PMAS
Proceedings of the Mongolian Academy of Sciences

Vol. 66 No 01(257) 2026
https://doi.org/10.5564/pmas.v66i01.5340

ARTICLE

Precise Earthquake Relocation along the Egiin Davaa fault Hangay Dome, Central Mongolia

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ARTICLE INFO: Received: 31 Oct, 2025; Accepted: 03 March, 2026

Abstract: This study presents a precise earthquake relocation along the Egiin Davaa fault in the Hangay Dome, Central Mongolia, using the double-difference algorithm (HypoDD). We analysed 289 events from a dense temporary deployment of 72 broadband seismic station network (2012–2014), resulting in a high-quality catalogue of 253 events. The relocation achieved a 38% reduction in mean RMS residuals (to 0.34 s) and significantly improved precision (0.36 km horizontal, 0.68 km vertical), effectively eliminating artificial depth clustering artifacts. Our results reveal a sharply defined, near-vertical (80–90° dip) fault plane extending approximately 80 km at depth, confirming the Egiin Davaa fault as a mature, active seismogenic structure. Relocated hypocentres are distributed between 2 and 30 km, with the primary seismogenic thickness constrained to the upper 20–25 km. Notably, localised deepening to 30 km occurs near the Tsenkher hot spring (Profile C-C'). We suggest that high-pressure hydrothermal fluid migration along the fault reduces effective normal stress, facilitating brittle failure in the lower crust despite elevated regional heat flow (70–90 mW/m²). This study provides the first high-resolution constraints on the Egiin Davaa fault geometry and its seismogenic potential. By identifying the brittle-ductile transition at 20-25 km and quantifying the magnitude of potential strong earthquake is Mw 7.2 and more, the research significantly elevates the understanding of seismic hazards in Central Mongolia.

Keyword: *HypoDD; earthquake relocation; Egiin Davaa fault; Hangay Dome; Central Mongolia; seismogenic thickness; intracontinental deformation; seismic hazard;*

INTRODUCTION

The Hangay Mountains in central Mongolia form a part of the Hangay–Khentii folded system within the Central Asian Orogenic Belt (CAOB), one of the world's largest accretionary orogenic systems [1–4]. Characterised by a high-elevation plateau exceeding 3,500 m, the Hangay Dome stands out due to its broad topography and deeply incised valleys [4–7; 17, 18]. Unlike the surrounding Mongol Altai and Gobi Altai ranges, which are dominated by major active strike-slip faults and a history of devastating Mw > 8 earthquakes, such as the 1905 Bulnay and 1957 Gobi-Altay events [7–12; 22] the central Hangay Dome lacks a historical record of large-scale seismicity [5, 6]. Instead, deformation in this region appears to be distributed across smaller, less studied structures, raising critical questions about strain accommodation in this buoyantly supported crustal block [13, 14].

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Vol. 66 No 01(257) 2026
https://doi.org/10.5564/pmas.v66i01.5340

A prominent feature within the high-elevation core of the dome is the Egiin Davaa fault, a northeast-trending normal fault with Quaternary surface ruptures, extending approximately 80 km. While geomorphic evidence indicates late Quaternary reactivation [13, 23], the fault's subsurface geometry and contemporary seismic role remain poorly understood. Notably, while strike-slip faulting characterises the broader CAOB, the Hangay Dome exhibits localised extension. This regime is potentially influenced by high regional heat flow (70–90 mW/m²) [1], which limits the brittle-ductile transition and the resulting seismogenic thickness to approximately 25 km.

In this study, we bridge the gap between surface geomorphology and subsurface seismicity by applying the HypoDD double-difference relocation method [14, 19] to data from the "Hangay Experiment" temporary broadband network [15]. Precise hypocentre relocation is essential in resolving the Egiin Davaa fault's geometry and evaluate the seismogenic thickness of the central Hangay crust.

