has a well-established track record of applying geophysical techniques, particularly ERT and CSAMT, to evaluate key geomechanical parameters (e.g., RQD, Kv, and RCI) for rock mass quality assessment across various depths. These studies have contributed to the successful completion of several major infrastructure projects in South China, including the High Intensity Accelerator Facility (HIAF), Accelerator Driven System (ADS), and the Jiangmen Underground Neutrino Observatory (JUNO). Results from these projects have been published in the top journals such as *Engineering Geology*, *RMRE*, *IJRMMS*, *JRMGE*, and *Scientific Reports*. The present work builds upon these prior methodologies and studies, extending their application, for the first time, from geotechnical engineering to hydrogeology, specifically to the characterization of deep groundwater systems.

The recent publication in *Scientific Reports* (DOI: 10.1038/s41598-025-85626-7) focused on the evaluation of site suitability for JUNO, located near our current study area at ~700 m depth. That study utilized CSAMT-derived RQD to assess the mechanical integrity and stability of the rock mass for large-scale underground construction.

In contrast, the current manuscript represents a **fundamentally different application**: the use of CSAMT and borehole data to estimate permeability (k) and to develop **2D and 3D k models for deep groundwater resource assessment**. To the best of our knowledge, this is the **first study** to use geophysical methods, particularly CSAMT, to construct detailed 2D/3D k models at depths exceeding 1 km in a geologically heterogeneous region composed of granite, sandstone, and hornstone. This hydrogeological application introduces a novel methodology for deep groundwater exploration in hard rock terrains.

While both studies were conducted in the broader Kaiping region of South Guangdong, a strategic zone currently hosting several national-level initiatives focused on deep subsurface exploration, their **scientific goals, methodologies, and interpretive frameworks are clearly distinct**. Specifically:

- **The *Scientific Reports* study** employed CSAMT to estimate RQD for the purpose of evaluating mechanical stability in support of underground construction.

- **The current study** uses CSAMT-derived resistivity, integrated with borehole core data, to estimate permeability (k), supporting deep groundwater exploration and aquifer characterization.

We acknowledge that similar geological settings and geophysical tools can result in some structural similarities between studies. However, the **data interpretation, modeling objectives, and final applications** diverge significantly across the geotechnical and hydrogeological domains.

To further emphasize the novelty of the current submission and address any potential concern of redundancy, we have taken the following steps:

1. **Redrawn all figures** to reflect the unique objectives and hydrogeological focus of this study.
2. **Substantially revised the manuscript**, including the Introduction, Methodology, Results, Discussion, and Conclusions, to highlight the shift from geotechnical to hydrogeological investigation.
3. **Incorporated all reviewer suggestions** and community feedback to enhance clarity and distinctiveness.

Importantly, each study is part of a **separate national research initiative**, targeting different scientific challenges, one focused on **geotechnical site assessment for underground construction**, and the other on **deep groundwater resource exploration**. Both fall under China’s broader strategic efforts to advance sustainable deep subsurface resource development, but they address different needs and use cases.

In addition, these past works have been cited at several points throughout the revised manuscript, as noted in our earlier response to the reviewer, including in the *Study Area and Hydrogeological Settings* section (Page 15, Lines 314–321) and in the *Discussion* (Pages 54–55, Lines 975–985).

We respectfully submit that the current manuscript constitutes an **original and independent contribution** to the field of hydrogeophysics. It provides valuable new insights into permeability modeling in complex, hard-rock terrains using CSAMT, an area that remains underexplored and critically important for deep groundwater assessment.

Comment 9:

The structure of the manuscript is OK, however, the writing is still unshaped. Many sentences are duplicated, such as lines 306-308 which appear many times. I think once you clarified the strengths of your approaches in the introduction, you only need to describe you approach in methodology and it is redundant to say this again. Also line 218 “About 1300 meters was the depth of investigation (DOI) in the CSAMT investigation.”, such an expression is awkward. Why not “the depth of investigation (DOI) in the CSAMT investigation was about 1300 meters”.

Response 9:

We thank the reviewer for their constructive feedback regarding the manuscript’s writing quality and structure.

In response, we have **carefully revised and reshaped the manuscript** in accordance with the suggestions provided. Specifically:

- **All duplicate or repetitive sentences**, including those previously appearing in multiple sections (e.g., lines 306–308), have been removed or appropriately rephrased to avoid redundancy.
- We have **streamlined the narrative** by presenting the strengths of our approach clearly in the **Introduction** and limiting their repetition in subsequent sections.
- As suggested, we have improved awkward or unclear expressions, such as line 218 (in old version). The sentence now reads: *"The depth of investigation (DOI) in the CSAMT survey was approximately 1300 meters."* **(Page 20, Lines 419/420)**

We believe these revisions enhance the overall clarity, coherence, and professionalism of the manuscript and we appreciate the reviewer's guidance in helping us improve the quality of the submission.

