

Fault-aware local correction framework for stratigraphic surface reconstruction under geological discontinuities

Rong Wang

China University of Mining and Technology - Beijing

Donglin Dong

ddl@cumtb.edu.cn

China University of Mining and Technology - Beijing

Zhao Yang

China University of Mining and Technology - Beijing

Yuqi Chen

China University of Mining and Technology - Beijing

Enyu Zhang

China University of Mining and Technology - Beijing

Research Article

Keywords: Stratigraphic surface modeling, Fault-aware correction, Fault displacement, Geostatistics, Geological constraints

Posted Date: September 11th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10873240/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Fault-aware local correction framework for stratigraphic surface reconstruction under geological discontinuities

Rong Wang¹, Donglin Dong^{1*}, Zhao Yang¹, Yuqi Chen¹, Enyu Zhang¹

1 China University of Mining and Technology (Beijing), Ding No. 11 Xueyuan Road, Haidian District, Beijing 100083, China

***Corresponding author**

Donglin Dong

Professor

China University of Mining and Technology (Beijing), Ding No. 11 Xueyuan Road, Haidian District, Beijing 100083, China

E-mail: ddl@cumtb.edu.cn

ORCID: 0000-0001-6404-0800

Telephone: +86 180 9832 7637

Abstract

Accurate reconstruction of stratigraphic surfaces remains challenging in regions affected by geological discontinuities. Conventional interpolation methods often assume spatial continuity and may smooth fault-related offsets. This study proposes a fault-aware local correction (FLC) framework for stratigraphic surface reconstruction under discontinuous geological conditions. The framework generates a continuous reference surface using universal kriging and introduces local corrections within fault-controlled zones. Fault displacement, asymmetric displacement partitioning, and distance-decay weighting are integrated to improve local accuracy while preserving unchanged areas outside the correction zone. The framework was evaluated using a real coalfield dataset and two synthetic experiments with known fault displacements. Independent validation and ablation analysis were conducted to assess accuracy and component contributions. Results show that FLC reduced the validation RMSE from 41.33 m to 36.60 m and improved

R^2 from 0.767 to 0.817 compared with the reference surface. Synthetic experiments further demonstrated improved reconstruction near discontinuities while maintaining regional surface stability. The proposed framework provides a geological constraint-based strategy for stratigraphic surface reconstruction under sparse subsurface observations.

Keywords

Stratigraphic surface modeling; Fault-aware correction; Fault displacement; Geostatistics; Geological constraints

1 Introduction

Fault-controlled stratigraphic surface reconstruction is an important problem in computational geoscience and subsurface modeling. Accurate surface reconstruction supports geological interpretation, resource evaluation, and engineering applications where subsurface observations are limited. Recent studies in computational geoscience have explored constrained geological surface prediction by integrating additional geological information into interpolation frameworks [29, 30]. Faults introduce abrupt spatial discontinuities, displacement offsets, and complex structural relationships that challenge conventional surface estimation methods [7, 8, 28]. In coal mine planning, reliable stratigraphic surfaces are required for coal seam boundary delineation, roadway design, and hazard assessment. However, modeling accuracy near faults and stability in unaffected regions represent two conflicting requirements. Improving predictions within fault-affected areas should not introduce artificial variations into regions where the geological surface remains unchanged [12].

Traditional geostatistical methods, such as universal kriging, are widely used for geological surface reconstruction because they provide statistically optimal estimates under defined spatial assumptions [16, 22, 27]. Recent advances in geological modeling algorithms have explored constrained geological surface prediction by integrating additional geological information into interpolation frameworks [29,30]. However, these methods generally assume spatial continuity and may smooth fault-related offsets when applied directly to discontinuous geological environments [21]. To overcome this limitation, previous studies have developed various fault-aware modeling strategies, including fault-constrained interpolation, displacement-based correction, and explicit or implicit structural reconstruction approaches [3, 10, 11, 32]. Computational methods have also been applied to extract geological structures and characterize spatial features from geological datasets [2, 13]. These approaches improve the representation of fault discontinuities under specific geological assumptions and data conditions. However, many

methods modify the entire modeling domain or require detailed geometric information that is often unavailable in practical subsurface applications. Therefore, a key computational challenge remains: how to introduce corrections within fault-affected regions while preserving the original interpolation surface outside these regions.

The localized influence of faults provides an alternative perspective for discontinuity-aware surface reconstruction. Fault displacement, damage-zone extent, and structural architecture vary with fault scale, lithology, and deformation history [8, 20, 28]. Under sparse subsurface observations, complete geometric reconstruction of fault systems is often difficult. Instead, fault effects can be represented as local geological constraints imposed on a stable regional surface. This strategy is suitable for cases where fault information is incomplete and where maintaining the reliability of non-faulted regions is equally important as improving predictions near discontinuities [3, 18]. The central issue is therefore not only how to reproduce fault-related offsets, but also how to define the spatial extent and intensity of local corrections.

In this study, a fault-aware local correction framework (FLC) is proposed for stratigraphic surface reconstruction under geological discontinuities. The framework uses a universal kriging surface as the reference surface and introduces corrections only within a predefined local correction zone. The correction zone is determined by fault displacement, dip, and lithological proxy information. The correction magnitude is controlled by fault-side information, asymmetric displacement partitioning, and distance-decay weighting. A zero-perturbation constraint is applied outside the correction zone to preserve unaffected regions [12, 16, 24]. The main contributions of this study are as follows: (1) A geological constraint-based local correction framework is developed to incorporate fault-related discontinuities into stratigraphic surface reconstruction without modifying unaffected areas. (2) The proposed framework is evaluated using a real coalfield dataset from the Banji Coal Mine and two synthetic experiments with predefined fault displacements. (3) An ablation analysis is conducted to quantify the contributions of asymmetric displacement partitioning and distance-decay weighting. The results demonstrate the applicability and limitations of the proposed framework for discontinuity-aware geological surface modeling under sparse subsurface constraints.

2 Methodology

2.1 Method overview

The proposed FLC framework is designed to improve stratigraphic surface prediction near faults while preserving the stability of non-faulted areas. The workflow starts from a baseline stratigraphic surface generated by universal kriging.

Fault attributes are then used to define a local correction zone. Within this zone, fault-side information, asymmetric displacement partitioning, and distance-decay weighting are used to construct a spatially restricted correction field. Outside the local correction zone, the correction weight is set to zero. The corrected surface is therefore identical to the baseline surface outside the fault-affected area. The framework contains four main steps: baseline surface construction, local correction zone definition, fault-aware correction, and validation. The workflow is shown in Fig. 1.

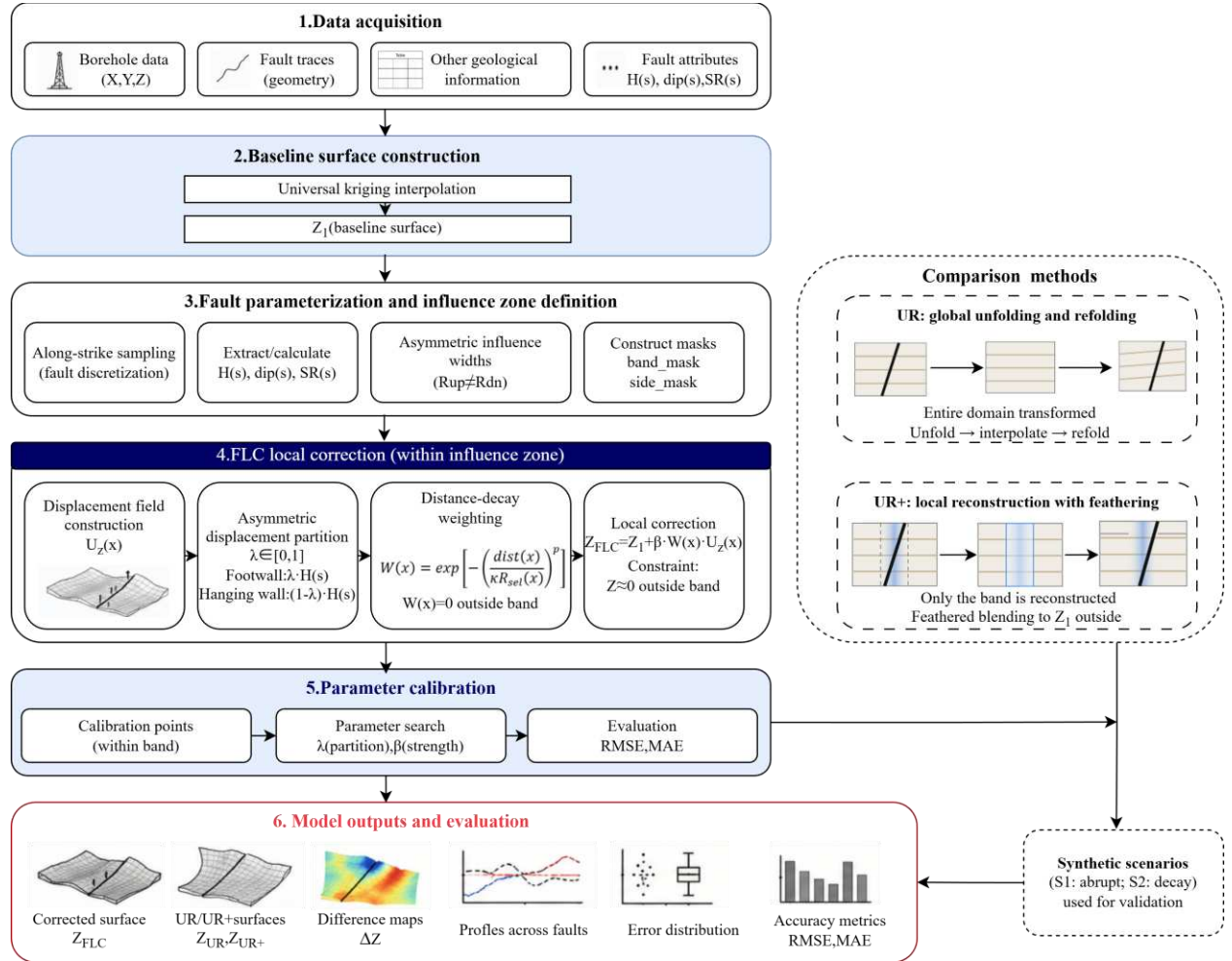


Fig. 1 Workflow of the proposed FLC framework and the localized UR+ comparison strategy

2.2 Construction of the baseline stratigraphic surface

A baseline stratigraphic surface, denoted as Z_1 , is first generated from borehole data using universal kriging. This surface represents the regional structural trend before fault-aware correction. It also serves as the fixed reference surface for all subsequent correction and comparison experiments. The baseline surface can be expressed as:

$$Z_1(x) = UK(x; D_b), \quad (1)$$

where x is a grid location, D_b is the borehole dataset, and $UK(\cdot)$ denotes universal kriging. Universal kriging is used because it can estimate a continuous surface from sparse borehole observations while considering a regional drift [17][22]. In this study, a spherical variogram model and a regional linear drift term are used. The detailed interpolation parameters are provided in Supplementary Table S4.