Our study goes beyond a simple confirmation of surface faulting. By determining the high-resolution subsurface geometry of the Egiin Davaa fault, we clarify its role within the broader South Hangay Fault System (SHFS) and reveal how strain is partitioned in the central Hangay region. This provides a more comprehensive view of the regional crustal deformation than previously available through regional-scale mapping alone. To achieve this, we tested the hypothesis that the Egiin Davaa fault operates as a mature, through-going structure with a near-vertical dip penetrating the entire seismogenic crust, rather than a series of disconnected, shallow segments [13, 22, 23]. Furthermore, we investigated whether current microseismicity correlates spatially with the large-magnitude prehistoric surface ruptures documented by Walker [13]. While the current study focuses on resolving the fault as a distinct structure, it establishes a critical baseline for future research into the full structural connectivity of SHFS.

MATERIALS AND METHODS

Dataset: Seismic data for this study were obtained from the Hangay Experiment, a temporary deployment of 72 broadband seismic stations across central Mongolia. Each station was equipped with STS-2 sensors and operated continuously from June 2012 through to April 2014 [15]. The network was designed with two SW–NE transects across the Hangay Dome, covering an area of approximately 500×600 km (44°–50°N and 95°–104°E). In the core of the array, the average station spacing was 10-15km, providing dense coverage that is well suited for high-precision earthquake relocation. This geometry ensured that seismic events near the Egiin Davaa fault were recorded by multiple nearby stations, thereby enhancing the quality of phase picks and the reliability of relocation results.

From the full experiment catalogue, we selected 289 events located within a 20 km buffer zone of the Egiin Davaa fault’s surface trace. The selection criteria required each events to have reliable P- and S-wave arrivals recorded at a minimum of ten stations. This rigorous filtering ensured that the dataset was representative of the fault zone and met the quality standards nesessary for double-difference analysis (Figure 1). Relocation was performed using a local 7-layer 1D velocity model specifically developed for the Hangay Dome region [24], which accounts for the region’s crustal thickness and Vp/Vs ratios (Table 1).

Vol. 66 No 01(257) 2026
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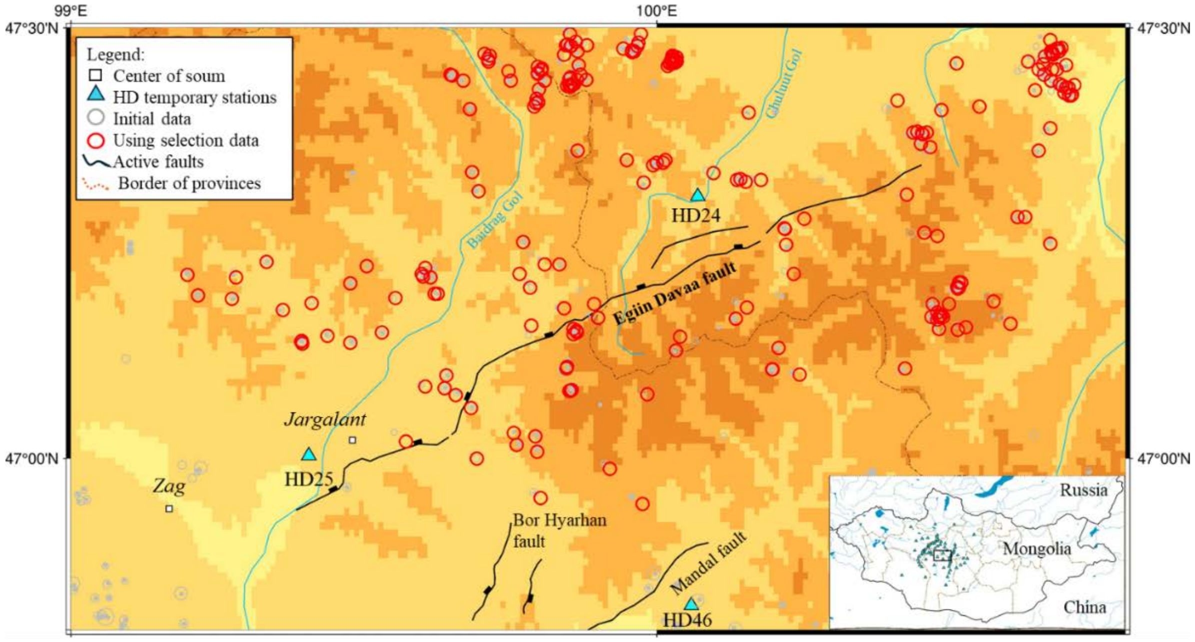