Comment 10:

What are you trying to get? Permeability or hydraulic conductivity? I don't think the unit of permeability is L/T.

Response 10:

We appreciate the reviewer's comment and the opportunity to clarify this point.

Our study focuses on **permeability**, and the correct unit is **milliDarcy (mD)**. In the initial version of the manuscript, permeability was mistakenly written using the unit **m/d**, which may have caused confusion with **hydraulic conductivity**, typically expressed in length per time (L/T) units such as m/day.

To address this:

- The **methodology section has been revised** to clearly state that permeability is measured in **mD**.
- This correction has been **applied consistently throughout the manuscript and all figures**.

We thank the reviewer for catching this important detail, which has now been rectified in the revised version.

<u>Referee Comments (RC2):</u>

This paper addresses the challenges associated with current groundwater exploration and evaluates the advantages and disadvantages of various methods for measuring hydraulic parameters. The author highlights the application of a novel approach, by using Controlled Source Audio-Frequency Magnetotellurics (CSAMT) method, which is employed to estimate 2D and 3D permeability at depths exceeding 1 km in highly heterogeneous rock environments. The study presents its methods and findings in a well-structured manner, offering insights into deep groundwater exploration.

However, certain assertions appear overly generalized and could benefit from further substantiation. Additionally, more detailed descriptions of the methodologies and the study area would enhance the clarity, reproducibility, and robustness of the research.

Response:

We sincerely thank the anonymous reviewer for his/her insightful and constructive feedback, which has significantly contributed to enhancing the quality of our work. We have made every effort to revise the manuscript thoroughly in line with the reviewer's suggestions.

In the revised version, we have expanded the descriptions of both the study area and the methodologies and all other sections to provide greater clarity and context. Additional explanations and supporting information have also been included in the revised manuscript to substantiate our findings and address the points raised. **All suggested changes have been clearly marked and are provided in the track-changes file for ease of review.**

Specific comments:

Comment 1:

Line108-119: the author might consider adding a little more evidence of the reason that CSAMT is selected for this study. For example, the author stated that VES method is used to evaluate groundwater resources in a single dimension by a broad of previous studies, but did not illustrate the background about why they did not use other methods, like CSAMT or ERT. Additionally, the author states that there are three main methods, but there are very few examples or introductions about ERT in this paragraph.

Response 1:

The entire paragraph from Lines 88–119 has been revised for improved clarity and structure in the updated manuscript. Both the original and the revised versions of the paragraph are provided below for comparison.

ORIGINAL PARAGRAPH (Old Version: Page 4-6, Lines 88-119):

“A number of prior groundwater investigations have made use of geophysical techniques (Bentley and Gharibi, 2004; Yadav and Singh, 2007; Fu et al., 2013; Vouillamoz et al., 2014; Robinson et al., 2016; Lin et al., 2018; Kouadio et al., 2020; Abbas et al., 2022; Kouadio et al., 2023; Zhang et al., 2024). A number of studies have shown that geophysical procedures outperform drilling techniques in terms of speed, ease of use, cost, and lack of invasiveness (Hu et al., 2013; Lin et al., 2018; Di et al., 2020; Fusheng et al., 2022; Hasan et al., 2024). Additionally, they are capable of conducting thorough geological evaluations in both the vertical and horizontal planes (Fu et al., 2013; Hasan et al., 2021). These methods are superior to others when it comes to collecting hydrogeological data from various subterranean habitats (Niwas and De Lima, 2003; Wynn et al., 2016; Kouadio et al., 2023). Groundwater studies nowadays often include resistivity surveys. Resistivity methods offer a broader resistivity range compared to other geophysical parameters, which is a major advantage (Bentley and Gharibi, 2004; Camporese et al., 2011; Robinson et al., 2016). The three main methods for measuring resistivity are the controlled source audio-frequency magnetotellurics (CSAMT), vertical electoral soundings (VES), and electrical resistivity tomography (ERT) (Soupios et al., 2007; Di et al., 2020; Zhang et al., 2024). Niwas and De Lima (2003), Soupios et al. (2007), Majumdar and Das (2011), Nwosu et al. (2013), Hasan et al. (2021), and Asfahani (2023) are among the previous groundwater-based geophysical studies that primarily utilized the VES method to evaluate groundwater resources in a single dimension. It is unusual to evaluate aquifer yield at great depths in hard rock terrains using two- and three-dimensional hydraulic properties. Recent studies have demonstrated that CSAMT, which aims to gather extensive subsurface data at very deep depths using 2D/3D evaluations, is the most cost-effective and appropriate geophysical method for researching hard rock (Smith and Booker, 1991; Simpson and Bahr, 2005; Bai et al., 2010; Fu et al., 2013; Hu et al., 2013; Wang et al., 2015; Wynn et al., 2016; Di et al., 2020; Zhang et al., 2021; Kouadio et al., 2023; Hasan et al., 2024). Advantages of CSAMT over other geophysical research methods include its lower cost, its responsiveness to low-resistance rocks, and its ease of usage in challenging topographic circumstances (An et al., 2016; Kouadio et al., 5 2020; Zhang et al., 2021). Compared to most geophysical technologies, including ERT, CSAMT's subsurface assessment capabilities are superior due to its depth capacity of up to one kilometer (Zonge and Hughes, 1988; Hasan et al., 2024). When combined with empirically based methodologies, CSAMT becomes an even more powerful tool for studying the incredibly diverse topographical features."