2.3 Definition of the local correction zone

The local correction zone defines the spatial range where fault-related modification is allowed. It is constructed along the mapped fault trace using fault displacement, fault dip, and lithologic proxy variables [20, 28]. These variables are used to estimate the correction width on the hanging-wall and footwall sides. The resulting zone mask determines whether a grid cell can be corrected. A side mask identifies whether each grid cell belongs to the hanging wall or the footwall. For a grid location x , the local correction zone can be defined as:

$$\Omega_c = \{x \mid d(x, F) \leq R_s\}, \quad (2)$$

where Ω_c is the local correction zone, $d(x, F)$ is the shortest distance from x to the fault trace F , and R_s is the side-dependent correction width. When the correction width differs between the two sides of the fault, R_s is assigned according to the fault-side mask. The local correction zone is used as a hard spatial constraint. Correction is only allowed within Ω_c . Grid cells outside Ω_c are not modified. This design prevents fault-related correction from propagating into stable non-faulted areas.

2.4 Fault-aware local correction

Within the local correction zone, FLC treats fault-related deformation as a spatially restricted perturbation added to the baseline surface. The corrected stratigraphic surface is defined as:

$$Z_{FLC}(x) = Z_1(x) + \beta W(x) U_z(x), \quad (3)$$

where $Z_{FLC}(x)$ is the corrected surface, $Z_1(x)$ is the baseline surface, $U_z(x)$ is the fault-related vertical displacement field, $W(x)$ is the distance-decay weight, and β is the correction intensity. The distance-decay weight controls how the correction decreases away from the fault trace. It is defined as:

$$W(x) = \begin{cases} \left(1 - \frac{d(x, F)}{R_s}\right)^p, & x \in \Omega_c, \\ 0, & x \notin \Omega_c \end{cases} \quad (4)$$

where p controls the decay shape. The weight is close to 1 near the fault trace and decreases to 0 at the boundary of the local correction zone. Because $W(x) = 0$ outside Ω_c , the corrected surface satisfies:

$$Z_{FLC}(x) = Z_1(x), x \notin \Omega_c. \quad (5)$$

This zero-perturbation condition is a key constraint of the FLC framework. The displacement field $U_z(x)$ is assigned according to the fault side. The parameter λ controls the displacement partitioning between the hanging wall and the footwall:

$$U_z(x) = \begin{cases} \lambda H, & x \in \text{footwall} \\ -(1 - \lambda)H, & x \in \text{hanging wall} \end{cases} \quad (6)$$

where H is the fault displacement and λ is the displacement partitioning parameter. A value of $\lambda = 0.5$ represents symmetric displacement partitioning. Values different from 0.5 allow asymmetric displacement partitioning. This is important because deformation near faults is often not evenly distributed on the two sides.

2.5 Parameter calibration and model validation

The correction parameters are calibrated using parameter-calibration points inside the local correction zone. These points are not used as independent validation points. The calibration objective is to minimize the prediction error between the corrected surface and the observed stratigraphic elevations. The parameter calibration can be written as:

$$\theta^* = \arg \min_{\theta} RMSE[Z_{FLC}(x_i; \theta), z_i], x_i \in D_{cal}, \quad (7)$$

where θ denotes the calibrated parameter set, D_{cal} is the parameter-calibration dataset, x_i is a calibration point, and z_i is the observed elevation. In the real-case experiment, the correction intensity β and the displacement-partitioning factor λ are jointly calibrated by grid search over the parameter-calibration points. In the synthetic experiments, both λ and β are searched to examine model behavior under controlled conditions. After calibration, the parameters are fixed. The model is then evaluated using independent validation points. These validation points are not involved in parameter calibration. Model performance is assessed using RMSE, MAE, ME and R^2 . RMSE and MAE measure prediction error. ME indicates bias. R^2 measures the agreement between predicted and observed elevations [5, 31].

2.6 Comparison methods and ablation design

Several comparison methods are used to evaluate the behavior of FLC. The first comparison surface is the baseline universal kriging surface Z_1 . It represents the result without fault-aware local correction. The second comparison

method is an unfolding-refolding strategy, denoted as UR. This method represents a geometric reconstruction approach. A localized variant, denoted as UR+, is also tested. UR+ restricts geometric reconstruction to the local correction zone and blends the reconstructed surface back to the baseline surface near the zone boundary. An ablation analysis is conducted to examine the roles of key FLC components. The full FLC model includes asymmetric displacement partitioning and distance-decay weighting. The symmetric variant fixes λ at 0.5. This variant tests whether equal displacement partitioning between the two fault sides is sufficient. The no-decay variant removes the distance-decay weighting and applies a uniform correction weight inside the local correction zone. This variant tests whether the decay term improves prediction or mainly acts as a geological regularization term. The ablation comparison was therefore interpreted from two perspectives: point-based validation accuracy and spatial regularity near the correction-zone boundary. All ablation variants are calibrated using the same parameter-calibration points. They are evaluated using the same independent validation points. This design allows the influence of each FLC component to be compared under consistent data conditions. Detailed ablation settings and supplementary results are provided in Supplementary Notes S1-S4.

3 Study area and data

The proposed FLC framework was evaluated using a real engineering geological case from the Banji Coal Mine. The study area is located in a fault-controlled coal mining setting. Faults in this area disturb the spatial continuity of the target stratigraphic surface and increase the uncertainty of interpolation from sparse borehole data. Accurate reconstruction of this surface is important for coal seam boundary delineation, roadway layout, and geological hazard assessment. The roof of the Taiyuan Formation was selected as the target stratigraphic surface. Borehole data were used to construct the baseline surface Z_1 . Fault traces and fault attributes were used to define the local correction zone and the fault-side mask. Additional observed points were divided into parameter-calibration points and independent validation points. The calibration points were used to estimate the FLC correction parameters. The validation points were used only for independent accuracy assessment. The spatial distribution of boreholes, faults, calibration points, and validation points is shown in Fig. 2. The input datasets and their roles are summarized in Table 1. This separation between calibration and validation data was used to avoid validation-data leakage during parameter calibration.

Table 1 Input datasets and their roles in the real-case experiment

Dataset	No.	Main role	Baseline construction Z_1	FLC constraint	Parameter calibration	Independent validation
Borehole points	79	Construction of the baseline Z_1 surface	Yes	No	No	No
Fault traces	21	Definition of fault geometry and correction-zone location	No	Yes	No	No
Fault attributes	12	Estimation of correction-zone width and displacement field	No	Yes	No	No
Calibration points	131	Calibration of correction parameters	No	No	Yes	No
Validation points	40	Independent accuracy assessment	No	No	No	Yes

4 Results

4.1 Baseline surface and local correction zone

The universal kriging surface Z_1 was used as the baseline stratigraphic surface. It represents the regional trend of the roof of the Taiyuan Formation before fault-aware correction. However, because Z_1 is generated as a continuous interpolation surface, it tends to smooth fault-related displacement effects near the fault trace. This smoothing can produce large local errors in the fault-affected area. The local correction zone was constructed around the mapped fault trace. This zone defines where fault-related modification is permitted. Grid cells outside this zone remain unchanged during FLC correction. The side mask was used to distinguish the hanging-wall and footwall sides. It controls the direction and partitioning of the fault-related correction. Fig. 3 shows the baseline surface, the local correction zone, and the fault-side mask. The correction zone is spatially limited around the fault trace. This confirms that the following FLC correction is restricted to the fault-affected area.