Figure 1. The map of the earthquake epicentres along the Egiin Davaa fault rupture, as recorded by the Hangay dome stations of the Central Mongolia Seismic Experiment. The fault rupture is shown in a black line [13]; station locations are indicated by triangles. The inset map shows the border of Mongolian territory, temporary deployment of 72 broadband seismic station network, and the black square represents the location of the study area within central Mongolia.

Table 1. Minimum 1D velocity model and corresponding Vp/Vs ratio used for eartquake relocation in the Hangay Dome (after Dashdondog. M et al., 2020).

Depth (km)	Vp (km/s)	Vs (km/s)	Vp/Vs
0.0	6.06	3.50	1.73
14.0	6.16	3.50	1.76
20.0	6.27	3.63	1.73
25.0	6.36	3.68	1.73
30.0	6.53	3.79	1.72
35.0	6.63	3.91	1.69
45.0	7.16	4.18	1.71
50.0	8.00	4.62	1.73

***Methods (Relocation Procedure)**:* Eartquake relocation was performed using the HypoDD double-difference algorithm[14, 19], which refines relative hypocentre locations by minimising residuals in travel-time differences between pairs of nearby events recorded at common stations. Unlike conventional location methods that rely on absolute travel times and are strongly affected by unmodeled velocity heterogeneity, HypoDD exploits the fact that differential travel times between closely spaced events are less sensitive to velocity errors. This makes it particularly effective in regions such as the Hangay Dome, where the crustal structure is complex and poorly constrained. Due to the variable quality of the temporary network, we utilised only catalogue phase arrival times ($dt.ct$) for the analysis.

To ensure structural stability and computational efficiency, we implemented specific relocation parametres, including a maximum event separation (MAXSEP) of 10 km and a maximum of 172 observations per pair (MAXOBS). Following the standard recommendations for double-difference relocation [19], we did not rely on a single set of parameters. Instead, we performed an extensive series of trials, varying MINOBS (from 1 to 8), MAXSEP, and damping coefficients. This systematic approach allowed us to identify a stable solution where the primary features of the Egiin Davaa fault were consistently recovered. This aligns with the "best practice" of testing parametre sensitivity to avoid artificial structural artifacts, as suggested in the HypoDD methodology.

While a threshold of MINOBS = 1 was initially selected to maintain connectivity within the sparse temporary network, our sensitivity tests using stricter criteria (e.g., MINOBS ≥ 4 and MINOBS ≥ 8) did not significantly alter the geometry of the primary seismic clusters. This consistency confirms with the fact that the solution is structurally stable even at lower threshold. Post-processing analysis further validates this approach, showing that 85% of the relocated events are ultimately constrained by 8 or more differential travel-time links.

The inversion was conducted using the LSQR solver over 10 iterations, with damping values systematically reduced from 45 to 20 to refine relative precision. After each iteration, residuals were examined to ensure convergence and identify outliers; events with unstable locations were excluded from the final catalogue (Table 2).

Table 2. Optimal Parametres for the HypoDD Relocation Process.

Parametre	Value	Description	Rationale for Selection
MINOBS	1	Minimum number of phase observations per event pair.	To ensure strong connectivity between linked events.
MINLINK	4	Minimum number of links required to define a cluster.	To maintain spatial consistency within seismic clusters.
MAXSEP	10 km	Maximum separation between event pairs.	To restrict relocation to local-scale fault structures.
MAXDIST	200 km	Maximum distance between an event and a station.	Optimised for the regional station distribution in Mongolia.
Damping	45 to 20	Damping factor for the LSQR inversion.	Selected through sensitivity tests to ensure solution stability.
Iteration Steps	10	Total number of iterations (Weighting adjustments).	To achieve convergence of RMS residuals.

