Referee #1

Dear Dr. Minisini, thank you very much for your detailed revision work. We sincerely appreciate your constructive comments and thoughtful suggestions towards the improvement of our manuscript. We revised the manuscript following your valuable suggestions. All minor comments (i.e. typos, wording, and grammar) have been incorporated directly in the revised version. Comments that required deeper discussion are answered in detail below. All changes were made are with track changes on.

This paper focuses on rock units that could host disposal of radioactive waste. The paper prepares the ground for future contributions on the same topic and same area. Its main goal is to prove that the Amaltheenton Fm represents an optimal stratigraphic unit to study how a rock unit, originally having self-similar characteristics, is affected by different burial histories. In fact, the authors would like to investigate the impact of burial history on barrier-relevant properties of claystones ("low permeability, self-sealing efficiency with respect to fractures, sorption capacity, and mechanical properties for long-term stability of the underground infrastructure").

This is emphasized in passages like the following:

- "Collectively, the initial findings … characterize the Amaltheenton Fm as a … homogeneous claystone formation... Thermal maturity quantifications…corroborate variable … burial depths, following a SE-NW trend. Both findings are vital for the MATURITY project and highlight the suitability of the Amaltheenton-Fm for the stated objectives."
- "The homogenous mineralogical composition and the gradually increasing trend of maximum burial are the two key prerequisites to conduct detailed parameter studies on the relationship between burial history and changes in the physical rock properties."

Although the authors explain how they understand the different thermal maturity in the area of study, they do not explain well how they understand that the rocks investigated in 5 wellbores are/were homogenous. The text says that the Amaltheenton-Fm is "a regionally relatively homogeneous claystone formation within the study area". Homogenous is a clear adjective that is not used with its significance in the paper. The quote itself says "relatively homogenous", which is an oxymoron. Actually it includes the term "regionally", as if zooming in, the formation would be heterogenous. In fact, the authors state that the Amaltheenton Fm "exhibits only slight variations between the individual borehole locations". But "slight" is not described in the text and their nebulous concept of "homogeneity" (among the 5 sites and within each site) rises a flag, as we are talking about the foundational work for potential nuclear waste disposal sites.

Sedimentary rocks are always variable, both in vertical and horizontal direction. However, as compared to lacustrine, fluvial, deltaic and coastal deposits, marine claystones can be regarded as homogeneous. Basically, the same Lower-Middle Jurassic sequence drilled (Amaltheenton, Posidonia Shale, Jurensismergel/Opalinuston extends from northern Germany towards southern Germany, Switzerland and France over large distances. Due to this fact, we call the units "homogeneous". However, there are variations, e.g. with respect to thickness of these units. A special aspect in the Amaltheenton are siderite concretions, often several cm thick, which occur randomly and thus cannot be predicted. Aside from this, there are only minor differences in clay mineralogy, organic carbon content, carbonate content etc. We expanded on these aspects in the paper and avoided the term "relatively" in combination with "homogeneous".

The authors could take advantage of the deep dives into these fine-grained rocks made by the Energy companies working on Unconventional resources. They might expand their views on fractures (permeability) and early diagenetic processes (porosity) affecting these claystones/mudstones.

Good idea, but based on German law, energy companies tend to keep their data confidential.

Since the authors themselves mention that they still need more ”analyses….to assess the elemental and mineralogical composition of the Amaltheenton Formation at each location. …and quantify spatial variability, which is crucial for understanding basin-wide depositional patterns and potential lateral facies changes”, it seems this contribution might benefit from another round of readings by the authors.

There will be a special contribution, later, which will deal with mineralogy, elemental data, porosity etc. Keep in mind that this paper should provide an overview. However, we modified the sentence "need more analyses.."

Also, there authors should explain better to the reader the reason why the chose the Amaltheenton Fm (i..e, prove that the Amaltheenton Fm represents an optimal stratigraphic unit to study how a rock unit, originally having self-similar characteristics, is affected by different burial histories).