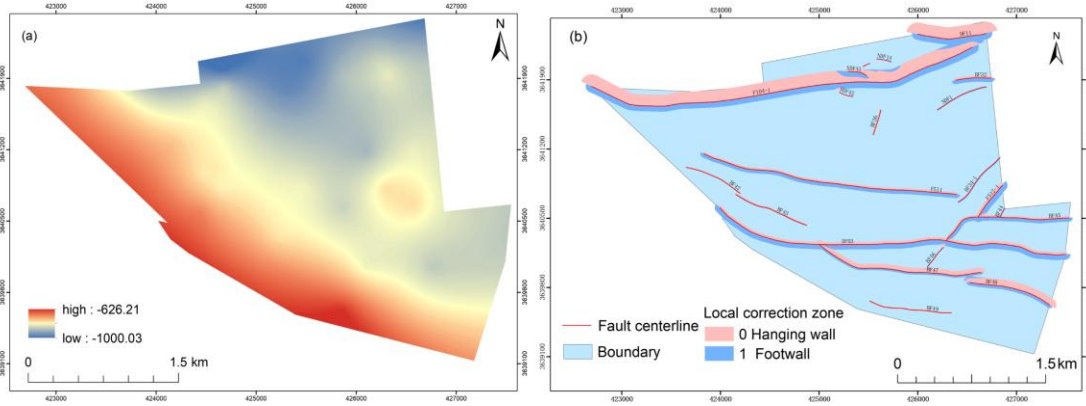


Fig. 3 Baseline stratigraphic surface and spatial constraints for FLC correction. (a) Universal kriging baseline surface Z_1 . (b) Fault-side mask used for asymmetric displacement partitioning

4.2 Real-case calibration and surface correction

4.2.1 Parameter calibration of FLC

The two key FLC parameters, the displacement partitioning factor λ and the correction intensity β , were calibrated by grid search using the 131 parameter-calibration points within the local correction zone. The parameter λ defines the proportion of interpreted fault displacement used for local correction. The parameter β controls the correction strength within the fault influence zone. As shown in Fig. 4, the RMSE surface contains a clear low-error region, rather than an isolated minimum. This suggests that the calibrated parameters are not caused by numerical instability. The lowest calibration RMSE was obtained at $\lambda = 1.00$ and $\beta = 0.37$, with an RMSE of 32.97 m. The MAE surface gave a slightly different calibration optimum, at $\lambda = 0.95$ and $\beta = 0.38$. However, MAE remains stable near the RMSE-optimal setting, while RMSE is more sensitive to large local errors near faults. Therefore, $\lambda = 1.00$ and $\beta = 0.37$ were selected as the final FLC parameters. This choice gives priority to reducing large fault-zone errors while maintaining a comparable mean absolute error. The one-dimensional profiles support this selection. When $\lambda = 1.00$, RMSE reaches its minimum near $\beta = 0.37$. When $\beta = 0.37$, RMSE decreases as λ approaches 1.00. This indicates that the full interpreted displacement should be used in the local correction. A moderate correction intensity is also needed to avoid excessive adjustment outside the fault-controlled zone. A sensitivity analysis was further conducted to test the robustness of the calibrated setting. Two fault-related attributes were perturbed: interpreted fault displacement and correction-zone width. The perturbation factors ranged from 0.8 to 1.2, representing $\pm 20\%$ uncertainty. As shown in Fig. 5, validation errors are weakly affected by changes in fault displacement. RMSE remains

almost unchanged over the tested range. In contrast, correction-zone width has a stronger effect on validation performance. This indicates that the spatial extent of correction is more important than moderate uncertainty in displacement magnitude. The two-dimensional perturbation surface also shows that the reference setting lies within a stable low-error region. The cell marked Ref. in Fig. 5(c) represents the unperturbed setting, where both the displacement scale and correction-zone width scale equal 1.0. Overall, the calibrated FLC parameters are robust to moderate uncertainty in fault interpretation. However, the correction-zone width should be carefully defined to ensure reliable predictions near faults.

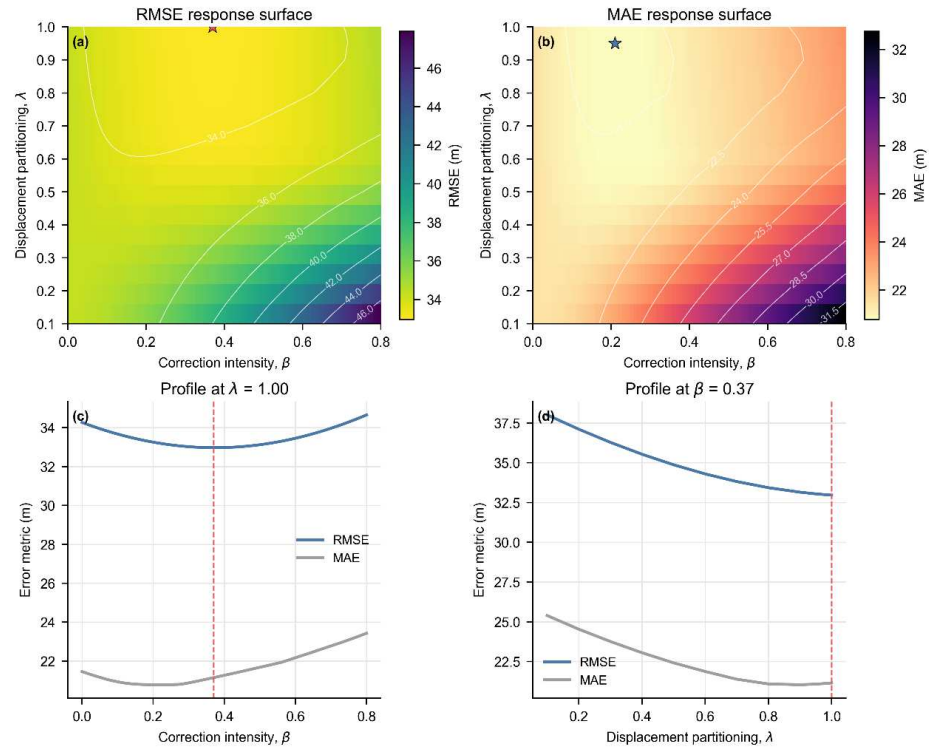


Fig. 4 Sensitivity of validation errors to FLC parameters (λ and β): response surfaces and one-dimensional profiles. (a) RMSE response surface; (b) MAE response surface; (c) RMSE and MAE profiles with λ fixed at 1.00; (d) RMSE and MAE profiles with β fixed at 0.37

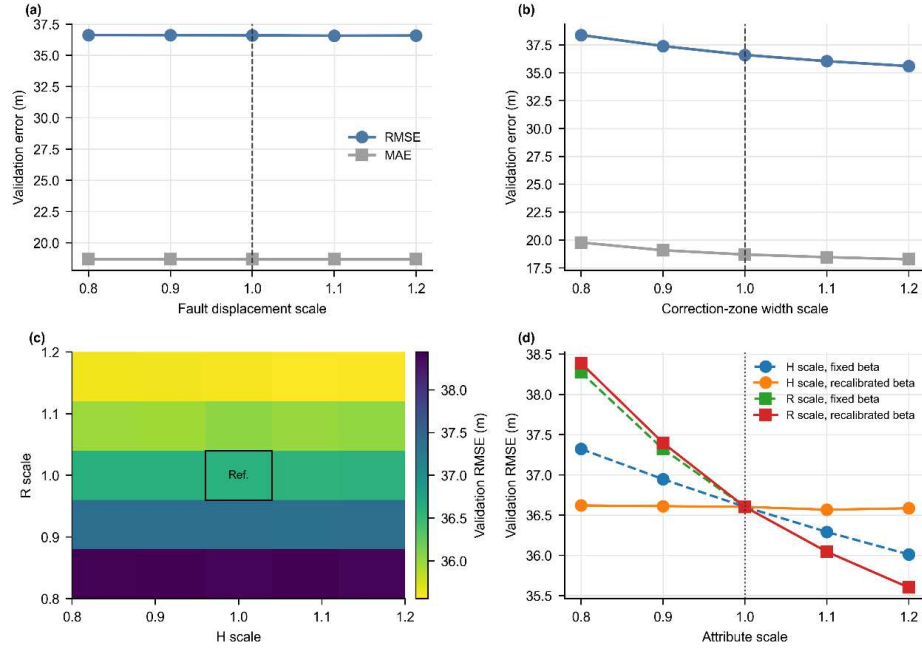


Fig. 5 Sensitivity of FLC validation performance to perturbations in fault displacement and correction-zone width. (a) Validation RMSE and MAE under fault-displacement scaling. (b) Validation RMSE and MAE under correction-zone-width scaling. (c) Validation RMSE under combined perturbations of fault displacement and correction-zone width. (d) Comparison between fixed-beta and recalibrated-beta responses

4.2.2 Corrected surface and local correction field

In this study, zero perturbation outside the local correction zone was imposed as a hard constraint, and its validity was directly evaluated using the difference field. Fig. 6 shows the spatial distribution of ΔZ . The results indicate that the differences are concentrated mainly within the local correction zone and gradually decay with increasing distance from the fault. Outside the zone, ΔZ remains close to zero, indicating that the FLC correction does not introduce overall drift into non-faulted areas. This difference-field analysis provides direct spatial evidence that the method achieves its intended design objective of local improvement with outside-zone preservation.

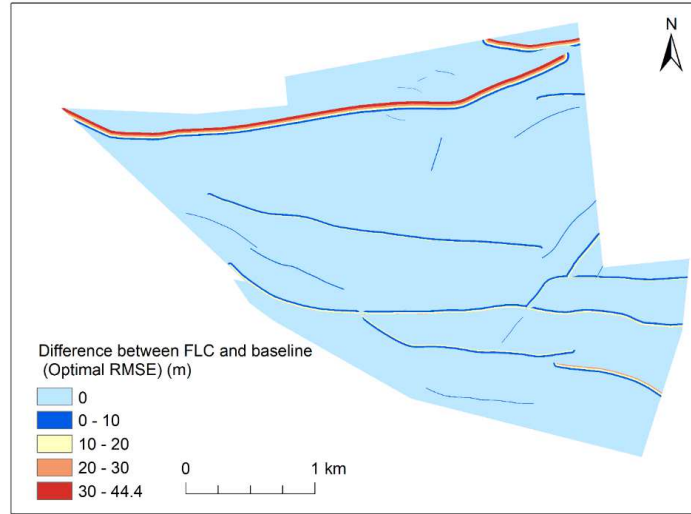


Fig. 6 Difference map of $\Delta Z(x) = Z_{\text{FLC}}(x) - Z_1(x)$

4.3 Independent validation and spatial error analysis

4.3.1 Independent validation results

As shown in Fig. 7, the spatial differences associated with FLC are mainly concentrated within or close to the local correction zone, whereas the reference surface remains unchanged outside the zone by design. In contrast, UR exhibits more extensive spatial modification beyond the local correction zone, reflecting the more global nature of geometric unfolding and refolding. UR+ reduces this effect by restricting reconstruction to the same local correction zone and feathering the result near the boundary, but it still represents a localized geometric reconstruction strategy rather than a strict no-perturbation scheme. This comparison highlights the essential distinction among the three approaches: FLC is explicitly designed to preserve the baseline surface outside the local correction zone, whereas UR and, to a lesser extent, UR+ may still modify the surrounding geometry. The independent validation results are summarized in Table 2. Compared with Z_1 , FLC reduced the RMSE from 41.33 m to 36.60 m. The MAE decreased from 23.75 m to 18.69 m. The coefficient of determination increased from 0.77 to 0.82. The ME also became less negative, indicating that FLC reduced the systematic bias of the baseline interpolation surface. Fig. 8 further shows the validation behavior of Z_1 , Z_{FLC} , $Z_{\text{UR+}}$ and Z_{UR} . The FLC predictions are closer to the observed elevations than the baseline predictions. The improvement is most relevant to the correction of fault-related local displacement.