This relocation procedure resulted in a substantial reduction of root-mean-square (RMS) residuals and successfully eliminated artificial depth clustering. By resolving hypocentres to within sub-kilometre relative accuracy (H: 0.36 km, V: 0.68 km), the final relocated catalogue provides a high-resolution view of the Egiin Davaa fault, allowing for detailed analysis of its geometry and seismogenic thickness.

Vol. 66 No 01(257) 2026
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RESULTS AND DISCUSSION

Relocation of the initial dataset yielded 253 high-quality events from the original 289, significantly refining the seismicity pattern within the central Hangay Dome. The process achieved a 38% reduction in mean RMS residuals (from 0.55 s to 0.34 s) and improved horizontal and vertical precision by over 70% (Table 3).

Table 3. Statistical comparision between initial and relocated earthquake catalogues

Parametre	Initial Catalogue (N=289)	Relocated Catalogue (N=253)	Improvement
Mean RMS Residual (s)	0.55 s	0.34 s	38%
Mean Horizontal Error (km)	~1.2 km	0.36 km	70%
Mean Vertical Error (km)	~2.5 km	0.68 km	72%
Depth Clustering at 10 km	Present (Artifact)	Removed	-

The relocation process significantly improved the hypocentral precision, achieving a mean RMS residual reduction to 0.34 s and average location uncertainties of 0.36 km (horizontal) and 0.68 km (vertical). Out of the initial 289 events, 12% (36 events) were excluded from the final catalogue due to insufficient phase connectivity or spatial outlying during iterations. The results reveal a sharply defined, near-vertical (dip 80–90°) fault plane extending approximately 80 km at depth, confirming the Egiin Davaa fault as a mature, active seismogenic structure. Relocated hypocentres are distributed between 2 and 30 km, with the primary seismogenic thickness constrained to the upper 20–25 km, broadly consistent with findings from other regions of central and western Mongolia [16].

Crucially, the relocation successfully resolved the artificial depth clustering at 2, 10, and 20 km respectively that was prevalent in the initial catalogue - likely a result of fixed depth constraints in the starting velocity model. The updated hypocentres now exhibit a broad, realistic depth distribution between 2 and 30 km, as illustrated in the depth histograms (Figure 2). This continuous distribution provides a more accurate representation of the brittle upper crust's seismic behaviour.

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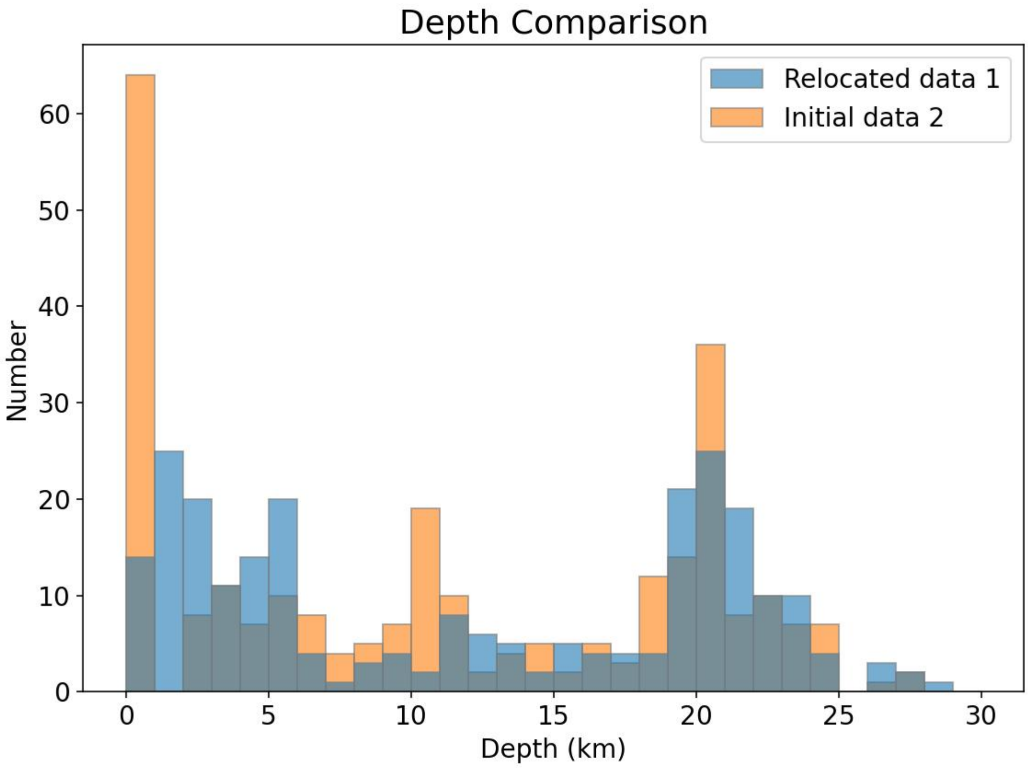

