

CoRSEER: The Calculator of Rock Surface Exposure Age and Erosion Rates for Rock Surface Luminescence dating

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MS No.: egusphere-2026-1303

Referee Comments are in black.

The author's comments are in blue.

CoRSEER is exactly what the luminescence community needs right now. It provides much-needed standardisation of the method, but also increases the accessibility of this technique. This is a major step-forward in the technique. The CoRSEER calculator is accompanied by this well explained paper, which shows how much testing has gone into it, which gives confidence to the user. It also acts as somewhat of a reference 'manual' for those less expert in the technique, which is a very useful addition to the literature. With this in mind, I have a few comments below where this paper could provide a little more instruction/guidance on the technique more generally (beyond just CoRSEER) given that it will be such a key reference paper for the technique. The paper identifies and tackles the issues with defining the saturated plateau at depth, providing a solution shown to reduce uncertainties quite dramatically, and presumably improve the accuracy – an important advancement as anyone who has tried to model luminescence depth profiles will know. This is an excellent addition to the literature and luminescence toolkit, and the authors should be commended for all their hard work on developing it. I include a few very minor comments below for the authors to consider.

We acknowledge your efforts in going through the minute details of this work and your very positive, encouraging, and constructive feedback. We appreciate your recognition of CoRSEER as a step forward for standardisation in the luminescence community. Below are our point-by-point responses to your specific comments. We have incorporated all the suggestions in the manuscript and modified the source code accordingly.

Specific Comments:

I may have missed it in the paper, but it would be good to know how the uncertainties are derived for the erosion rates. A short description in Section 3.2 could help.

We acknowledge the referee for this suggestion. Now, we have added the codes to derive uncertainty in erosion rates, which were previously missing.

We have added a plot in CoRSEER III: Erosion Estimation, where the error estimation can be visualised.

Further, we have added a short description in Section 3.2.3 L278 as:

"Furthermore, we perform a Gaussian distribution operation on $\dot{\epsilon}$ column associated with steady erosion onset exposure age (t_{ss})"

The detailed description of error estimation is provided in the Supplementary Section 4.3.2 L321-330

"The main objective was to extract the minimum erosion-onset time at which the best-fit erosion solution becomes stable, and then estimate the representative erosion rate with uncertainty using a Gaussian probability distribution. The analysis was performed using the final misfit/probability matrix generated during the erosion-age modelling step. At first, we search for the best-fitting values in each column associated with each t_s . The unique best-fitting pairs of $\dot{\epsilon}$ and t_s is smoothed using the moving median interpolation method. The algorithm searches for the point where the slope of this line becomes zero, and then the closest matrix associated with that point is chosen for the Gaussian distribution operation to calculate the mean and $\pm 1\sigma$. It must be noted that the in-built parameter to detect the onset time of erosion is adjusted based on the analysed dataset and might fail in some exceptional circumstances. In that case, we suggest using a matrix of the erosion rates, the onset time of erosion and the resulting *norm_chi* can be used to perform the Gaussian probability distribution operation manually. We recommend the user to adjust the limits of erosion and/or increase resolution to enhance the quality of the dataset."

Added the modified results in Section 4.3 L375-L395:

"The CoRSEER-III-derived erosion rates broadly agree with the literature erosion-rate values. The literature erosion rates range from 0.0035 to 4.3 mm/a, whereas the CoRSEER-III-derived erosion rates range from 0.003 to 4.327 mm/a. Using the literature values as reference, the absolute percentage difference ranges from 0.6% to 86.7%. The minimum difference occurs for IR50_MBTP6, where CoRSEER-III gives 4.327 mm/a compared with the literature value of 4.3 mm/a. The largest difference occurs for IR50_MBTP5, where CoRSEER-III gives 0.560 mm/a compared with the literature value of 0.300 mm/a.

The uncertainty associated with CoRSEER-III-derived erosion rates remains within a reasonable range for most samples. The relative upper error in the CoRSEER-III erosion rates varies from 10.8% to 44.9%, whereas the relative lower error varies from 10.8% to 33.3%. The lowest relative uncertainty occurs for IR50_MBAM2, where the erosion rate is 0.037 mm/a with an uncertainty of approximately $\pm 10.8\%$. The highest upper uncertainty occurs for IR50 BALL02, where the upper error reaches

approximately 44.9%. These values show that the algorithm provides bounded erosion-rate estimates rather than single manually selected solutions.

