

2nd REVIEWERS' COMMENTS

Short summary to reflect my understanding

The authors have resubmitted their previously reviewed manuscript. They provided a comprehensive author response letter as well as a rewritten manuscript with track changes highlighted. Both documents are polite, concise, reflect the willingness to improve the manuscript and proved very useful in my 2nd reviewing. All comments regarding the scientific content have been addressed well – ‘Thank you’ to the authors.

Nevertheless, I suggest to accept the resubmitted version for publication only after a renewed minor revision aimed at improving conciseness and structure. While the authors have added additional detail—particularly in the introduction—the remaining challenge appears less related to missing scientific content than to the previously noted need for greater semantic precision, which I fully acknowledge is no easy feat in such a multi-method study.

The authors have incorporated smaller review comments well, and focus their response to points that require a deeper discussion. I follow that procedure, leaving only larger points.

Review on the response to the referee #1 (Dr. Minisini, apparently openly non-anonymous)

Comment #1 - Better define “homogeneous” and terms the like

The authors did well in simply deleting previously imprecise occurrences of the term “homogenous”, leaving it only in three occasions where it now refers to a uniform contribution of mineralogical phases “at the fm. scale”. To me, this is fine, as it conveys the important interpretation that sample differences are not -at least not foremost- caused by mineralogical variability but by maturity. However, if the authors fancy, they could even completely avoid the term and thus not give rise to any need of a complex (or incomplete) definition.

[With many publications the term “homogeneous” is used in an imprecise manner. That is unfortunate, as most of the time the term can be simply changed with what is actually meant, like “rock volumes of similar mechanical properties” or, as with this manuscript, “...samples are uniform in mineralogical composition, with clay minerals being the consistent dominant phase throughout the entire sampled formation”.]

Comment #4 – Selection of site

The changed manuscript part (now line 204ff) is not concise. It can be summarized, maybe like:

“To study the explicit influence of maturity on physical rock properties, investigated samples should ideally show a high variability in maturity while other controlling factors being of as little effect as possible – in particular the mineralogical variability. Fortunately for this purpose, previous studies (Bruns, Koch, Littke, Mackenzie,...) attest notable maturity variations in close distances for the here investigated ... site.”

Comment #inline 53ff – chemical lithification over mechanical consolidation

The authors did well in their response here, maybe they want to add Corkum et al. (2007), who also described for OPA at Mont Terri, that pores are larger than anticipated by pure depth relation – also due to chemical lithification that preserved pore structures (diagenetic bonds).

Corkum, A.G., Martin, C.D., 2007. The mechanical behaviour of weak mudstone (Opalinus Clay) at low stresses. *International Journal of Rock Mechanics and Mining Sciences* 44, 196–209.

<https://doi.org/10.1016/j.ijrmms.2006.06.004>

(Note: I have made this suggestion earlier in my 1st review)

Review on the response to the referee #2 (myself, openly non-anonymous)

Comment #1 – Risk of misinterpretation

For the conclusion part that seems to be addressed in line 880ff:

“It is important to emphasize that these deviations illustrate the site-specific nature of burial-related property trends. Local processes such as overpressure generation, hydrochemical evolution, or changes in effective stress can modify or even invert depth-dependent trends. Consequently, the observed relationships should not be interpreted as universally beneficial or detrimental for repository performance.”

I like to suggest an improvement here to better match my previous concern on misinterpretation (sorry for not being clearer earlier). What I suggest to emphasize is that knowing material properties alone is not sufficient to speculate on material behaviour (or suitability for a repository in this case). Instead, it is the interplay of material properties and environmental controls (see first review for example cases and also in the now rewritten introduction). I acknowledge that this interplay is somewhat trivial, yet find it often overlooked. I do not want to encourage the start of a deep discussion here, just a one sentence disclaimer to avoid that burial trends are thought of as a straight-forward proxy for ranking clays on their suitability for a radioactive waste repository, like: “the deeper it has been, the higher in strength, the better it is”. For the same reason I earlier wondered about the term “barrier properties”, which the authors now have omitted. Anyhow, the now emphasized limitation - to be careful in assuming a universality for the here presented site-specific trend - is also valuable yet not quite what I meant.

Moreover, I suggest to avoid the term “performance” (here and in other occasions) as it leaves ambiguous what is meant. Similar to “homogenous”, the term “performance” can be replaced by a precise wording in almost all cases that I am aware of.