Figure 2. Depth distribution of earthquakes before and after relocation. The initial catalogue exhibits artificial clustering of events at fixed depths (e.g., ~2, 10, and 20 km), whereas the relocated catalogue exhibits a broad, realistic depth range (2–30 km), highlighting the improved hypocentral resolution achieved using HypoDD.

The relocation process significantly improved the hypocentral precision, achieving a mean RMS residual reduction to 0.34 s and an average location uncertainties of 0.36 km (horizontal) and 0.68 km (vertical). Out of the initial 289 events, 12% (36 events) were excluded from the final catalogue due to insufficient phase connectivity or spatial outlying during the iterative relocation process. This data filtering ensured that the final 253 events represent a robust and high-resolution view of the subsurface geometry along the Egiin Davaa fault (Figure 3). Cross-sectional profiles oriented perpendicular to the fault strike reveal that hypocentres define a steeply dipping plane (dip > 85°), which is structurally consistent with the fault's geomorphic expression.

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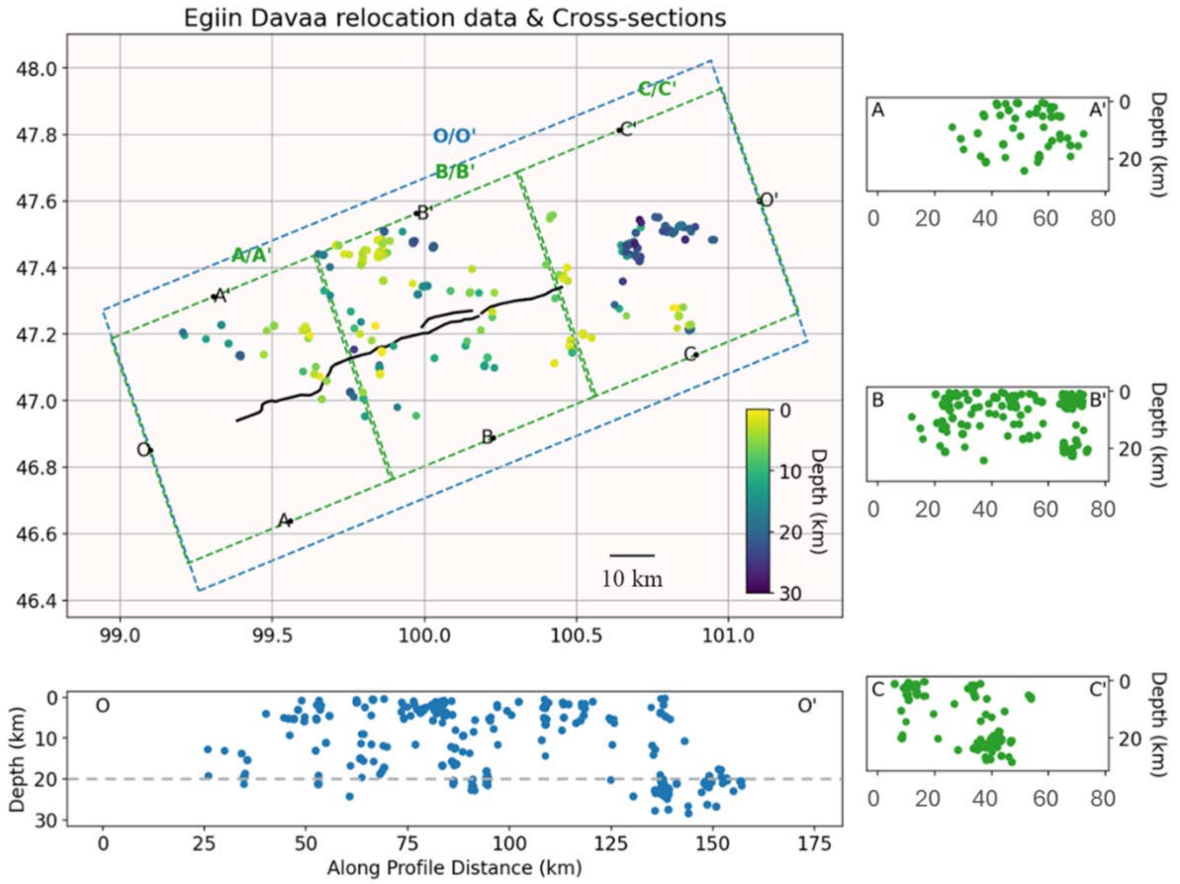