In contrast, the erosion-onset time, t_{ss} , shows a considerably larger departure from the literature values. The literature t_{ss} values range from 4 to 3146 a, whereas the CoRSEER-III-derived t_{ss} values range from 3 to 3080 a. Using the literature values as reference, the absolute percentage difference ranges from 18.0% to 64.1%. In most samples, CoRSEER-III estimates a younger erosion-onset time than the literature value. The only exception is IR50_MBTP1, where CoRSEER-III gives a larger onset time of 3080 a compared with the literature value of 2610 a, corresponding to an increase of approximately 18.0%. The maximum difference occurs for IR50_MBTP5, where CoRSEER-III estimates 23 a compared with the literature value of 64 a, corresponding to a reduction of approximately 64.1%.

Overall, the results indicate that CoRSEER-III reproduces the erosion-rate field reasonably well, as presented in Table 5, but it estimates erosion-onset time differently from the literature. This difference is expected because the CoRSEER-III estimate is derived from an automated best-fitting erosion-time slope detection algorithm, whereas previous studies relied more strongly on manual or interpretative selection of model solutions."

We modified the discussion accordingly in Section 5.4 L479-488:

"One of the most important observations is that CoRSEER-III captures the same broad erosion-rate scale as the literature values. This indicates that the erosion-rate extraction algorithm is able to preserve the first-order structure of the erosion solution space. In practical terms, this is encouraging because the algorithm avoids subjective manual picking while still recovering erosion-rate estimates comparable to previous studies. This is also a possible reason for the large relative difference between CoRSEER and literature results in a few cases. Thus, for maximum accuracy and precision, we recommend following the guidelines. The users should not run the model once over a very large erosion-exposure window and treat the result as final. A better strategy is to run the model in multiple stages. First, use a broad search window to identify the approximate high-likelihood region. Then shrink the exposure-erosion window around that region. Finally, increase the matrix density so that the best-fitting slope is resolved with higher numerical precision. This stepwise refinement should reduce grid artefacts and improve the stability of both erosion-rate (and errors) and onset-time estimates."

In Section 3.2, please could you also explain to the reader why you provide the median alongside the best fit. What use could it have, in addition to the best fit?

The best-fit value represents the highest-probability or least-misfit solution, whereas the median represents the central value of the accepted parameter after the Bayesian approach. Ideally, both values should be the same. If the matrix resolution is low or the input range is too broad or the input parameter range is biased toward higher or lower values, the median may deviate substantially from the best-fit value. Therefore,

we report both values, use the best-fit value for subsequent calculations, and ensure that the best-fit and median values remain close in the final analysis.

We have added a sentence in Supplementary Section 4.1.2 L193-197 as:

"It must be noted that both the best fitted value and median of accepted values after the Bayesian approach should, ideally, overlap with each other. However, if the matrix resolution is low or the input range is too broad or the input parameter range is biased toward higher or lower values, the median may deviate substantially from the best-fit value. Thus, for precise and accurate output, the input calibration parameter range and the number of pairs must be adjusted in such a way that the best-fit and median should be closest to each other"

The landform dated in Smedley et al. (2021) was a rock avalanche, not just an avalanche. It's worth saying this explicitly.

We have updated all references from "avalanche" to "rock avalanche" throughout the manuscript.

Line 296 – Given the importance of using the GOK for fitting luminescence depth profiles determined for feldspar, it would be useful to add a few words to the end of the sentence to emphasise this to the reader. For example, "However, CoRSEER has the flexibility of using $r > 1$, which is important when fitting data derived from feldspar that is not described by first order kinetics". Or something similar that you would advise.

Thank you for the suggestion. We have added the sentence shown in the line L310-310.

"However, CoRSEER has the flexibility to use $r > 1$, which is important when luminescence depth profiles are derived using feldspar IRSL, which follows non-FOK behaviour."