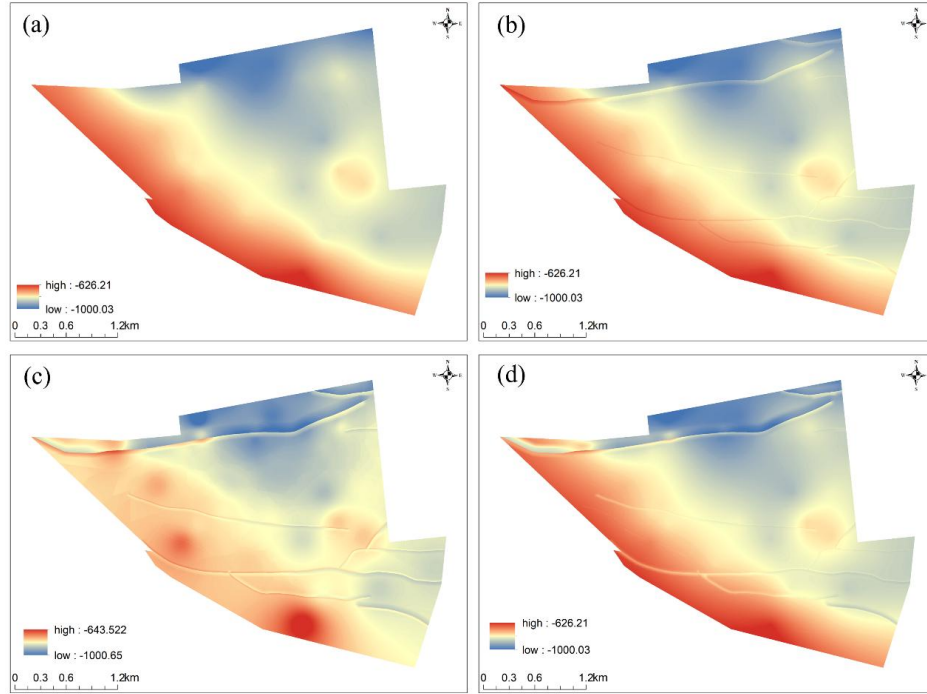


Fig. 7 Comparison of Z_1 , Z_{FLC} , Z_{UR} , and Z_{UR+} surfaces, (a) Continuous reference structural plane Z_1 , (b) FLC ($\lambda = 1.00$, $\beta = 0.37$), (c) Unfold/Refold (UR), (d): localized variant UR+

Table 2 Accuracy comparison within the local correction zone (the best results are highlighted in bold)

Method	RMSE	MAE	ME	R^2
Z_1	41.328	23.753	-18.818	0.767
Z_{FLC} ($\lambda=1.00$, $\beta=0.37$)	36.642	18.701	-11.500	0.817
Z_{UR+}	45.486	26.264	-21.012	0.718
Z_{UR}	57.645	34.979	-21.238	0.546

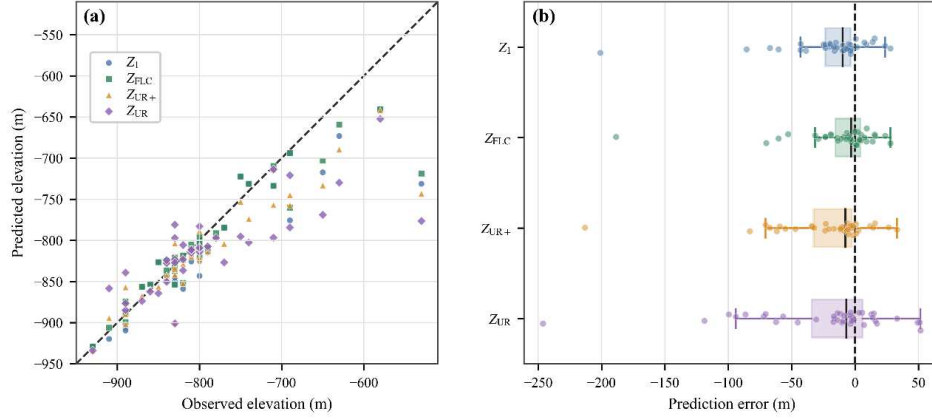


Fig. 8 Independent validation results of the real-case experiment. (a) Comparison between observed and predicted elevations for Z_1 , Z_{FLC} , Z_{UR+} , and Z_{UR} . (b) Prediction-error distributions of the four methods. The dashed line in (a) is the 1:1 reference line. The dashed line in (b) indicates zero prediction error. Z_{FLC} was generated using $\lambda = 1.00$ and $\beta = 0.37$

4.3.2 Spatial distribution of errors

To further identify the main sources of error near the fault, this study analyzed the along-strike distribution of FLC residuals in combination with the spatial positions of the independent validation points. Fig. 9 shows that the errors are not randomly scattered, but display clear along-strike zonation. Larger residuals are concentrated mainly near the fault tips [6, 7], whereas errors in the central segment are generally smaller and more stable. The spatial error map, the along-strike scatter plot, and the grouped boxplots all show the same trend, indicating that the fault-tip segments are likely to be the main zones where residuals are amplified in the present validation dataset. The grouped statistics further support this pattern, although the small number of tip-segment validation points means that this result should be interpreted cautiously. Based on 40 independent validation points, the fault-tip segments at 0-20% and 80-100% together contain 10 points, with an RMSE of 63.57, an MAE of 34.30, and a mean error of -28.36. By contrast, the central fault segment at 20-80% contains 30 points, with an RMSE of 21.05, an MAE of 13.50, and a mean error of -5.88. FLC can improve local structural prediction more stably in the central segment, but still shows stronger negative bias and greater error dispersion near the fault tips. This suggests that the current local correction framework is better suited to the central segment, but remains less responsive to the more complex structural variations and weaker data constraints near the fault tips. From the spatial distribution, points with larger absolute errors do not appear uniformly, but tend to cluster near the fault ends and in areas with local bends and branch development. The variation along the

normalized strike position also shows that larger negative errors are more likely to occur near both ends, whereas most points in the central segment are distributed near zero error, with only a few moderate deviations. These patterns collectively indicate that residual amplification near fault tips reflects a systematic structural control rather than random scatter, as further confirmed by the wider error distributions and more pronounced outliers in the grouped boxplots (Fig. 10).

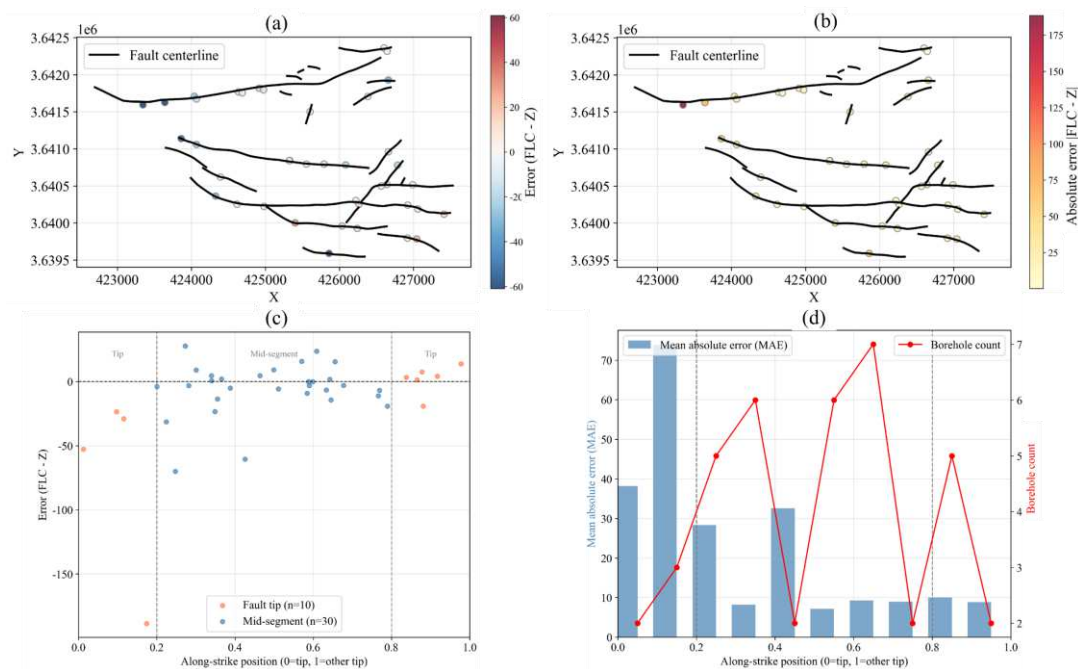


Fig. 9 Spatial distribution and structural controls of FLC modeling errors. **(a)** Spatial distribution of signed error (red: overestimation; blue: underestimation). **(b)** Spatial distribution of absolute error. **(c)** Error variation along the normalized fault strike (0 = tip, 1 = opposite tip). **(d)** Relationship between borehole density and mean absolute error, illustrating higher errors in poorly constrained fault-tip zones