Figure 3. Relocated epicentres (n = 253 well-connected events) plotted in map view with corresponding cross-sections along and across the Egiin Davaa fault. The color scale represents focal depth, from yellow (shallow) to dark blue (deep). The O–O′ profile is oriented along the fault trace, while A–A′, B–B′, and C–C′ are perpendicular sections showing depth distribution.

The longitudinal profile (O-O’) demonstrates that the majority of relocated seismicity is distributed at depths shallower than 25 km, defining the general seismogenic thickness of the region. However, a notable anomaly is observed in the C-C’ profile, where hypocentres persistently reach depths of 30 km. Visually, the relocated seismicity also suggests a degree of spatial segmentation along the fault trace, likely reflecting the presence of secondary structures or stepovers [13].

We suggest that the localised deepening of the seismogenic zone observed in Profile C-C’ is likely linked to the influence of hydrothermal activity. This profile is situated in close proximity to the Tsenkher hot spring, a major geothermal feature. The circulation of high-pressure hydrothermal fluids along the fault plane may locally elevate pore-fluid pressures, thereby reduce effective normal stress and facilitate brittle failure at greater depths (up to 30 km).

While regional heat flow values are reported as relatively high (70–90 mW/m²) [1], which typically promotes a shallower brittle-ductile transition, the presence of deep-seated fluids near Tsenkher may locally extend the brittle regime further into the lower crust. The abrupt decrease in seismicity below 25 km in other segments indicates a general transition to ductile flow, consistent with regional models of an extensional plateau maintained by lower-crustal flow and localised brittle faulting.

The Egiin Davaa fault is situated within the high-elevation core of the Hangay Dome, a region, which is characterised by low strain rates (<2mm/yr)[20, 21]. The active, shallow seismicity indicates ongoing crustal extension, likely driven by the gravitational collapse of the thickened crust or far-field stresses originating from the India–Eurasia collision [4, 17, 18].

Our findings confirm that the Egiin Davaa fault is a mature, crustal-scale structure accommodating ongoing extension within the high-elevation core of the Hangay Dome. The predominance of shallow seismicity (<20 km) highlights a persistent potential for significant ground motion, underscoring the necessity of integrating these high-resolution results into regional probabilistic seismic hazard models to refine engineering design standards across central Mongolia.