Section 5.2 – this section provides some recommendations on the age of the sample used for calibration (i.e. younger is better as they will have been subjected to less erosion). However, it does not mention anything about the factors that can influence the attenuation rate (μ) or σ_{ϕ} . Given that this paper is likely to be a key reference for the community in this technique, it is worth using a short paragraph to emphasise the importance of rock opacity, surficial coatings, aspect and other factors on μ and σ_{ϕ} (e.g. Luo et al. 2018; Meyer et al. 2018; Ou et al. 2018; Smedley et al. 2021, 2025; Fuhrmann et al. 2022; Cui et al. 2024). It would be good to make sure that the reader understands the importance of ensuring that the characteristics controlling μ and σ_{ϕ} of the calibration sample are identical to the unknown sample.

Literature review in the context on what factors affect the sigma phi and mu in context of rock opacity, surficial coating, aspect (Solar insolation) and many more. That means

We appreciate your suggestion and understand the necessity to add a section discussing these micro and macro factors influencing the calibration.

We have added a new paragraph in Section 5.2 L444-455 as:

"When selecting a calibration sample, it is critical to recognise that the light attenuation coefficient (μ) and the effective detrapping rate at the surface ($\overline{\sigma\varphi_0}$) of the calibration samples are the best representatives of the actual sample. Recent empirical studies demonstrate that photon penetration and attenuation are highly sensitive to micro-mineralogical heterogeneity, such as the spatial distribution of opaque and translucent minerals, which can cause localised 'light piping' or 'shadowing' (Meyer et al., 2018; Cui et al., 2024). Furthermore, μ is strongly wavelength-dependent and can be drastically altered over time by dynamic surficial boundary conditions, including the accretion of rock varnish (Luo et al., 2018) or localised iron-hydroxide precipitation due to moisture (Meyer et al., 2018; Smedley et al., 2021). The effective detrapping rate ($\overline{\sigma\varphi_0}$) is similarly sensitive to external environmental geometries, fluctuating significantly based on the target surface's topographic aspect, inclination, and seasonal solar incidence angles (Fuhrmann et al., 2022). High-resolution spatial analyses reveal that these optical properties can vary significantly even on a sub-millimetre scale within contiguous rock formations (Ou et al., 2018; Smedley et al., 2025). Consequently, to avoid severe systematic chronological errors, it is imperative to ensure that the optical characteristics, dynamic surficial coatings, and spatial orientation governing μ and $\overline{\sigma\varphi_0}$ in the calibration sample, the measurements are meticulously matched to those of the unknown target sample."

Section 5.4 is quite short. Could you further comment on whether CoRSEER improves accuracy and precision of erosion rates? Expand more on deriving transient erosion rates.

We have appended discussion section 5.4 L479-488, which is already mentioned in earlier comments, emphasising accuracy and precision in presenting the limitations associated while deriving transient erosion rates.

Line 356 – space missing.

Done

Consistency of "CoRSEER" vs "CoRSEr". (Standardised to CoRSEER).

Done

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This is a well-written paper that provides valuable tools for luminescence-based exposure dating. The tests against previously published datasets are convincing and demonstrate that the tool produces reliable results consistent with the current state of the art. I have only a few minor comments, which are included in the annotated PDF.

We are happy to see the positive comments on our manuscript and on the tool's utility. Also, we are much obliged to the referee for their keen observations and constructive comments throughout this manuscript. Here, we provide point-by-point feedback for each comment.

L9: Rock surface dating is also used for burial dating. Not a part of this study, but I'd still call it rock-surface luminescence exposure dating for clarity's sake.

We agree that the previous nomenclature could be confusing. Therefore, we have revised the terminology to "luminescence rock surface exposure dating" (LRSED) and have implemented this change consistently throughout the manuscript.

L10: think this sentence needs rephrasing. 1) subjective plateau selection and different models are not "practical issues". Also, how have these issues limiting subsequent studies? 2) I think this phrasing overemphasise the challenges this study aims to correct in relation to other (in my opinion much larger) issues with exposure dating: e.g., finding good calibration samples, measuring representative depth-profiles, finding good lithologies that both bleach and have a signal, for eroding surfaces - what is the actual exposure age etc,...

Thanks for the thoughtful comment. We admit that this manuscript addresses mathematical analysis limitations rather than practical limitations.