REVISED PARAGRAPH (New Version: Page 7-9, Lines 146-188):

"A diverse range of groundwater studies has effectively incorporated geophysical methods to improve subsurface characterization (Bentley and Gharibi, 2004; Yadav and Singh, 2007; Fu et al., 2013; Vouillamoz et al., 2014; Robinson et al., 2016; Lin et al., 2018; Abbas et al., 2022; Kouadio et al., 2023; Zhang et al., 2024). These methods provide notable benefits compared to traditional drilling, especially regarding cost-efficiency, rapid deployment, minimal environmental impact, and ease of field implementation (Hu et al., 2013; Lin et al., 2018; Di et al., 2020; Fusheng et al., 2022; Hasan and Shang, 2022). Geophysical tools offer significant practical advantages, including strong vertical and lateral imaging capabilities, which enhance their effectiveness in capturing the hydrogeological complexity of diverse subsurface conditions (Niwas and De Lima, 2003; Fu et al., 2013; Hasan et al., 2021; Wynn et al., 2016; Kouadio et al., 2023). Resistivity-based methods are pivotal in contemporary groundwater exploration, owing to their sensitivity to diverse subsurface conditions and materials (Bentley and Gharibi, 2004; Camporese et al., 2011; Robinson et al., 2016). The main methods in this category are vertical electrical sounding (VES), electrical resistivity tomography (ERT), and controlled-source audio-frequency magnetotellurics (CSAMT) (Soupios et al., 2007; Di et al., 2020; Zhang et al., 2024). VES has been utilized for one dimensional profiling, especially in areas with horizontally layered aquifers (Niwas and De Lima, 2003; Soupios et al., 2007; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). This method is particularly appropriate for small-scale applications (less than 200 m depth), providing low operational

costs and reduced logistical requirements. However, its lateral resolution is limited, and its performance can be compromised in geologically complex settings with highly resistive or conductive layers. ERT, by contrast, enables two and three dimensional imaging up to intermediate depths (~300 m) with significantly improved resolution. It is particularly effective for characterizing complex geological settings, such as fractured zones or karst systems, and is widely used for detailed assessments of aquifer geometry and contamination (Bentley and Gharibi, 2004; Camporese et al., 2011; Lin et al., 2018; Abbas et al., 2022; Hasan and Shang, 2022). Nonetheless, it requires greater field effort, careful electrode spacing, and, like VES, may encounter challenges in highly resistive or conductive environments. CSAMT, a more advanced method, is ideally suited for deep investigations (hundreds to thousands of meters), especially in hard rock terrains. It provides two and three dimensional subsurface imaging with strong sensitivity to deep conductive structures, making it highly effective for delineating deep-seated aquifers and geothermal systems (Smith and Booker, 1991; Simpson and Bahr, 2005; Bai et al., 2010; Fu et al., 2013; Hu et al., 2013; Wang et al., 2015; Wynn et al., 2016; Zhang et al., 2021; Kouadio et al., 2023). While CSAMT typically offers lower spatial resolution than ERT, it excels in deep structural mapping, performs well in areas with high cultural noise due to its controlled-source signals, and can be further enhanced when integrated with empirical or model-based approaches (Zonge and Hughes, 1988; An et al., 2016; Hasan et al., 2025). The choice among these resistivity techniques depends on various factors, including investigation depth, target resolution, geological complexity, logistical constraints, cost, field conditions, and resistivity contrast (Di et al., 2020; Hasan and Shang, 2022). Given these considerations, particularly the need to investigate deep aquifer systems in hard rock environments, CSAMT was determined to be the most suitable method for the present study.”

Comment 2:

Line 120- 138: the author might consider reorganizing this paragraph to make the significance of the resistivity method stand out.