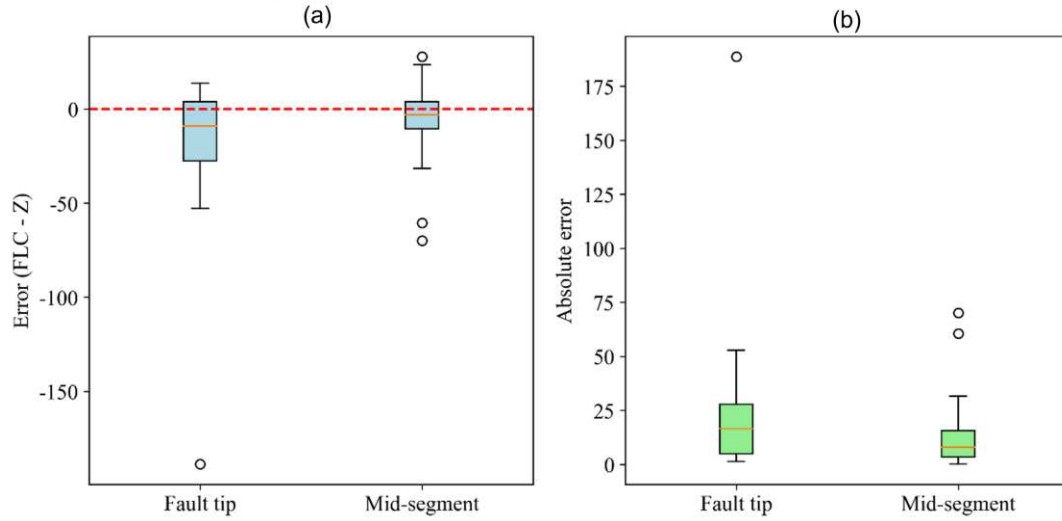


Fig. 10 Error statistics of FLC along the fault strike, showing (a) error distribution ($FLC - Z$) and (b) absolute error distribution for fault-tip and mid-segment validation points. Higher dispersion and larger errors occur near fault tips

4.3.3 Profile results and geological consistency

To further evaluate the geological plausibility of the modeled surfaces near faults from the perspective of profile geometry, cross-fault profiles were extracted from both Z_1 and Z_{FLC} . Six representative sections were selected, and their locations are shown in Fig. 11. The profile results in Fig. 12 show that the FLC-induced correction is mainly confined to the local correction zone. Its magnitude is greatest near the fault and gradually decreases with increasing distance from the fault, consistent with a distance-decaying displacement pattern. Meanwhile, the transition near the boundary of the local correction zone remains smooth, and no obvious drift is observed outside the zone. This indicates that the adopted decay weighting and boundary treatment effectively suppress artificial separation between corrected and uncorrected areas. In terms of the hanging-wall and footwall response, the parameter λ controls the relative partitioning of correction between the two sides. Under the RMSE-optimal solution, with $\lambda=1.00$, the correction places greater emphasis on the footwall side, producing a more pronounced relative offset across the fault in the extracted profiles. In the calibration results for the study area, λ consistently tends toward values close to 1, suggesting that, within the present local correction framework, assigning a stronger relative correction contribution to the footwall side yields lower in-zone prediction error. However, λ should be interpreted as a parameterized control variable for local correction rather than as the true one-sided deformation ratio in a structural kinematic sense. In this study, it reflects the numerically preferred partitioning strategy under the dual constraints of improving prediction

within the local correction zone and maintaining zero perturbation outside it. Although the Banji mine field is dominated by normal faults, and the implied correction direction is broadly compatible with the relative uplift of the footwall, reverse faults and composite structures are also present in the area. Therefore, the value of λ is not overinterpreted here as evidence for a single structural mechanism.

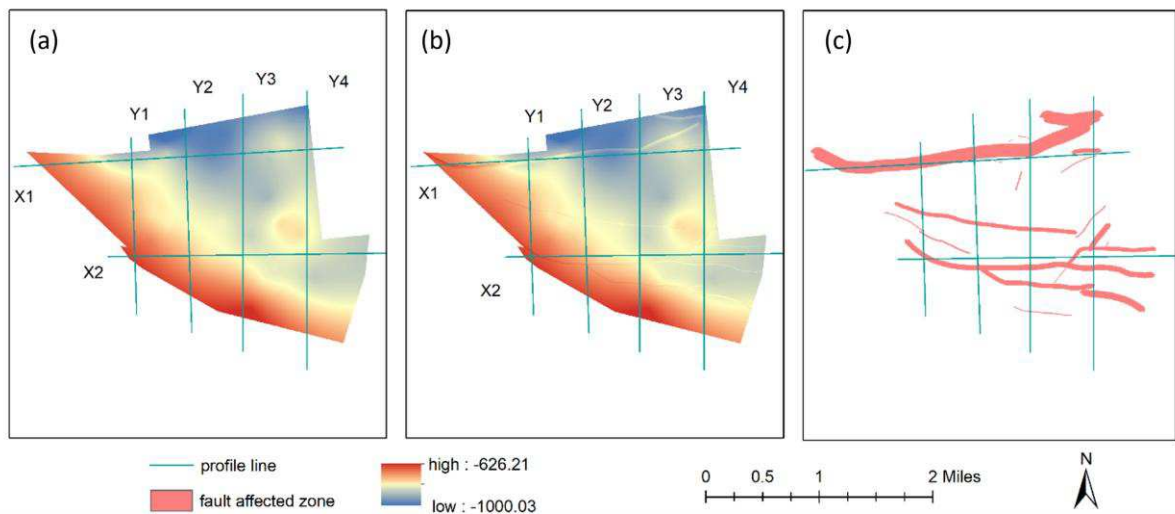


Fig. 11 Profile-line locations for Z_1 and Z_{FLC} and their relation to the local correction zone. (a) Profile lines on Z_1 . (b) Profile lines on Z_{FLC} . (c) Profile-line distribution within the local correction zone

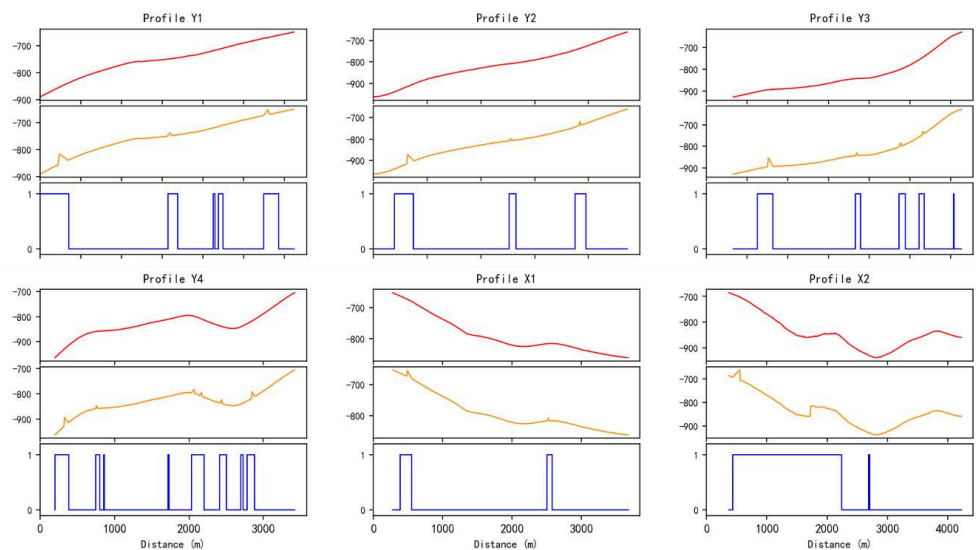


Fig. 12 Comparison of six section lines between Z_1 and Z_{FLC} , red represents Z_1 , yellow represents Z_{FLC} , and blue indicates whether the point is inside (1) or outside (0) the local correction zone

4.4 Synthetic experiment results

Two synthetic scenarios were used to compare fault-treatment strategies under controlled conditions. S1 represents a hard-truncation case, where the fault effect forms a sharp break within the local correction zone. S2 represents a continuous-decay case, where the anomaly gradually weakens toward the zone boundary. The true surfaces, profile locations, H1 profile comparisons, and quantitative results are shown in Fig. 13 and Fig. 14 and Table 3.

In S1, the true H1 profile contains a clear elevated segment within the local correction zone. Z_1 strongly smooths this feature and fails to reproduce the abrupt discontinuity. FLC restores the uplift more effectively and gives the lowest in-zone error. UR also improves the in-zone fit relative to Z_1 , but it produces non-zero perturbations outside the local correction zone. This indicates loss of locality. UR+ removes this outside-zone disturbance by restricting the reconstruction to the local correction zone. However, its in-zone recovery remains weaker than that of FLC in the hard-truncation case. The in-zone RMSE decreases from 16.04 for Z_1 to 4.66 for FLC. UR and UR+ reduce it to 6.64 and 8.24, respectively. FLC keeps the outside-zone error at the baseline level, whereas UR increases both outside-zone error and outside-zone perturbation.