We agree and adapted the respective section as follows: "A claystone formation with a natural maturity sequence as result of differential burial and stable environmental conditions during deposition form the site requirements for the stated project objectives. Regional depositional consistency is important to ensure comparable mineralogical composition of the target formation, as mineralogy has influence on the parameters investigated along the course of the MATURITY project. Such conditions are given within parts of the Lower Saxony Basin (LSB), Germany. Various authors have identified strongly variable thermal maturity of Lower Cretaceous and Jurassic rocks linked to deep burial during the Late Cretaceous (Bruns et al., 2016). Notable maturity variations were observed for the Toarcian Posidonienschiefer-Fm on a relatively small regional scale in southeastern Lower Saxony, as documented (among others) by Koch & Arnemann (1975), Littke et al. (1988), and Mackenzie et al. (1988). However, the Posidonienschiefer-Fm itself is not regarded as a potential host rock for radioactive waste disposal due to its distinctive composition, characterized by a high carbonate and organic matter content, thus holding the potential for microbial activity, enhanced chemical reactivity, and oil and gas generation (Rullkötter et al., 1988). In contrast, both the underlying Upper Pliensbachian Amaltheenton-Fm, and the overlying upper Toarcian to Aalenian sequences, comprising the Jurensismergel-Fm and Opalinuston-Fm, are being evaluated as discrete sub-areas for potential host rock suitability (Fig. 3). Additionally, these units were uplifted to near surface levels by Cretaceous inversion tectonics, making them an ideal target horizon for shallow drillings within the scope of the MATURITY project. Apart from that the Jurensismergel-Fm/Opalinuston-Fm is located in the hanging wall, above of the Posidonienschiefer-Fm and has experienced strong and brittle deformations due to the degassing of the Posidonienschiefer in the eastern part of the transect, where thermal maturity reaches the gas window. Consequently, the Amaltheenton-Fm was selected as primary target formation suiting the project objectives."

Finally, although the authors focus on burial history, they mention other factors ("mineralogy, temperature, stress and water content") that affect the barrier properties they want to study. They should better explain why, among the several factors, they focus on burial history (beyond writing that "burial history and thus compaction affects porosity, permeability, and mechanical properties").

Our study cannot cover all aspects of nuclear waste storage in claystones. Here, the important aspect of burial and temperature history is mainly considered, because many Mesozoic and older claystones have been buried to great depth and later uplifted towards the surface. This burial history affects rock various properties important for barrier considerations. We revised parts of the introduction intending to introduce the reader to the choice of focussing on burial history related alterations. Also we added a subchapter introducing the MATURITY project objectives in a clearer manner.

Introduce why you focus on "claystones", in other words, explain why this is the most appropriate among the several different rock types (sandstones, limestones, evaporites, magmatic, metamorphic rocks).

As lithologies suitable for nuclear waste storage, claystones, salt (halite) and crystalline rocks (granite/gneiss) are considered. In our paper, we investigate claystones. Research questions regarding salt and granite/gneiss would be vastly different.

52: why "up to 1 Ma"?

Under the German Site Selection Act (Standortauswahlgesetz, StandAG), the proposed time frame for the safe disposal of high-level radioactive waste is at least 1 million years.

This is explicitly stated in the law as the period during which the containment of radioactive waste must be ensured without the need for human intervention, using passive safety provided by a deep geological repository.

We adapted the respective passage for clarity.

53 and 92-94: although most literature support the idea of "the deeper the less porous", the last decade dedicated to study the claystones/mudstones for Unconventional Resources demonstrated that some of these rocks get lithified before compaction, this understanding has implications for the idea of "the deeper the less porous". My colleague Macquaker and I wrote few weeks ago a piece about it in Marine and Petroleum geology and I hope this can help you with a different point of view on the same rocks we are analyzing in different industries. Maybe something to tie with your comments in lines 68-70. Also lines 75-79 may take in consideration the new literature derived from the Unconventional plays (it would be wonderful from their point of view if fractures would contribute to permeability, as they would produce more hydrocarbon resources; unfortunately the role of fractures does not go into that direction).

Thank you for the insightful comment. We agree that early cementation and lithification at shallow burial depths can significantly alter porosity-depth relationships. Fig.1a was designed to reflect this process (see arrow III), but we recognize that this was not sufficiently emphasized in the text. We have included a new sentence directly after the paragraph discussing causes of under-compaction (lines 68–70), where such deviations are addressed, and have cited Minisini et al. (2025) to incorporate this important perspective: „Another potential deviation from the general porosity–depth trend may result from early cementation during shallow burial, where chemical lithification occurs prior to significant mechanical compaction. This process has been increasingly recognized in studies of mudstones and claystones from unconventional resource settings, where early diagenetic cementation can "lock in" porosity and lead to complex, non-monotonic porosity–depth relationships (Aplin & Macquaker, 2011; Minisini et al., 2025)."

71 -537: examples where nomenclature may be improved/refined. E.g. use "as muds are compacted to lower porosity mudstones…" 537:" as argillaceous mudstone". In sum, the rocks you are describing are mudstones (grains up to 64 micrometers, including grain size of clay -up to 4 micrometers- and silt -between 4 and 64 micrometers). They are not claystones (whose components are up to 4 micrometers). As an example, if a rock is composed by large clasts made 100% by clay minerals is not considered a claystone, it is a conglomerate.