Response 2:

The paragraph previously located in Lines 120–138 has been reorganized for improved clarity in the revised manuscript. For reference, both the original and the revised versions of the paragraph are provided below.

ORIGINAL PARAGRAPH (Old Version: Page 6/7, Lines 120-138):

"Several factors, such as the type of rock, fault, weathering degree, fluid content, permeability, pore-spacing, fracture, lithology, saturation, and joints, as well as the same structural heterogeneities, determine the geophysical and aquifer characteristics (Singh, 2005; Sinha et al., 2009; Hasan et al., 2021). Several prior studies utilized geophysical parameters in conjunction with hydraulic data or lithological logs to characterize underlying rock mass units hydrogeologically (De Lima and Niwas, 2000; Hubbard and Rubin, 2002; Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Sinha et al., 2009; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). Resistivity methods provide an alternate option for aquifer parameter estimation by creating a beneficial relationship between electrical resistivity and the aquifer parameters (obtained from drilling tests). An innovative aspect of this work is its use of non-invasive geophysical techniques to create two- and three-dimensional k models in a diverse environment with a variety of rock types and significant depths. The planned study will necessitate the boring of a handful of boreholes at key spots all around the project site. A more trustworthy CSAMT study will allow us to evaluate the extensive research area. Then, by directly connecting geophysical and borehole data, k can be established for the entire researched site, even without drilling tests. Two- and three-dimensional k models are generated by applying the resulting equations to the full study area. This approach would reduce the need for costly boreholes to obtain a thorough and complete evaluation of subsurface hydrogeological conditions."

REVISED PARAGRAPH (New Version: Page 10-12, Lines 207-253):

"In fractured rock environments, including granitic, metamorphic, and sandstone formations, fluid movement is primarily influenced by the arrangement and connectivity of fractures, rather than the inherent porosity of the rock matrix. A precise assessment of hydraulic behavior in these environments necessitates the application of integrated methodologies. Recent studies emphasize the necessity of integrating geophysical and hydrogeological methods to accurately identify and characterize hydraulic properties (McKeown et al., 1999; Medici et al., 2023). Interdisciplinary approaches are crucial for improving the precision of flow modeling and for guiding groundwater management and geo-energy development in structurally complex terrains. Resistivity-based methods are essential in groundwater investigations for their ability to delineate subsurface structures and identify areas with water-bearing potential. Recent hydrogeophysical studies have focused on the correlation between electrical resistivity and permeability, as both are closely related to the fluid content and physical structure of subsurface materials. Electrical resistivity, which reflects a material's resistance to the flow of electrical current, is influenced by various factors. These include rock type, porosity, weathering extent, connectivity of the pore network, saturation level, structural features like faults and fractures,

and the salinity of pore fluids. Numerous parameters significantly affect permeability, highlighting the utility of resistivity measurements as indicators for evaluating groundwater flow potential (Singh, 2005; Sinha et al., 2009; Hasan et al., 2021). Numerous studies have investigated empirical and semi-empirical correlations between these two parameters, with the objective of utilizing resistivity as a proxy for estimating hydraulic conductivity or permeability in regions with limited data (De Lima and Niwas, 2000; Hubbard and Rubin, 2002; Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Jardani et al., 2007; Sinha et al., 2009; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). Niwas and De Lima (2003) developed an analytical model linking formation resistivity to transmissivity in porous media. Similarly, Jardani et al. (2007) demonstrated the feasibility of employing geophysical inversions to infer permeability distributions in heterogeneous aquifers. Recent studies have applied these approaches to fractured and hard-rock environments; however, such correlations are less common and frequently constrained by site-specific geological variability (Soupios et al., 2007; Hasan et al., 2021; Asfahani, 2023). Despite recent advancements, the development of robust, high-resolution 2D and 3D permeability models from resistivity data, particularly in geologically complex environments at significant depths, remains a major challenge. To date, no previous studies have successfully achieved this, underscoring the critical need for improved integration of geophysical measurements with sparse borehole data. The relationship between resistivity measurements and borehole-derived data provides an efficient and cost-effective method for estimating aquifer properties over extensive spatial areas and varied depth profiles. This study, for the first time, demonstrates a novel application of the CSAMT technique to create high-resolution two and three dimensional permeability models reaching depths of around 1300 m in a geologically complex and heterogeneous environment *characterized by sandstone, granite, and hornstone. A selected number of boreholes were strategically drilled at critical points within the study area. Following this, several CSAMT survey lines were conducted, encompassing both the borehole locations and their surrounding zones. By linking resistivity data from the CSAMT surveys with permeability measurements obtained from borehole core testing, we derived a reliable empirical relationship between resistivity and permeability. This correlation was then applied throughout the entire CSAMT dataset, allowing for the generation of detailed 2D and 3D permeability models even in regions lacking direct borehole data. The method provides a cost-effective and comprehensive framework for evaluating deep groundwater potential, significantly minimizing the reliance on extensive and expensive drilling operations."*

Comment 3:

Line 139- 140: the statement is too arbitrary; the language can be modified or more evidence is provided.