In S2, the true H1 profile shows a continuously decaying anomaly rather than a flat elevated block. Z_1 still underestimates the disturbed zone and weakens the attenuation pattern. FLC gives the best in-zone reconstruction under the tested setting. It also better captures the gradual decay from the zone center to the boundary. UR remains broader and less localized, with non-zero outside-zone perturbation. UR+ removes this disturbance, but its in-zone accuracy is still slightly lower than that of FLC. The in-zone RMSE decreases from 11.70 for Z_1 to 6.75 for FLC. UR and UR+ reduce it to 7.60 and 7.03, respectively. As in S1, FLC keeps zero outside-zone perturbation, while UR modifies the surface outside the local correction zone.

Overall, the two scenarios show that locality strongly controls the performance of fault-handling strategies. In both S1 and S2, FLC gives the lowest in-zone RMSE and maintains zero outside-zone perturbation. This indicates a better balance between local correction and outside-zone preservation. UR can partly recover the fault-related geometry, but its full-domain reconstruction introduces unintended outside-zone changes. UR+ suppresses these changes, but its in-zone correction remains weaker than that of FLC in the present synthetic tests. Complete profile comparisons are provided in Supplementary Figs. S4-S5.

Table 3 Quantitative comparison of synthetic results under S1 and S2 based on grid-wide evaluation. (Z_1 denotes the baseline surface generated by universal kriging; the best results are highlighted in bold)

Scenario	Method	Over the entire study area		Within local correction zone		Outside the local correction zone	
		RMSE	MAE	RMSE	MAE	RMSE	MAE
S1	Z ₁	11.282	9.265	16.038	14.77	9.121	7.397
	FLC	8.224	6.497	4.663	3.842	9.121	7.397
	UR	9.102	7.393	6.64	5.262	9.797	8.116
	UR+	8.907	7.107	8.244	6.251	9.121	7.397
S2	Z ₁	9.839	7.957	11.701	9.607	9.121	7.397
	FLC	8.583	6.933	6.749	5.565	9.121	7.397
	UR	9.062	7.425	7.6	6.222	9.507	7.833
	UR+	8.64	6.971	7.034	5.715	9.121	7.397

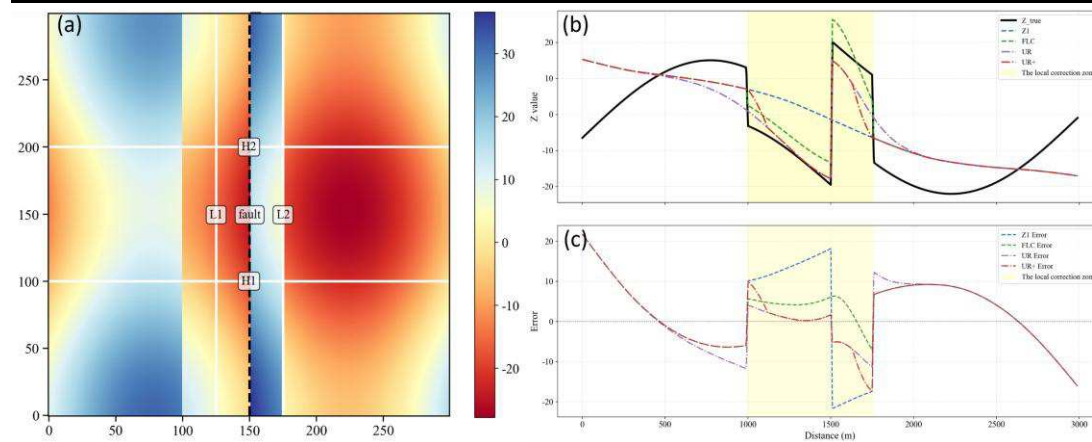


Fig. 13 Synthetic scenario S1, including the true surface and profile location (a), H1 profile Z comparison (b), and error comparison (c)

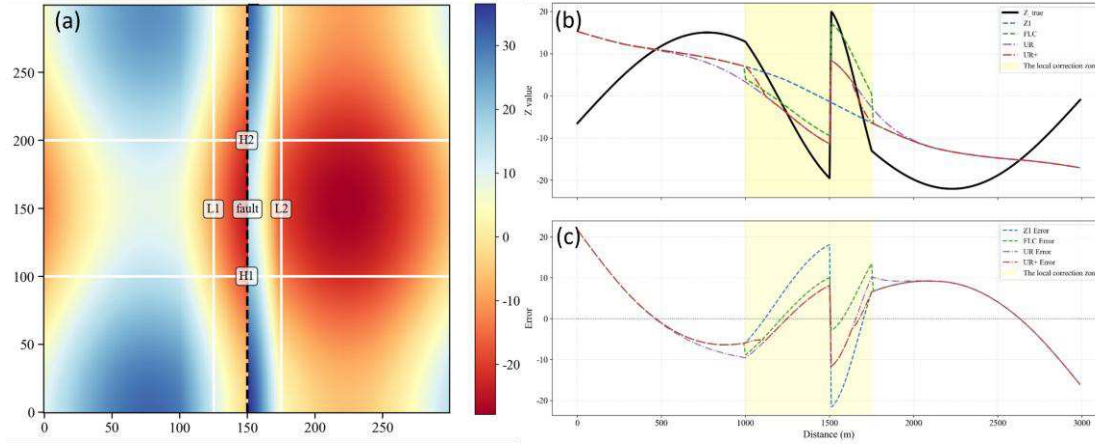


Fig. 14 Synthetic scenario S2, including the true surface and profile location (a), H1 profile Z comparison (b), and error comparison (c)

4.5 Ablation analysis of key FLC components

Ablation analysis was used to test the effects of displacement partitioning and distance-decay weighting. The full FLC model was compared with the Z_1 baseline, a no-decay variant, and a symmetric-displacement variant. The symmetric variant fixed λ at 0.5. The no-decay variant used the same local correction zone but removed distance-decay weighting within the zone. All variants were calibrated with the same calibration points and evaluated with the same independent validation points.

The point-based validation results are summarized in Fig. 15(a)-(b) and Table 4. Compared with Z_1 , the full FLC model reduced RMSE from 41.33 m to 36.60 m, and MAE from 23.75 m to 18.69 m. The symmetric variant showed weaker improvement, with an RMSE of 40.65 m and an MAE of 22.96 m. This indicates that equal displacement partitioning across the fault is too restrictive for the real case. Asymmetric displacement partitioning is therefore a key component of the FLC framework.

The no-decay variant gave the lowest point-based validation error, with an RMSE of 34.07 m and an MAE of 18.19 m. This suggests that uniform in-zone correction can fit sparse validation points more strongly than the distance-decay model. However, the spatial regularization results in Fig. 15(c)-(d) and Table 4 show a clear cost. The improved point accuracy is achieved by much stronger correction near the zone boundary. At $d/R = 0.95$, the median boundary correction is 0.85 m for the full FLC model, but 11.04 m for the no-decay variant. The 90th percentile also increases from 2.22 m to 28.80 m.

These results show that distance-decay weighting acts mainly as a geological regularization term. It suppresses abrupt correction near the boundary of the local correction zone and produces a smoother transition from the corrected area to the unchanged baseline surface. This distinction is important for engineering geological modeling, where the final surface should fit validation points, maintain geologically plausible transitions, and avoid artificial boundary discontinuities. Therefore, the no-decay variant is regarded as the point-error optimum under the present validation-point distribution, whereas the full FLC model is retained as the recommended engineering model because it provides a better compromise between validation accuracy, boundary regularity, and geological plausibility.

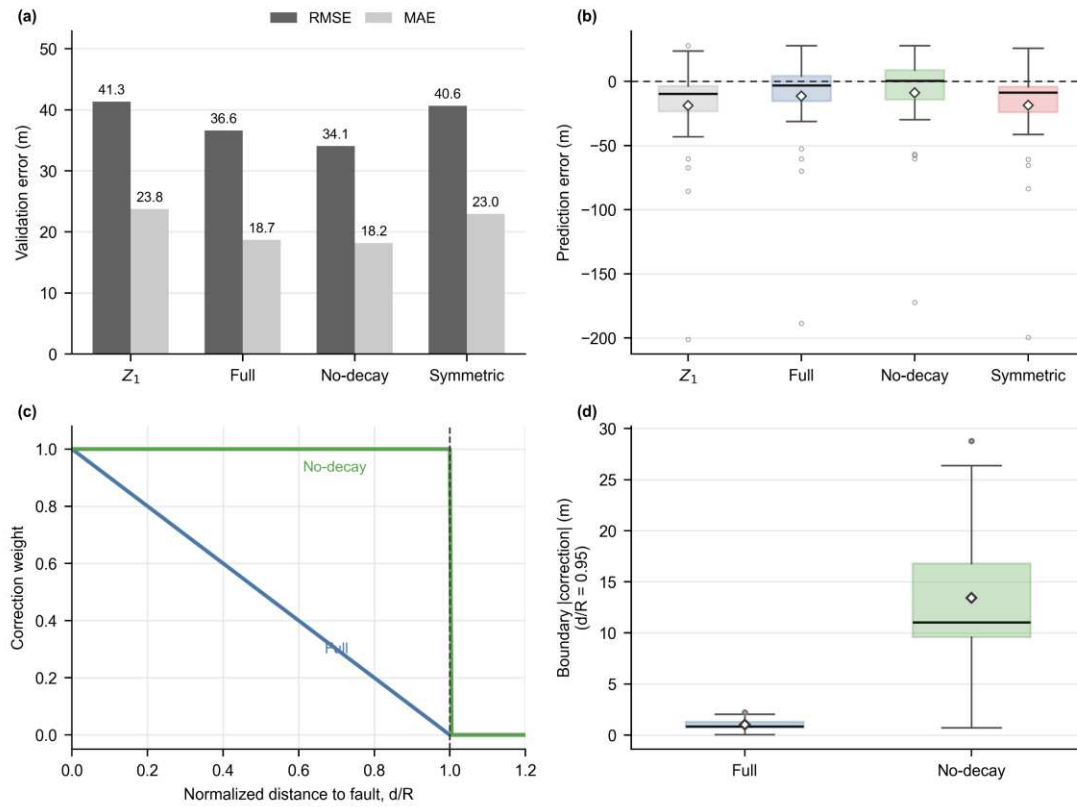


Fig. 15 Ablation comparison of the key FLC components. (a) RMSE and MAE of different model variants. (b) Prediction-error distributions at the independent validation points. (c) Correction weights for full and no-decay; (d) Comparison of boundary correction amounts