We appreciate the suggestion regarding terminology and the distinction between mudstones and claystones. In our manuscript, the term "claystone" follows the lithostratigraphic nomenclature commonly applied in regional geological literature (e.g., Arp et al., 2021; Burnaz et al., 2024), where the Amaltheenton Formation is consistently referred to as a monotonous claystone unit. This terminology reflects not just grain size, but the mineralogical composition—with clay minerals (primarily illite and illite-smectite interlayers) consistently dominating the bulk rock (>55%, often >70%). Furthermore, high Al_2O_3 concentrations and low MinC values support this classification. We therefore believe that the use of the term "claystone" remains appropriate for describing this formation in its geological context.

117: "mineralogically homogeneous claystone" explain the scale you are thinking about when using the term homogenous (e.g. bed scale, lamina scale, grain scale, cement scale, pore scale). Mention also the geological time encapsulated in the thickness of the formation taken in consideration (Amaltheenton Fm). This would make you wonder on the likelihood of "homogenous" environments of deposition (i.e. if the formation was deposited in 1 Million years, is it likely that the env of dep remained the same?)

We have revised the manuscript to clarify our use of the term "mineralogically homogeneous". In our study, homogeneity is considered at the formation scale, referring to both the spatial extent (approximately 50 km SE-NW directed transect) and vertical thickness (up to 90 m) of the Amaltheenton Formation, as sampled across five boreholes.

Specifically, we refer to bulk mineralogical composition, based on XRD analysis, which consistently shows a clay mineral content >55 wt.% at all locations and throughout the sampled depth intervals (see Figure 10a and Table 2; exceptions are siderite concretions). In comparison, the Opalinus Clay (the promising HLW host rock candidate in Switzerland) shows clay mineral contents between 43% and 73%. This deviation is linked to stratigraphic subunits (shaly versus sandy facies). However, the formation is also considered homogenous. Based on the first results of this study the Amaltheenton Fm has a bulk mineralogical composition similar to the Opalinus Clay. Also, the gamma ray logs show similar values across the individual boreholes and almost no fluctuations, indicating very consistent composition in horizontal and lateral extension.

Regarding the temporal aspect, we agree that the deposition period of the Amaltheenton Fm raises valid questions about environmental stability. However, detailed and recent paleoenvironmental studies by Burnaz et al. (2024) and Wijesinghe et al. (2025) indicate that the depositional environment during the Upper Pliensbachian was relatively stable, characterized by shallow marine conditions, high detrital influx, and oxic bottom waters. These findings support the assumption of a broadly consistent sedimentary regime, which is reflected in the mineralogical composition across our boreholes.

- *Burnaz, L., Littke, R., Grohmann, S., Erbacher, J., Strauss, H., & Amann, F. (2024). Lower Jurassic (Pliensbachian–Toarcian) marine paleoenvironment in Western Europe: Sedimentology, geochemistry and organic petrology of the wells Mainzholzen and Wickensen, Hils Syncline,*

Lower Saxony Basin. International Journal of Earth Sciences. *https://doi.org/10.1007/s00531-023-02381-8*

- *Wijesinghe, P., Littke, R., Burnaz, L., Blumenberg, M., Erbacher, J., Mann, T., Amann, F., & Bauersachs, T. (2025). Black shale deposition during the Early Jurassic: Geochemistry of Pliensbachian and Toarcian sedimentary rocks of the Hunzen Well, Hils Syncline, Northwest German Basin. The Depositional Record, dep2.70037. https://doi.org/10.1002/dep2.70037*

118: "This formation should be i) accessible with shallow drillings (less than 100m)" explain why.

An explanation in this regard was added to the revised version. Drilling deeper than 100 m requires an application process which is much more complex according to German law. In addition, drilling deeper would be much more expensive.

119: "and ii) covered by rock strata to minimize the influence of weathering processes " Report the thickness of the "strata" covering the Amaltheenton in each borehole (use Table 1) and explain what is the assumed safety thickness to avoid weathering (if possible, reporting data supporting the thickness declared). Adjust with statement in line 165. Be ready to tackle the data from BO4.0 where the Amaltheenton is only covered by 6 m of Quaternary strata.