We have made the necessary changes as shown in L10-12:

"The wider use of this method has been slowed by limitations in mathematical analysis, such as: the subjective selection of the deep plateau for profile normalisation, inconsistent modelling choices across studies, and the lack of a unified inverse-modelling workflow that delivers both parameter estimates and uncertainty bounds".

We also added this paragraph in the discussion section in L405-408 as:

"Although this method is affected by broader challenges such as availability of calibration samples, representative luminescence depth-profile selection, lithological suitability, and independent exposure-age constraints, additional methodological uncertainty can arise from subjective plateau selection and the use of non-standardised modelling approaches."

L42: This sentence reads very awkwardly.

The sentence has been changed and shown in L41-L45.

"Generally, there are two major reconstruction scenarios: (i) Establishing the exposure ages of host rocks (e.g., valley walls, bedrock, or strath surface) that can predict the age of the natural (e.g., deglaciation) and anthropogenic (e.g., stripping of regolith and quarrying) events that creates an freshly exposed surface (Owen and

Dortch, 2014; Gliganic et al., 2019). (ii) The transportation, deposition, and reworking histories of transportable clasts, such as cobbles and boulders (Luo et al., 2018)"

L46: "Furthermore"?

Complied

L68: Sohbaty et al., 2018?

We have added the citation.

L90: Please elaborate on how this erosion model is different from Sohbaty et al. 2018 and Freiesleben et al. 2023.

Both models, Sohbaty et al. (2018), which was further incorporated into Freiesleben et al. (2023) and Lehman et al. (2019a), incorporate erosion into the exposure history, are mathematically correct, but their handling approaches differ. The Sohbaty et al. (2018) model alters the depth term (based on erosion) in the equation, and the current model (Lehman et al., 2019) incorporates the erosion effect independently as advection. We find the current model is easier to solve numerically.

Lehman et al. (2019a) compared both approaches and found similar results.

L93: I'd definitely rephrase this to something softer than "far from accurate", especially since you demonstrate your tool further down using FOK.

We have softened the statement in L92-93 as:

"However, in the case of polymineral or feldspar samples, where the infrared stimulated luminescence (IRSL) of feldspar minerals exhibits non-first-order decay, the GOK model is more suitable for these samples."

L98: open parenthesis

Corrected

Section 2.4: I think this section would benefit from making crystal clear what improvement came from which study, elaborate on how these models are

improvement over previous ones, and then give an overview on what will be included into Corseer.

Thanks for the suggestion. We have appended the paragraph in L108-114 and clearly stated the contribution, such as:

"Lehmann et al. (2019a) introduced the advection term in response to erosion as $\dot{\epsilon} \frac{d\bar{n}}{dx}$ but for the FOK ($r = 1$) in addition to earlier models. This model can be solved with the finite-difference method with a second-order upwind scheme for the advection term rather than altering the depth term (Sohbati et al., 2018). Furthermore, Biswas et al. (2023) modified this model for a zero erosion scenario by incorporating GOK ($r > 1$) in the decay term and demonstrated the severe underestimation of the exposure age if FOK was used. Pathan et al. (2024) solved the GOK model (Eq. 15) for a non-zero erosion scenario and reported an overestimation of the erosion rate when FOK was used. Thus, we incorporate the most recent model, as in Eq. 15, into the mathematical framework of CoRSEER."

L104: "The modeling framework adopted in this study brings together key components that have not previously been combined within a single model."

Complied.

We have made changes as shown in L104-106:

"The modelling framework adopted in this study brings together the current understanding of rock-surface luminescence signal evolution within a single computational framework. It includes: (1) general-order kinetics, (2) advection through the natural mechanism of erosion, and (3) ambient dose-rate-driven signal accumulation."

L105: You don't really explain why this erosion model is more realistic.

Please see the answer to the previous comment.

L105: I think it would make sense to elaborate here.

The sentence has been changed to (L104-106)

"The modelling framework adopted in this study brings together the current understanding of rock-surface luminescence signal evolution within a single computational framework. It includes: (1) general-order kinetics, (2) erosion through the natural mechanism of advection, and (3) dose-rate-driven signal accumulation."

L106: Please elaborate.