Table 4 Ablation results at independent validation points

Method	Settings	Validation metrics	Boundary correction (median; P90)
Z ₁ baseline	-	RMSE 41.33; MAE 23.75; ME -18.82; R ² 0.78	-
FLC full	$\lambda = 1$; decay = yes; $\beta = 0.37$	RMSE 36.60; MAE 18.69; ME -11.48; R ² 0.82	0.85 m; 2.22 m
FLC no-decay	$\lambda = 1$; decay = no; $\beta = 0.24$	RMSE 34.07; MAE 18.19; ME -8.98; R ² 0.84	11.04 m; 28.80 m
FLC symmetric	$\lambda = 0.5$; decay = yes; $\beta = 0.09$	RMSE 40.65; MAE 22.96; ME -18.64; R ² 0.77	-

5 Discussion

5.1 Geological constraints for discontinuity-aware reconstruction

Geological modeling commonly involves uncertainty caused by incomplete observations and imperfect prior geological knowledge. Previous studies have emphasized the importance of incorporating additional constraints to improve the reliability of subsurface models under uncertainty. The proposed FLC framework treats fault-related deformation as a local correction applied to a baseline stratigraphic surface. Universal kriging can effectively represent regional spatial trends. However, its continuity assumption may smooth local offsets near faults and reduce the representation of geological discontinuities [14, 26]. FLC preserves the regional characteristics of the baseline surface and introduces corrections only within fault-affected regions. This localized strategy provides a way to integrate geological constraints into interpolation-based surface reconstruction. Fault effects are usually spatially heterogeneous. Displacement magnitude, damage-zone extent, and structural architecture vary with fault geometry, lithology, and deformation history [8, 20, 28]. Therefore, representing fault influence as a spatially limited correction can be more practical than modifying the entire surface when subsurface observations are sparse. The real-case results support this interpretation. The correction field is mainly concentrated within the local correction zone, and independent validation shows improved prediction accuracy after applying FLC. These results indicate that part of the error in the baseline surface originates from fault-controlled local deformation. The ablation analysis further clarifies

the roles of individual components in the FLC framework. Asymmetric displacement partitioning improves the representation of fault-side differences. The symmetric variant with λ fixed at 0.5 produced weaker validation performance, indicating that equal correction on both sides of the fault may not sufficiently describe the observed deformation pattern. Such asymmetry is consistent with geological observations because hanging-wall and footwall responses may differ due to fault geometry, displacement history, and lithological conditions [1, 9, 25]. In this study, λ represents an empirical side-dependent correction weight. It should not be interpreted as the true proportion of geological displacement accommodated by each fault block. The no-decay variant achieved the lowest point-based validation error, suggesting that uniform correction can provide stronger fitting performance under sparse validation constraints. However, distance-decay weighting serves as a spatial regularization mechanism rather than a direct error-minimization component. It reduces abrupt transitions near the correction boundary and maintains a gradual change between corrected and unchanged regions. Therefore, the full FLC framework provides a balanced solution between prediction accuracy, spatial continuity, and geological plausibility.

5.2 Comparison with existing spatial modeling strategies

The conceptual difference between FLC and geometric reconstruction methods is illustrated in Fig. 16. Conventional interpolation methods, represented by the baseline Z_1 surface, provide continuous surface estimation from sparse observations. However, they do not explicitly incorporate fault-side information or local displacement characteristics. Consequently, fault-related discontinuities may be smoothed during surface reconstruction. Geometric reconstruction methods, such as unfolding and refolding approaches, provide another strategy for handling faulted geological surfaces. These methods explicitly represent structural deformation and can recover geometrically consistent surfaces under appropriate geological assumptions. However, they usually require more complete fault geometry and stronger structural constraints. In addition, corrections may influence regions beyond the target fault-affected area. FLC provides an intermediate strategy between continuous interpolation and full geometric reconstruction. It does not replace the baseline interpolation surface. Instead, it uses the baseline surface as a regional reference and introduces fault-aware corrections only within a predefined local correction zone. This design reduces unnecessary modifications outside fault-affected regions and is suitable for geological modeling scenarios with incomplete structural information. Recent advances in computational geoscience have introduced stochastic and data-driven approaches for geological model generation, which provide powerful tools for representing complex geological variability when sufficient geological information is available [4]. Meanwhile, implicit structural modeling has further improved the

representation of complex geological structures by integrating geological knowledge with geometric constraints [10, 12]. These approaches are powerful when dense structural observations and comprehensive geological constraints are available. In contrast, FLC focuses on data-limited scenarios where borehole observations are sparse and fault attributes are only partially known. Therefore, FLC and implicit structural modeling address different modeling conditions. The former emphasizes localized correction under limited information, whereas the latter focuses on comprehensive structural reconstruction.

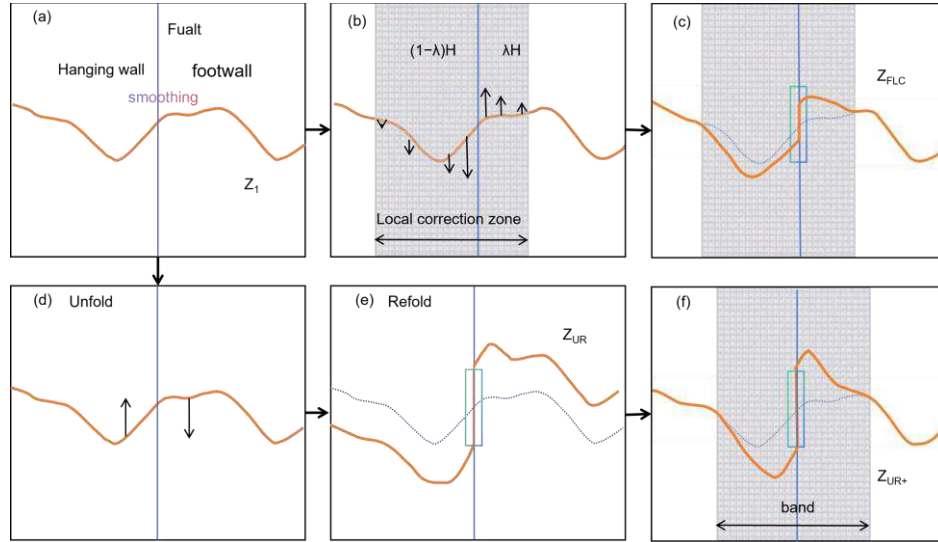


Fig. 16 Conceptual comparison of interpolation-based reconstruction, FLC, and geometric reconstruction strategies for fault-affected stratigraphic surfaces. (a) Input baseline surface Z_1 . (b) FLC displacement partitioning between the hanging wall and footwall. (c) FLC output with localized distance-decay correction. (d) Unfold step of geometric reconstruction. (e) Refold step of geometric reconstruction. (f) UR+ localized reconstruction within the fault influence zone

5.3 Applicability, limitations, and future development

The FLC framework is designed for geological surface reconstruction under three conditions. First, a baseline stratigraphic surface can be generated from borehole or other subsurface observations. Second, basic fault geometry and displacement-related information are available. Third, local improvement near discontinuities is required while preserving the stability of surrounding regions. Each component of FLC has a clear geological interpretation. The local correction zone defines the spatial extent of fault influence. The fault-side mask distinguishes hanging-wall and footwall regions. The displacement partitioning parameter controls asymmetric correction allocation. The distance-

decay function regulates the transition between corrected and unchanged areas. These components improve the interpretability of the correction process and reduce the dependence on purely statistical adjustment. Several limitations should also be considered. First, the correction performance depends on the accuracy of fault traces, displacement estimates, dip information, and lithological proxy variables [23]. Uncertainty in these inputs may influence the resulting correction field. Second, the real-case validation used 40 independent validation points. Although these points provide an independent assessment, they may not fully represent spatially heterogeneous errors, particularly near fault tips where observations are limited. Therefore, the reported improvement should be interpreted together with spatial error patterns and validation-point distribution. Third, this study focuses on a single stratigraphic surface. Extension to multi-layer reconstruction requires additional geological constraints to maintain stratigraphic order and thickness consistency. Future studies should incorporate uncertainty quantification, multi-layer geological modeling, and complex fault-network representations to improve the applicability of FLC for broader subsurface reconstruction problems.

6 Conclusions

This study proposed a fault-aware local correction (FLC) framework for stratigraphic surface reconstruction under fault-related geological discontinuities. The framework integrates fault-side information, asymmetric displacement partitioning, and distance-decay weighting into a universal kriging-based surface while preserving the baseline surface outside the local correction zone. The main conclusions are summarized as follows.

(1) The proposed FLC framework improves stratigraphic surface reconstruction near faults while maintaining stability in unaffected regions. In the real coalfield case, FLC reduced the independent validation RMSE from 41.33 m to 36.60 m and the MAE from 23.75 m to 18.69 m. The coefficient of determination increased from 0.77 to 0.82, demonstrating the effectiveness of localized geological correction.

(2) Synthetic experiments and ablation analysis revealed the roles of different components in controlling correction behavior. FLC substantially reduced reconstruction errors within fault-affected zones under controlled displacement scenarios. Asymmetric displacement partitioning improved fault-side representation, whereas distance-decay weighting acted as a spatial regularization mechanism to maintain smooth transitions between corrected and unchanged regions.