Response 3:

ORIGINAL STATEMENT (Old Version: Page 7, Lines 139-146):

"No one had ever tried to estimate K using direct or indirect methods in such a heterogeneous context before this work, where a broad diversity of rock types are present at a depth of 1 kilometer. Volumetric measurements of 2D/3D k have never been obtained in hard rock exploration using a geophysical technique. Furthermore, no previous research has previously derived permeability using the CSAMT method in the same way as this one. Our more precise

2D and 3D k model predictions of complex hydrogeological circumstances surpass prior investigations, bridging the gap between dependable hydraulic models and limited borehole data".

REVISED STATEMENT (New Version: Page 12-13, Lines 267-277):

"This study introduces several important advancements in the assessment of deep groundwater resources. It is the first to estimate permeability beyond depths of 1,000 m within a hard-rock environment and to develop detailed two and three dimensional permeability models through geophysical techniques. The innovative use of CSAMT for volumetric hydraulic parameter estimation represents a notable methodological breakthrough. Carried out in a geologically intricate setting dominated by sandstone, granite, and hornstone, where such deep assessments were previously unattempted, this work also highlights the effective integration of limited borehole data to generate high-resolution hydrogeological models. This strategy offers a practical and cost-efficient alternative to widespread deep drilling, significantly decreasing the number of boreholes required to achieve similar spatial detail in permeability mapping."

Comment 4:

Line 161: in section 2.1 Study area, the author might consider adding more details about the rocks and geology of the study area.

Response 4:

This section (new heading: *Study area and hydrogeological settings*) has been thoroughly revised based on the reviewer's valuable suggestions. Additional details regarding the rock types and geological characteristics of the study area have been incorporated, as outlined below.

ORIGINAL (Old Version: Page 9, Lines 173-181):

"Intruding rocks from the Indosinian, Caledonian, and Yanshanian eras are among the many geological formations and periods represented in the study region. Other layers from the Paleogene period are also present. The most common types of rock that have been discovered are sandstone, granite, and hornstone. The complex Kaiping concave fault and fold systems were the dominant geological features in the project region, which were developed as a result of magmatic processes and various structures (Qin, 2017). Emergence of joint fissured features symbolizes the various tectono-geological periods, with the local tectonic line corresponding with the faults strike, especially in the northeast orientation (Yang et al., 2021)."

REVISED (New Version: Page 16-17, Lines 333-366):

"The Jinji region exhibits a complex geological evolution shaped by various tectono-magmatic events, particularly during the Caledonian (Silurian–Devonian), Indosinian (Late Triassic), and Yanshanian (Jurassic–Cretaceous) orogenic phases. The geodynamic episodes have resulted in a diverse lithological landscape, mainly consisting of granite, sandstone, and hornstone (hornfels) (Qin, 2017; Yang et al., 2021). Extensive granitic intrusions indicate deep crustal magmatism linked to continental collision and subduction processes. Hornstone exemplifies contact metamorphism resulting from the intersection of intrusive bodies with pre-existing sedimentary layers. Paleogene formations, primarily consisting of fluvial and lacustrine deposits, overlay

*these units and signify a subsequent phase of basin sedimentation. The region is characterized by the Kaiping concave fault-fold system, a significant deformation zone formed through recurrent crustal stress and magmatic processes. This structural framework encompasses various fault types, including reverse, thrust, and strike-slip, indicative of a prolonged history of crustal shortening and lateral displacement. Compressional folds that developed during the Caledonian and Indosinian periods were subsequently modified by strike-slip faulting in the Yanshanian phase. The prevalent northeast-trending orientation of these features aligns with regional stress patterns and significantly influences the subsurface architecture (Qin, 2017; Yang et al., 2021). Fracture networks, consisting of joints and fissures, are widespread in granite, sandstone, and hornstone units. The brittle features, characterized by variations in spacing, orientation, and continuity based on lithology and structural history, function as essential conduits for groundwater flow. Their spatial alignment with major fault systems highlights a significant relationship between structural geology and hydrogeology, with critical implications for subsurface fluid dynamics in this fractured terrain***.**