Thank you for this important suggestion. We have added a column in Table 1 indicating the depth to the top of the Amaltheenton Formation (mbgs) for each borehole. This provides a clear overview of the overlying strata thickness at each site. While there is no universally fixed threshold, several studies suggest that weathering in clay-rich formations typically affects the uppermost 0–30 m, depending on local conditions (see i.e. Studies from shallow boreholes in the Opalinus Clay: https://doi.org/10.1016/j.clay.2022.106793; https://doi.org/10.1007/s00767-017-0363-2, *https://publikationen.uni-tuebingen.de/xmlui/handle/10900/56824). In the case of borehole BO4.0, although the Amaltheenton Formation is only covered by 6 m of Quaternary deposits, the entire 96 m borehole section consists of unweathered Amaltheenton claystone. Therefore, samples used for analysis were retrieved from greater depths (far below any potential weathering front), minimizing the risk of alteration by surficial processes. This is now clarified in the text to ensure consistency with the statement in line 165.*

146 : report the duration of the "safe long-term conditions" in years

See reply to comment no. 1.

152: northern not Northern

This was changed accordingly.

Fig 3 and Fig 5: Specify what formation the vitrinite maps refers to. If vitrinite refers to the Amaltheenton Fm, then note figure 1c of this article https://link.springer.com/article/10.1007/s00531-024-02477-9 showing a data point with 0.8 vitrinite in the Amaltheenton formation that does not match with your maturity map in fig 3. I see there is no discussion around that specific value, but hope you may find the information useful.

Thank you for this information. Please note that this specific data point is far outside of our own study area.

232-248: clarify better that all the data are referred to another formation, not the object of study. Add a sentence highlithing the imporantce of the data from the Posidonia for the overlying Amaltheenton formation.

We agree on your suggestion and have revised the section to explicitly state that these data are derived from the overlying Posidonienschiefer Formation and are not direct measurements from the Amaltheenton Formation. We added a sentence highlighting the importance of the Posidonienschiefer data for interpreting thermal maturity trends in the Amaltheenton due to their close stratigraphic and burial relationship. Note: the difference in depth by just a few tens of meters does not cause any significant difference in thermal maturity.

250 and 591: the measurements of porosity and permeability on rocks recovered more than 40 years ago ("core materials from the 1980´s drilling campaign") rise a red flag. Rock was very likely dissecated and unsuitable for those measurements. Geologists and engineers working in Unconventional reservoirs have proven that those measurements are not reliable and so they spend millions of Euros/Dollars to collect fresh samples to have right values for their expectations on hydrocarbon production. Sealing radioactive waste might be considered more important than hydrocarbon production, hence this point should be clearly highlighted to the readers.

We fully agree that porosity and permeability measurements on core materials recovered more than 40 years ago must be viewed critically due to potential alterations caused by storage under ambient conditions. As such, we have added a sentence explicitly stating this concern and referring to the detailed discussion by Gaus et al. (2022), who carefully evaluated the extent of possible changes in the samples. Their study considered multiple lines of evidence, including preservation of pyrite, absence of gypsum, consistent bulk density values, and lack of significant macroscopic fracturing during drying, all of which suggest that the matrix properties of the core material remained largely intact. Nonetheless, we agree this limitation must be highlighted clearly and have done so accordingly in the revised manuscript. And keep in mind: our new cores were analysed in a fresh state to avoid any weathering after drilling.

253: "Their results align with the previous studies on the organic-rich Posidonienschiefer-Fm" If you investigate the range of values both for the studies made by Gaus et al. (2022) on the Amaltheenton, and for the studies made by Mann (1987) on the Posidonia, you'll discover that their different values represent different rock fabrics, in turn related to different environments of deposition. In this view, remember your previous statements on the "homogenous" environments of deposition (see comment on line 117).

This may be a misunderstanding. Of course, Posidinia Shale and Amaltheenton are completely different lithologies with different petrophysical properties. Therefore you can expect different values for the Posidonia Shale (Mann et al.) and Amaltheenton (Gaus et al.,), even if they are from the same borehole. We clarified this in the text.

260-264: are these statements conclusions from your work? Are they inferences? Or are they statements derived from previous studies?

We thank the reviewer for pointing this out. The statements in lines 260–264 are not conclusions or inferences from our own analyses but are derived from previous studies—specifically, Gaus et al. (2022) and Castro-Vera et al. (2024). To make this clearer, we have added the appropriate citation at the end of the paragraph. These referenced works provide the interpretations regarding overpressure *development and burial trends that help explain the observed deviations from typical porosity and density patterns.*

552: are you sure that TOC “documents the increase in thermal maturity”?

Yes, TOC changes with thermal maturity (see Rullkötter et al., 1988, Organic Geochemistry, for Posdonia Shale). During oil and gas generation, carbon is lost; roughly 50 % is transformed into liquid and gaseous products. However, this can be only tracked for rocks rich in organic matter (such as Posidonia Shale) and not for organic lean rocks such as Amaltheenton.