Comment #2 – Improving Conciseness

TITLE:

The revised title remains unclear with respect to what is meant by “different scales.” It is not specified whether this refers to spatial scale, methodological scale (e.g. laboratory vs. borehole), or another dimension. Even after reading the manuscript, I still don’t know what is meant, too. I frankly suggest a slightly changed, more specific alternative, for example:

“The influence of burial history on physical rock properties: A case study of Lower Jurassic claystones from the Hils and Sack Synclines (Germany).”

INTRODUCTION:

The introduction contains all the necessary elements, but it remains rather long (~7 pages) and would still benefit from a more streamlined formulation. In its current form, it provides limited guidance on what is most relevant for which of the now listed specific aims (good!).

I perceive the introduction to be currently structured as:

1. relevance of claystones in radwaste disposal
2. relevance that claystone properties are dependent on multiple controls
3. relevance of the control burial history
4. relevance of fracture permeability
5. relevance of sealing capacity
6. relevance of mechanical behaviour (and its controls, including burial history) (?)
7. relevance of unloading effects due to uplift (kind of belonging to burial history again)
8. relevance of burial history (again) / maturity (sensu property, not the project name)
9. outline of the project MATURITY (single subchapter)
10. reasoning for site-selection
11. aims of the paper
12. material / fm description

A rigorous condensation of the arguments would help the authors sharpen the motivation of the study and more clearly articulate the rationale underlying their work.

Moreover,

- i) I feel that the now added subchapter on outlining the MATURITY project gives redundant argumentation on the relevant aspects listed. Plus, a single subchapter is unnecessary if it is not contrasted with other subchapters (I guess that “1.1...” ends at line 204: “A claystone formation exhibiting...”, right?).
- ii) I made a suggestion in shortening the “reasoning of site-selection”, line 204ff, see reviewer 1, comment 4 on first page.

STUDY AREA:

Commonly, chapters as “study area” or “sampling material” and the like are listed under methods, following the usually strict procedure in scientific publications of abstract, intro, methods, results, discussion, summary & outlook, acknowledgements.

A brief introductory sentence under each main heading might better guide the reader in this many, many, multiple investigations presented (moreover, a direct transition from a section heading to a subheading (e.g. “2” to “2.1”) is redundant). This holds true for other headings, e.g. “3 Methods”.

The heading 2.2 “Previous Studies” should be defined by what kind of studies is meant. (“Previous studies on the maturity gradient in the ... region”, right? Previous studies on geology have been given just before)

OUTLOOK:

There is a well-written and concise outlook at the end of the summary chapter, too:

Currently, individual studies carried out in the framework of the MATURITY project aim to further investigate the complex dependencies and interactions between burial history and mineralogical (CEC and reactive surface area), petrophysical (porosity, permeability), mechanical (rock strength and elasticity), and hydrogeological (hydraulic conductivity, storativity) claystone properties. These detailed studies will complement the previous analyses to deliver an important data set for the further site selection process in Germany. Ultimately, this effort will (a) enhance the understanding of the processes altering claystone properties throughout their burial and uplift and (b) facilitate robust site and scale data transferability by establishing transfer functions for the investigated parameters.

Hence, I suggest to delete the OUTLOOK chapter itself entirely.

DISCUSSION AND SUMMARY:

While the four general aims are now explicitly listed in the introduction, the discussion and conclusions would benefit from a structure that more directly and sequentially addresses these aims. Instead, new headings (e.g. “5.2 Scale- and depth-dependent hydraulic behavior”) are introduced without being clearly linked to the stated aims, although they appear to correspond to them (e.g. Section 5.2 to Aim 4). Aligning the structure more closely with the stated aims would improve focus and readability. Maybe reformulate one paragraph explicitly for each aim in the conclusion section.

Some “left-over” In-line comments

L6 & L7 “Chair” – I guess “Institute for / Department of” as the authors do not hold the chair positions themselves, correct? (in German, “Lehrstuhl für” would be correct).

Maybe this was overlooked?

L 77 “control larger scale behaviour” – Counterargument: Fractures in clays have impermeable side walls. Calcite veins prove to have isotope signatures unrelated to close-by Ca-fossils that microstructurally often seem intact. Moreover, tracer profiles across faults (e.g. Main Fault in Mont Terri) show now deviation from an diffusion profile.