This study primarily examines the vertical stratification of aquifer-bearing formations in the Jinji region. Highly productive groundwater zones are linked to deeply buried sandstone formations that possess well-developed fracture systems conducive to water storage and flow. The sandstone units are covered by a substantial granite layer with low permeability, which serves as a confining cap that limits vertical recharge from the surface. A hornstone (hornfels) stratum is situated between these two layers, exhibiting intermediate hydraulic properties while providing limited connectivity between the overlying granite and the deeper sandstone. This configuration effectively isolates deep sandstone aquifers from near-surface hydrological processes, making them inaccessible to conventional shallow geophysical or drilling techniques. Targeted deep *exploration is essential for the accurate identification and characterization of concealed aquifers, as well as for guiding their sustainable management in this structurally complex hard rock environment."*

Comment 5:

Line 204: what does "5-20%" represent for? More specific content is preferred for this sentence.

Response 5:

ORIGINAL (Old Version: Page 10, Lines 204-205):

"The vertical resolution of 5–20% can be assessed by CSAMT when exploring depths ranging from 20 to 1000 meters".

REVISED (New Version: Page 18-19, Lines 392-399):

"The vertical resolution in CSAMT, indicating the capacity to differentiate between neighboring subsurface layers, generally varies from 5% to 20% of DOI (depth of investigation), which spans approximately 20 to 1000 meters. At shallower depths (e.g., 20–100 m), vertical resolution is higher (closer to 5%), enabling better differentiation between thin layers. At greater depths (up to 1000 m), resolution may degrade toward the 20% mark due to signal attenuation and broader averaging of resistivity data. This makes CSAMT a valuable tool for identifying significant lithological contrasts, fault zones, and resistivity anomalies related to geological structures".

Comment 6:

Line 217: in section 2.2.2, why were 6 profiles selected? How did the author determine the locations of the profiles? The author might consider providing more evidence of the site location and data collection in the supporting material.

Response 6:

Further details regarding the selection criteria and rationale for the survey profiles have been provided in the revised manuscript.

ORIGINAL (Old Version: Page 11, Lines 217):

“The CSAMT data was acquired using six profiles (1–6) with a 50 meter interval between each station”.

REVISED (New Version: Page 19-20, Lines 412-419):

“CSAMT data were collected along six profiles (Profiles 1–6), with a station spacing of 50 m between successive measurement points. The selection and location of 6 CSAMT profiles were chosen based on several factors, including geological targets and objectives, surface geology and mapping data, topography and terrain accessibility, orientation relative to structures, spacing and coverage requirements, resistivity contrast expectations, integration with other data (boreholes), environmental and regulatory constraints, and source-receiver geometry requirements, etc. Carefully selected survey profiles enhanced the ability to resolve critical subsurface features and minimized ambiguities in the geophysical interpretation”.

Comment 7:

Line 251-253: The author might consider providing more details of the static correction and the Hanning window spatial filtering method.

Response 7:

Additional details on static correction and Hanning window spatial filtering have been included in the revised manuscript to enhance clarity and support the interpretation of CSAMT data.

ORIGINAL (Old Version: Page 12, Lines 251-253):

"The static corrections were made using a Hanning window spatial filtering method, which involved geological information and curve analysis."

REVISED (New Version: Page 21-22, Lines 460-473):

"Static correction and spatial filtering using a Hanning window are essential preprocessing steps in CSAMT data analysis, aimed at improving data quality and enhancing the reliability of subsurface resistivity models. Static correction mitigates the impact of near-surface resistivity inhomogeneities, which can distort electric field measurements and result in static shifts, leading to vertical displacements in apparent resistivity curves that misrepresent deeper subsurface conditions. To improve data quality, measured electric fields were calibrated against a stable baseline or averaged field, thereby reducing the impact of shallow subsurface layers and isolating signals from deeper sources. Simultaneously, spatial filtering techniques were

employed to mitigate noise resulting from environmental and instrumental interference. The Hanning (Hann) window demonstrated notable effectiveness in suppressing spectral leakage and smoothing fluctuations while preserving underlying trends. The Hanning window, when applied in spatial filtering, executed weighted averaging among adjacent measurement stations, preserving coherent spatial patterns and reducing high-frequency noise. This method markedly enhanced the stability and interpretability of the resulting inversion models".

Comment 8:

Figure 1: typos in (b), "uncertainty"; also the words are too small to read.

Response 8:

Figure 1, along with all other figures, has been redrawn and improved for better clarity and presentation (New Version: Fig. 1 on Page 14).

Comment 9:

Figure 7 and Figure 8: a little confused about the legend of the north direction in both figures

Response 9:

The north direction in these revised figures (New Version: Fig. 10 and 11 on Page 43/45) is correctly oriented, though slightly tilted, to provide a clearer and more informative view of the 3D permeability (k) models.