The sentence has been changed to (L104-110)

"The modelling framework adopted in this study brings together the current understanding of rock-surface luminescence signal evolution within a single computational framework. It includes: (1) general-order kinetics, (2) erosion through the natural mechanism of advection, and (3) dose-rate-driven signal accumulation. This formulation was required to simulate the luminescence-depth profile more accurately and builds upon earlier work by Lehmann et al. (2019a), Biswas et al. (2023), and Pathan et al. (2024). Lehmann et al. (2019a) introduced the advection term in response to erosion as $\dot{\epsilon} \frac{d\bar{n}}{dx}$ for the FOK ($r = 1$) in addition to earlier models. This model can be solved with the finite-difference method with a second-order upwind scheme for the advection term rather than altering the depth term (Sohbati et al., 2018)."

L114: Did both studies provide separate improvements regarding the inclusion of GOK?

Biswas et al. (2023) applied the GOK model for a non-erosion scenario, whereas Pathan et al. (2024) applied the GOK model in the presence of an erosion scenario. We have modified the text at the beginning of Section 2.4.

L118: Maybe provide some examples from aforementioned studies of how it improved.

We have elaborated the section. Please see L104-L114.

Section 3.1: Could you please elaborate on why this logistic pre-fitting step is preferable to allowing the model to define the saturation limit directly? Is the normalisation to 1 really necessary?

Normalisation is necessary because the forward equation (Eq. 15) is solved on a relative luminescence scale, where the maximum field-saturated signal at depths beyond light penetration is set to 1. Experimentally, the test-dose-corrected luminescence intensity (L_x/T_x) at the saturation plateau may vary between samples

and measurement conditions. Therefore, each LDP must be normalised to its plateau value before mathematical comparison and modelling.

In all previous studies, this plateau value was estimated subjectively by visually selecting the saturated region and taking its mean value, which can introduce user-dependent bias. Here, we provide an objective logistic pre-fitting approach to calculate the plateau value, remove manual intervention, which improves the results, as shown in Fig. 2d and e.

L165: Meaning the normalised L_x/T_x points?

No, it's the simulated luminescence depth profile using best sigmoidal fitting, a , b and c parameters.

L188: Is this really fair to describe this as an error though? The kinetic parameter the normalisation is scaled to is the field-saturated, test-dose corrected luminescence intensity, correct? Does your SCF normalisation really accurately constrain this kinetic phenomenon? Isn't your argument that using the SCF that makes the modeling more reproducible and comparable, which ultimately makes comparing calibration profiles and their corresponding unknown age/erosion more accurate?

The SCF normalisation does not directly constrain the kinetic saturation process; rather, it provides an objective estimate of the field-saturated plateau value. By reducing user-dependent subjective plateau selection, this procedure improves the reproducibility and comparability of calibration and unknown-age luminescence-depth profiles, thereby supporting more consistent apparent-age and erosion-rate estimation.

Figure 2e: I'd include a legend here even if the colour coding conforms with Fig 2D

Thanks, the legend is added.

Figure 3: Is it just for me or does this figure look blurry? Please check.

The figure has been updated to a high-resolution format.

L272: This sentence is awkward. Please rephrase.

Yes, we have changed it to in L282-287:

"If the t_{app} of a sample is much lower than the expected age as observed for IR50_BALL02, the LDP is in a steady state. To derive the erosion rates, the model should run for t_{max} . But, if the true exposure age is known by independent means, we suggest running the model for that exposure age."

L289: calibration

Complied

L290-293: "and and and" in Section 4

Corrected

L336-338: Is it corrected that Brill et al actually used Corseer for their own analysis or is this a typo?

Thank you for pointing it out. It was a typo.

We have corrected this in L350-353 as:

"For Brill et al. (2021), we use CoRSEER-I to evaluate the parameters of IR50_RAB 5-1 CAL for the samples of IR50_RAB 1-1, IR50_RAB 1-2, and IR50_RAB 5-1 (these samples were evaluated using IR50_HAR 1-1 CAL I in the literature due to the large uncertainty in IR50_RAB 5-1 CAL)."

L357: missing space

The paragraph is modified in revision.

L392: missing parenthesis

Corrected.