We generally agree, that fractures at a large scale do not necessarily need to enhance fluid flow, especially in low to moderately indurated formations such as OPA or COx, where self-sealing especially due to swelling of clay minerals is efficient. However, strongly indurated formations tend to lose the attribute of effective and rapid self-sealing due to swelling as result of clay mineral conversion with increasing temperatures during burial. This will also result in increased brittleness, facilitating fractures to form while the loss of swellable clay mineral phases prevents effective self-sealing. In such cases induced fractures might remain open and accessible for fluid flow, ultimately leading to pronounced scale effects between the low permeable matrix and the higher permeable rock mass (see i.e. Mazurek et al, 2009: Natural Tracer Profiles Across Argillaceous Formations: The CLAYTRAC Project). However, we adapted the wording to account for those differentiations. A dedicated study that investigates these kind of phenomena is currently on the way.

I am good with the simple addition of the word “can” here (line).

Note:

Yet, swelling of clay minerals is likely not a relevant self-sealing mechanism in tectonic, fully saturated settings. In EDZ and bentonite, this mechanism is frequently studied and I sense that it is often assumed to be valid in general. Or what do the authors think: Why are there frequently veins in OPA (and other shales)? Shouldn't the relatively slow vein precipitation be overruled by the much more rapid process of smectite swelling then? There are good arguments for smectite swelling to be even unimportant in tectonic settings (don't get me wrong: in EDZ and Bentonite, I do consider it the dominant mechanism). Hence, my argument might still hold true: undeformed claystone might retain its porewater just very next to fracture. The fracture might be hydraulically active though, maybe conducting fluids from below through the claystone fm. to the top of it, but not necessarily from it. The formations overall integrity is not in immediate question if there are localized fractures – they do not necessarily control the “larger scale behaviour”.

L 83 “self-sealing” this is an often missed opportunity to state what the term actually means. With ductility, as stated here, the fm. is “self-sealing” in the sense that it hinders larger brittle fractures to form by easily giving in to stress in a viscous manner. This is strictly different to “self-sealing” of fractures, where clay swelling CAN play a crucial role if the fm is not already saturated and/or if a pore fluid change to lower-ionic strength is at play.

I thank the authors for reformulating the section, which I do not request to be further changed. The authors may double-check if “...clay swelling CAN play a crucial role if the fm is not already saturated and/or if a pore fluid change to lower-ionic strength is at play” should be addressed, similar to comment above.

L 89ff See Rutter et al. 2001 for a good differentiation on what controls the mechanical behaviour, to become more precise here. Applies to L 93ff, too. (Evrn. controls vs. material intrinsic ones)

Thank you very much for this suggestion. We included the paper as important reference but do not see the need for further discussion as this study does not predominantly focusses on mechanical properties.

Sorry, this was meant more as an interesting hint rather than a request for a change. I did not mean to address the fault zone weakening subject or citing the paper. I just

wanted to highlight that there is a good approach in justifying the complex controls of mechanical behaviour (which is likely used elsewhere, too) expanding more comprehensively what is stated in (a), (b) and (c) of this section. Consider deleting Rutter again, topic does indeed not fit well.

L 347 Isit also Sr reduction

Could you specify what Sr stands for? Do you mean saturation ratio?

Yes. The decompacted sample has a lower Sr than the in-situ one. In particular relevant to unconfined lab tests (next to the mentioned pore water loss due to exposure to air).

Table2: Can Pyrite be listed, too? That is crucial in weathering

We agree, that Pyrite is crucial in weathering. A former study by Littke et al. (1993) was exactly about the strong effect of weathering on pyrite, while organic matter is less affected. However, at depth below 5-10 m pyrite is fresh in the Hils Syncline and not affected by weathering. See also the Burnaz et al. and Wisinghe et al. papers, where sulphur data are presented and discussed for two of our five locations. A dedicated publication is currently prepared that will target detailed mineralogical composition of the Amaltheenton-Fm.

Just optional: Maybe it is still helpful as an estimate for what weathering severeness could be expected when exposed to air, like within a future repository?

L 656: 'properties particular for site selection' – This phrasing suggests a hierarchy of importance. Which property is considered more important than the others, and by whom was this order established? Perhaps the authors mean to say that they 'address those parameters which, in their view, would most severely compromise the repository's suitability if they fall outside a certain range.' If so, that would still require argumentation.

"[...] particular emphasis will be placed on rock properties that directly affect barrier performance of the formation and that might undergo alteration processes along gradual burial and uplift."

This change does not provide a list of what properties are specifically meant and does not provide argumentation why these are "directly affecting". It still seems vague. I suggest to delete it. Otherwise, replace "performance". Do the authors mean "integrity"?