<u>Community Comment (CC1):</u>

General comments:

Very good and novel research in the area of deep hydrogeology with a variety of applications in the geo-energy sector. However, some detail is missing. Please, consider the following minor comments to improve the manuscript before publication.

Response:

We sincerely thank the community member for the encouraging and constructive feedback. We appreciate the recognition of the novelty and significance of our research in deep hydrogeology and its relevance to geo-energy applications.

We agree that the manuscript can benefit from additional detail, and we have carefully addressed all the minor comments and suggestions to enhance the clarity and completeness of the work. We believe the revised version better reflects the scope and contributions of our study. **All suggested changes have been clearly marked and are provided in the track-changes file for ease of review.**

Specific comments:

Comment 1:

Lines 69-72. “Consideration of hydraulic properties is crucial in groundwater evaluations. Permeability is the most popular aquifer measure and is mainly used to assess the water-holding capacity of rocks all over the world". Insert these papers where there is discussion on the role of geophysical and hydrogeological methods to detect the hydraulic properties of fractured rocks to inform flow models in granites, metamorphic and sandstone lithologies.

- Medici, G., Ling, F., Shang, J. 2023. Review of discrete fracture network characterization for geothermal energy extraction. Frontiers in Earth Science 11, 1328397.

- McKeown, C., Haszeldine, R.S., Couples, G.D. 1999. Mathematical modelling of groundwater flow at Sellafield, UK. Engineering Geology 52(3-4), 231-250.

Response 1:

The following revision was made to improve clarity and integrate the suggested references (Revised Version: Page 10, Lines 207-215):

"In fractured rock environments, including granitic, metamorphic, and sandstone formations, fluid movement is primarily influenced by the arrangement and connectivity of fractures, rather than the inherent porosity of the rock matrix. A precise assessment of hydraulic behavior in these environments necessitates the application of integrated methodologies. Recent studies emphasize the necessity of integrating geophysical and hydrogeological methods to accurately identify and characterize hydraulic properties (McKeown et al., 1999; Medici et al., 2023). Interdisciplinary approaches are crucial for improving the precision of flow modeling and for guiding groundwater management and geo-energy development in structurally complex terrains."

Comment 2:

Lines 146-152. Lots of multiple objectives (5). Please, clarify the general aim of your hydrogeological research.

Response 2:

ORIGINAL (Old Version: Page 7, Lines 146-152):

“The primary goals of this study were as follows: (1) to rapidly predict two- and three dimensional k models using geophysical methods; (2) to reliably assess the hydrogeological properties of rock formations for deep groundwater assessments in challenging geological settings; (3) to minimize costly boreholes and maximize the use of scarce drilling resources to collect hydrogeological data over large areas; (4) to decrease uncertainties in hydrogeological models; and (5) to promote the use of non-invasive geophysical techniques for hard rock groundwater investigations instead of costly drilling that can damage the rock.”

REVISED (New Version: Page 13, Lines 277-284):

"The primary aim of this study is to develop and implement a geophysical-based approach for accurately predicting the spatial distribution of permeability in deep, hard rock environments. By integrating CSAMT data with strategically selected borehole measurements, this research enhances the two and three dimensional assessment of hydrogeological properties across various rock types in geologically complex settings, reduces reliance on extensive and costly drilling, and highlights the advantages of using non-invasive geophysical techniques as a more efficient alternative for deep groundwater exploration."

Comment 3-5:

- Lines 173-181. The geometrical relation between the different lithologies is unclear.
- Lines 173-181. The detail is not enough on presence of faults. Which type of faults?
- Lines 173-181. Nature of the joints? I am talking about the tectonic genesis.

Response 3-5:

This section (new heading: *Study area and hydrogeological settings*) has been thoroughly revised. Additional details addressing the above points have been incorporated to enhance clarity and completeness, as outlined below.

ORIGINAL (Old Version: Page 9, Lines 173-181):

"Intruding rocks from the Indosinian, Caledonian, and Yanshanian eras are among the many geological formations and periods represented in the study region. Other layers from the Paleogene period are also present. The most common types of rock that have been discovered are sandstone, granite, and hornstone. The complex Kaiping concave fault and fold systems were the dominant geological features in the project region, which were developed as a result of magmatic processes and various structures (Qin, 2017). Emergence of joint fissured features symbolizes the various tectono-geological periods, with the local tectonic line corresponding with the faults strike, especially in the northeast orientation (Yang et al., 2021)."

