Response to Referee #1

Beyond hydraulic diffusion: reaction front propagation and timescales in metamorphic (de)volatilization processes

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We thank Referee #1 for the careful reading of our manuscript, the accurate summary of its main results, and the positive assessment. We appreciate the constructive suggestions, which have helped us clarify the assumptions, notation, and range of applicability of the analytical solutions. We have revised the manuscript accordingly, as detailed below.

Comment 1: Assumptions and limitations

Referee comment: *The assumptions and limitations of the proposed model need to be stated clearly. For example, the model is only valid if the matrix is rigid. This assumption makes the model useful in the absence of mechanical loading only. This model may also fail if the front profile changes shape (the case where v_{front} is dependent on space) or the reaction presents wave fingers.*

Response: We agree that the principal assumptions and limitations should be stated more clearly. We have therefore added a concise statement at the beginning of Section 2.1 and clarified the existing discussion in Section 4.6.

The revised text states that the analytical solution assumes a one-dimensional, planar, laterally uniform, and sharp reaction front propagating through a stationary solid matrix. The front velocity may vary with time but is uniform along the front. Solid velocity, mechanical deformation, and poromechanical coupling are neglected. Accordingly, the solution is applicable only when mechanical loading does not significantly alter front propagation, porosity, or permeability.

We also state explicitly that hydraulic equilibration is much faster than front propagation, the Darcy flux ahead of the front is negligible, the reaction remains at local thermodynamic equilibrium, and hydraulic properties are uniform within each region. Reaction kinetics, temperature gradients, heat transport, diffusive mass fluxes, gravity, and capillary effects are not included. These assumptions limit the solution to cases in which deformation, variations in front geometry, reaction kinetics, and heat transport do not significantly control front propagation.

Comment 2: Pressure gradient in Equation (9)

Referee comment: *In Equation (9), the gradient is unusual. It should be $\Delta P/\Delta x$, because, in the end, x_{front} and x_{behind} do move.*

Response: We thank the referee for this comment. In the geometry used in the manuscript, the hydraulic boundary is fixed at $x = 0$, whereas the reaction front is located at $x = x_{\text{front}}(t)$. The distance over which the pressure difference acts is therefore $x_{\text{front}}(t) - 0 = x_{\text{front}}(t)$. Thus, $\Delta P/x_{\text{front}}(t)$ in Equation (9) is already the finite-difference approximation $\Delta P/\Delta x$ for the region between the fixed boundary and the moving front.

We also clarify that z_{behind} does not denote the position of a second independently moving boundary. It denotes the one-sided state evaluated immediately behind the same moving sharp front. We have added this explanation after Equation (9) and retained the original equation and notation.

Comment 3: Permeability in Darcy's law

Referee comment: *In Darcy's law, why is k dependent on z_{behind} and not on z_{front} or z_{average}?*

Response: We thank the referee for this question. The permeability is evaluated at z_{behind} because the jump condition uses the Darcy flux on the side immediately behind the reaction front. The flux ahead of the front is assumed negligible because the unreacted region ahead of the front is assumed to be in a state of equilibrium. In the sharp-front approximation, permeability may be discontinuous across the interface, so a unique value exactly at the front is not generally defined.

The closed-form solution further assumes that the reacted region behind the front is hydraulically homogeneous. Consequently, $k(z_{\text{behind}})$ is also the representative permeability of the region across which the quasi-stationary pressure gradient is evaluated. If permeability varied significantly within that region, a spatially effective permeability would be required; this more general case lies outside the assumptions of the present analytical solution. We have added this explanation to the manuscript and retained the original Darcy-law expression and all subsequent formulas.

Comment 4: Properties in the coupled two-front solution

Referee comment: *In many situations, the coupled two-front solution seems to require that density, permeability, and viscosity are all different (see Equations A19–A21), but this is not required. It is sufficient that one of them changes. For example, in the case of gypsum, the density and viscosity of water remain the same at room temperature, but permeability may change significantly.*

Response: We agree that the subscripts in Equations (A19)–(A21) may incorrectly suggest that all the indexed properties must be different. The subscripts identify the corresponding regions; they do not impose inequalities between the property values. In the application to the gypsum experiment, we explicitly assume the same permeability for the two regions. We have added a statement after Equations (A19)–(A20) explaining that any subset of the fluid densities, permeabilities, and viscosities may be equal.

We have also clarified the distinction between the pore-fluid density, ρ_{fluid}, and the total-density jump across a reaction front, $\Delta\rho_{\text{total}}$. The latter includes changes in the solid assemblage and porosity. Thus, during gypsum dehydration, the density and viscosity of liquid water may remain essentially unchanged while the gypsum-to-bassanite reaction still produces a non-zero change in total bulk density.

A non-zero $\Delta\rho_{\text{total},j}$ is required for the particular mass-balance closure derived here. If a transformation changes only permeability while $\Delta\rho_{\text{total},j} = 0$, permeability will modify the fluid flux, but mass conservation alone will not determine the front velocity. An additional closure based, for example, on reaction kinetics, heat transport, or chemical-species transport would then be required. We now state this limitation explicitly.

Comment 5: Typographical errors

Referee comment: *Please check the text for typographical errors. For example, on page 16, "generate a reaction front with a **witdth** of 1 m" should be changed to **width**.*

Response: We thank the referee. We have corrected "witdth" to "width" and carefully proofread the complete manuscript. We corrected several additional grammatical and typographical errors, including "occurring", "monotonically", "results from", and the duplicated "do not".

During this check, we also corrected two equation-level typographical inconsistencies. First, the jump condition in Equation (7) is now written as

$$[-v_{\mathrm{front}}\rho_{\mathrm{total}} + \rho_{\mathrm{fluid}}q_{\mathrm{D}}]_{\mathrm{behind}} = [-v_{\mathrm{front}}\rho_{\mathrm{total}} + \rho_{\mathrm{fluid}}q_{\mathrm{D}}]_{\mathrm{ahead}}\,, \tag{1}$$

consistent with Equation (6) and Equation (A10).

Second, differentiating Equation (17) gives

$$v_{\mathrm{front}} = \frac{\mathrm{d}x_{\mathrm{front}}}{\mathrm{d}t} = \sqrt{\frac{D_{\mathrm{eff}}}{2t}}, \tag{2}$$

and the prefactor in Equation (27) has been corrected accordingly. These corrections do not affect the square-root-of-time scaling, the analytical–numerical comparisons, or the conclusions of the study.

We again thank the referee for the constructive comments and the positive recommendation.