(3) The FLC framework provides an interpretable post-interpolation correction strategy for data-limited geological surface reconstruction. It offers an intermediate approach between continuous interpolation and full geometric reconstruction when fault information is incomplete. Future developments should consider multi-layer stratigraphic reconstruction, complex fault networks, and uncertainty quantification.

Acknowledgements

The authors gratefully acknowledge Banji Coal Mine of China Coal Xinji Energy Co., Ltd. for providing access to the geological and borehole data.

Statements and declarations

Clinical trial registration: not applicable.

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Funding: This work was supported by the Doctoral Top-notch Innovation Fund under Grant No. 81001201B046 and the National Key Research and Development Program of China under Grant No. 2023YFC3012100.

Author contributions: Rong Wang: Methodology, conceptualization, software, formal analysis, and writing - original draft. Donglin Dong: Supervision, writing - review and editing, and funding acquisition. Zhao Yang: Data curation and validation. Yuqi Chen: Investigation. Enyu Zhang: Data curation.

Code availability: The FLC workflow was developed in Python 3.12 using NumPy, Pandas, Matplotlib, SciPy, GeoPandas, Shapely, Rasterio, and PyKrig. No special-purpose hardware is required.

Source code: https://github.com/wangrong989588/FLC-UR/tree/main/FLC_GitHub_Code_Package_20260511

Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1. Berg, S.S., Skar, T.: Controls on damage zone asymmetry of a normal fault zone: Outcrop analyses of a segment of the Moab fault, SE Utah. *J. Struct. Geol.* 27(10), 1803–1822 (2005). <https://doi.org/10.1016/j.jsg.2005.04.012>
2. Bonetto, S., Facello, A., Ferrero, A.M., Umili, G.: A tool for semi-automatic linear feature detection based on DTM. *Comput. Geosci.* 75, 1–12 (2015). <https://doi.org/10.1016/j.cageo.2014.10.005>
3. Cao, X., Liu, Z., Hu, C., Song, X., Quayle, J.A., Lu, N.: Three-dimensional geological modelling in Earth science research: An in-depth review and perspective analysis. *Minerals* 14(7), 686 (2024). <https://doi.org/10.3390/min14070686>
4. Chan, S., Elsheikh, A.H.: Parametric generation of conditional geological realizations using generative neural networks. *Comput. Geosci.* 23, 925–952 (2019). <https://doi.org/10.1007/s10596-019-09850-7>
5. Chicco, D., Warrens, M.J., Jurman, G.: The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Comput. Sci.* 7, e623 (2021). <https://doi.org/10.7717/peerj-cs.623>
6. Cowie, P.A., Roberts, G.P.: Constraining slip rates and spacings for active normal faults. *J. Struct. Geol.* 23(12), 1901–1915 (2001). [https://doi.org/10.1016/S0191-8141\(01\)00036-0](https://doi.org/10.1016/S0191-8141(01)00036-0)
7. Crider, J.G., Peacock, D.C.P.: Initiation of brittle faults in the upper crust: A review of field observations. *J. Struct. Geol.* 26(4), 691–707 (2004). <https://doi.org/10.1016/j.jsg.2003.07.007>
8. Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J., Withjack, M.O.: A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *J. Struct. Geol.* 32(11), 1557–1575 (2010). <https://doi.org/10.1016/j.jsg.2010.06.009>
9. Ferrill, D.A., Morris, A.P., McGinnis, R.N., Smart, K.J., Ward, W.C.: Fault zone deformation and displacement partitioning in mechanically layered carbonates: The Hidden Valley fault, central Texas. *AAPG Bull.* 95(8), 1383–1397 (2011). <https://doi.org/10.1306/12031010065>
10. Gao, K., Wellmann, F.: Fault representation in structural modelling with implicit neural representations. *Comput. Geosci.* 199, 105911 (2025). <https://doi.org/10.1016/j.cageo.2025.105911>

11. Giraud, J., Caumon, G., Grose, L., Ogarko, V., Cupillard, P.: Integration of automatic implicit geological modelling in deterministic geophysical inversion. *Solid Earth* 15(1), 63–89 (2024). <https://doi.org/10.5194/se-15-63-2024>
12. Grose, L., Ailleres, L., Laurent, G., Caumon, G., Jessell, M., Armit, R.: Modelling of faults in LoopStructural 1.0. *Geosci. Model Dev.* 14(10), 6197–6213 (2021). <https://doi.org/10.5194/gmd-14-6197-2021>
13. Holden, E.J., Wong, J.C., Wedge, D., Martis, M., Lindsay, M., Gessner, K.: Improving assessment of geological structure interpretation of magnetic data: An advanced data analytics approach. *Comput. Geosci.* 87, 101–111 (2016). <https://doi.org/10.1016/j.cageo.2015.11.010>
14. Jarmołowski, W., Wielgosz, P., Ren, X., Krypiak-Gregorczyk, A.: On the drawback of local detrending in universal kriging in conditions of heterogeneously spaced regional TEC data, low-order trends and outlier occurrences. *J. Geod.* 95(1), 2 (2021). <https://doi.org/10.1007/s00190-020-01447-8>
15. Jia, Q., Che, D., Li, W.: Effective coal seam surface modeling with an improved anisotropy-based, multiscale interpolation method. *Comput. Geosci.* 124, 72–84 (2019). <https://doi.org/10.1016/j.cageo.2018.12.008>
16. Jia, Q., Li, W., Che, D.: A triangulated irregular network constrained ordinary kriging method for three-dimensional modeling of faulted geological surfaces. *IEEE Access* 8, 85179–85189 (2020). <https://doi.org/10.1109/ACCESS.2020.2993050>
17. Keskin, H., Grunwald, S.: Regression kriging as a workhorse in the digital soil mapper's toolbox. *Geoderma* 326, 22–41 (2018). <https://doi.org/10.1016/j.geoderma.2018.04.004>
18. Krajnovich, A., Zhou, W., Gutierrez, M.: Uncertainty assessment for 3D geologic modeling of fault zones based on geologic inputs and prior knowledge. *Solid Earth* 11(4), 1457–1474 (2020). <https://doi.org/10.5194/se-11-1457-2020>
19. Kyne, R., Torremans, K., Güven, J., Doyle, R., Walsh, J.: 3-D modeling of the Lisheen and Silvermines deposits, County Tipperary, Ireland: Insights into structural controls on the formation of Irish Zn-Pb deposits. *Econ. Geol.* 114(1), 93–116 (2019). <https://doi.org/10.5382/econgeo.2019.4621>

20. Lathrop, B.A., Jackson, C.A.L., Bell, R.E., Rotevatn, A.: Displacement/length scaling relationships for normal faults: A review, critique, and revised compilation. *Front. Earth Sci.* 10, 907543 (2022). <https://doi.org/10.3389/feart.2022.907543>
21. Léger, M., Clochard, V.: Fast interpolation method for surfaces with faults by multi-scale second-derivative optimization. *Oil Gas Sci. Technol.* 75, 62 (2020). <https://doi.org/10.2516/ogst/2020057>
22. Li, J., Heap, A.D.: Spatial interpolation methods applied in the environmental sciences: A review. *Environ. Model. Softw.* 53, 173–189 (2014). <https://doi.org/10.1016/j.envsoft.2013.12.008>
23. Lindi, O.T., Aladejare, A.E., Ozoji, T.M., Ranta, J.P.: Uncertainty quantification in mineral resource estimation. *Nat. Resour. Res.* 33(6), 2503–2526 (2024). <https://doi.org/10.1007/s11053-024-10394-6>
24. Livio, F.A., Ferrario, M.F., Frigerio, C., Zerboni, A., Michetti, A.M.: Variable fault tip propagation rates affected by near-surface lithology and implications for fault displacement hazard assessment. *J. Struct. Geol.* 130, 103914 (2020). <https://doi.org/10.1016/j.jsg.2019.103914>
25. Ma, S., Beroza, G.C.: Rupture dynamics on a bimaterial interface for dipping faults. *Bull. Seismol. Soc. Am.* 98(4), 1642–1658 (2008). <https://doi.org/10.1785/0120070201>
26. Mesić Kiš, I.: Comparison of ordinary and universal kriging interpolation techniques on a depth variable (a case of linear spatial trend), case study of the Šandrovac Field. *Rud.-Geol.-Naft. Zb.* 31(2), 41–58 (2016). <https://doi.org/10.17794/rgn.2016.2.4>
27. Shawky, M.M.: A comparative study of interpolation methods for the development of ore distribution maps. *Discover Geosci.* 3, 2 (2025). <https://doi.org/10.1007/s44288-025-00108-7>
28. Torabi, A., Berg, S.S.: Scaling of fault attributes: A review. *Mar. Pet. Geol.* 28(8), 1444–1460 (2011). <https://doi.org/10.1016/j.marpetgeo.2011.04.003>
29. Vázquez, A.A., Dahle, P., Abrahamsen, P., et al.: Conditioning geological surfaces to horizontal wells. *Comput. Geosci.* 26, 1223–1236 (2022). <https://doi.org/10.1007/s10596-022-10154-6>
30. Vázquez, A.A., Dahle, P., Abrahamsen, P., et al.: Consistent prediction of well paths and geological surfaces. *Comput. Geosci.* 28, 1099–1113 (2024). <https://doi.org/10.1007/s10596-024-10310-0>
31. Willmott, C., Matsuura, K.: Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Clim. Res.* 30, 79–82 (2005). <https://doi.org/10.3354/cr030079>

559 32. Yuan, J., Liu, G., Chai, S.: 3D geological fine modeling and dynamic updating method of fault slope in
560 open-pit coal mine. *Sci. Rep.* 14, 29906 (2024). <https://doi.org/10.1038/s41598-024-81872-3>

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformation.docx](#)