REVISED (New Version: Page 16-17, Lines 333-366):

"The Jinji region exhibits a complex geological evolution shaped by various tectono-magmatic events, particularly during the Caledonian (Silurian–Devonian), Indosinian (Late Triassic), and

Yanshanian (Jurassic–Cretaceous) orogenic phases. The geodynamic episodes have resulted in a diverse lithological landscape, mainly consisting of granite, sandstone, and hornstone (hornfels) (Qin, 2017; Yang et al., 2021). Extensive granitic intrusions indicate deep crustal magmatism linked to continental collision and subduction processes. Hornstone exemplifies contact metamorphism resulting from the intersection of intrusive bodies with pre-existing sedimentary layers. Paleogene formations, primarily consisting of fluvial and lacustrine deposits, overlay these units and signify a subsequent phase of basin sedimentation. The region is characterized by the Kaiping concave fault-fold system, a significant deformation zone formed through recurrent crustal stress and magmatic processes. This structural framework encompasses various fault types, including reverse, thrust, and strike-slip, indicative of a prolonged history of crustal shortening and lateral displacement. Compressional folds that developed during the Caledonian and Indosinian periods were subsequently modified by strike-slip faulting in the Yanshanian phase. The prevalent northeast-trending orientation of these features aligns with regional stress patterns and significantly influences the subsurface architecture (Qin, 2017; Yang et al., 2021). Fracture networks, consisting of joints and fissures, are widespread in granite, sandstone, and hornstone units. The brittle features, characterized by variations in spacing, orientation, and continuity based on lithology and structural history, function as essential conduits for groundwater flow. Their spatial alignment with major fault systems highlights a significant relationship between structural geology and hydrogeology, with critical implications for subsurface fluid dynamics in this fractured terrain.

This study primarily examines the vertical stratification of aquifer-bearing formations in the Jinji region. Highly productive groundwater zones are linked to deeply buried sandstone formations that possess well-developed fracture systems conducive to water storage and flow. The sandstone *units are covered by a substantial granite layer with low permeability, which serves as a confining cap that limits vertical recharge from the surface. A hornstone (hornfels) stratum is situated between these two layers, exhibiting intermediate hydraulic properties while providing limited connectivity between the overlying granite and the deeper sandstone. This configuration effectively isolates deep sandstone aquifers from near-surface hydrological processes, making them inaccessible to conventional shallow geophysical or drilling techniques. Targeted deep exploration is essential for the accurate identification and characterization of concealed aquifers, as well as for guiding their sustainable management in this structurally complex hard rock environment."*

Comment 6:

Line 538. I prefer "Discussion". You have a unique discussion on a scientific paper where you face different topics. This point also depends on the guidelines.

Response 6:

Thank you for your valuable suggestion. We agree that "Discussion" is a more appropriate and conventional title for this section, as it aligns with standard scientific writing practices for presenting and interpreting key findings. Accordingly, we have changed the section title from "Discussions" to "Discussion" (Page 51, Line 899) in compliance with the journal's formatting guidelines. Furthermore, the entire Discussion section has been thoroughly revised and enhanced based on the suggestions provided by both the reviewers and the community, with the aim of improving clarity, depth, and overall scientific value.

Comment 7:

Lines 600-837. Insert the relevant literature suggested above on the hydraulic properties of deep aquifers in a variety of sites worldwide.

Response 7:

The relevant literature suggested above and many others have been incorporated into the revised *References* section of the manuscript (New Version: Page 61-73)

Comment 8:

Figure 1. Letters are too small in both the figures. Please, make the figure larger.

Response 8:

Figure 1, along with all other figures, has been redrawn and improved for better clarity and presentation (New Version: Fig. 1 on Page 14).

Comment 9:

Figure 1. Pay lot of attention of figure 1b. This is a conceptual model and you can get citations from the figure. Make the figure larger and increase the font of the words.

Response 9

Fig. 1b has been improved accordingly (New Version: Fig. 1 on Page 14).

Comment 10:

Figure 2. There is room to make the figure larger.

Response 10:

Fig 2 has been improved/enlarged (New Version: Fig. 2 on Page 23).

Comment 11:

Figure 4. Check the depth of the boreholes.

Response 11:

The depth of boreholes in the updated Fig. 3 (Page 24), Fig. 6 (Page 36) and Fig. 7 (Page 37) has been corrected.

Comment 12:

Figure 9. The words are too small. The figure is difficult to read. Please, improve it.

Response 12:

The updated Fig.12 has been improved (Page 47)

Community Comment (CC2):

The authors submitted the same manuscript to JoH.

Response:

We appreciate the comment. The manuscript submitted to the *Journal of Hydrology* (JoH) focused on a different hydraulic parameter, hydraulic conductivity, whereas the current submission emphasizes permeability estimation using CSAMT data. To avoid any overlap and maintain academic integrity, we have promptly withdrawn the JoH submission in response to this comment.