Nevertheless, several limitations should be acknowledged. First, while a 7-layer velocity model was developed to improve vertical resolution, the use of a 1D model may not fully account for 3D structural complexities within the Hangay Dome. Second, the dataset is restricted to the 2012–2014 period. This temporal limitation was a deliberate methodological choice, as the dense temporary seismic network active during this interval provided the sub-kilometer focal depth precision currently unattainable with the sparse permanent national network. Consequently, while these results represent a high-resolution snapshot rather than a continuous record, they remain the most robust source for resolving the Egiin Davaa fault geometry. Future studies incorporating 3D tomographic models and expanded permanent networks will be essential in monitoring long-term tectonic evolution.

CONCLUSIONS

This study utilised the HypoDD double-difference relocation method to refine earthquake hypocentres along the Egiin Davaa fault, leveraging high-quality data from a dense, temporary broadband seismic network in central Mongolia. The relocation of 253 seismic events significantly enhanced depth resolution and elucidated the geometric relationship between subsurface seismicity and mapped surface ruptures.

Our results reveal a distinct, fault-parallel alignment extending approximately 80 km, confirming the Egiin Davaa fault as a primary, active seismogenic structure within the Hangay Dome. Based on the fault length, we estimate that the Egiin Davaa fault has the potential to generate a maximum magnitude earthquake of Mw 7.2–7.4 [25]. This underscores the critical importance of monitoring microseismicity to assess long-term seismic hazards in central Mongolia.

The relocated hypocentres are distributed between a depth of 2 and 30 km. The primary concentration depth distribution above 20 km defines a seismogenic thickness of approximately 20 km, indicating that brittle deformation is the dominant mechanism in the upper crust. The notable persistence of events below 30 km, particularly in the vicinity of the Thenkher hot spring (Profile C-C’), suggests that high-pressure hydrothermal fluid circulation may locally extend brittle failure into the lower crust. Conversely, the abrupt decrease in seismicity below 25 km in other segments indicates a general transition to ductile flow, consistent with regional thermal models.

Overall, this study provides the first high-resolution constraints on the Egiin Davaa fault geometry and its seismogenic potential. By identifying the brittle-ductile transition at 20-25 km and quantifying the magnitude of potential strong earthquake as Mw 7.2 and more, the research significantly elevates the understanding of seismic hazards in central Mongolia.

These findings demonstrate that tectonic strain within the Hangay Dome is accommodated by crustal-scale structures capable of rupturing the entire seismogenic column. Despite the absence of large historical earthquakes, the prevalence of shallow seismicity (< 20 km) and the confirmed structural maturity of the fault, underscore a persistent potential for significant ground motion. Integrating these precise relocations into probabilistic seismic hazard analyses is essential for refining hazard models and improving engineering design standards for infrastructure across the region.

Future research should integrate these high-resolution locations with focal mechanism solutions and 3D velocity modeling to further constrain stress orientations, slip kinematics, and the structural connectivity between the Egiin Davaa fault and adjacent tectonic systems within the Hangay region.

Acknowledgments

The authors thank the IRIS PASSCAL Instrument Center for providing the seismic equipment and technical support during the Hangay Experiment. We are grateful to the Institute of Astronomy and Geophysics, Mongolian Academy of Sciences (IAG) for supporting the fieldwork, and extend our special thanks to the local teams and communities for their assistance. We would like to express our gratitude to Felix Waldhauser for his valuable guidance and technical insights on the double-difference relocation method provided during previous collaborations, which greatly benefited the analysis in this study. We also thank Anne Melzter for her continued professional support. This research was funded by the Mongolian Academy of Sciences and its partner institutions. The seismic data used in this study are available through the EarthScope (formerly IRIS) Data Management Center."

Ethical approval

Not applicable. This study does not involve human participants, animal subjects, or sensitive personal data. The research is based on the analysis of observational seismic catalogue data provided by the Institute of Astronomy and Geophysics, Mongolian Academy of Sciences.

Author contribution

The authors confirm contribution to the paper as follows: DM was responsible for conceptualisation, methodology, software implementation, formal analysis, investigation, visualisation, and writing the original draft. DA contributed to supervision, project administration, and writing - review & editing. SO provided data curation, software support, and writing – review & editing. All authors reviewed the results and approved the final version of the article and authors have read and agreed to the published version of the manuscript.

Source of funding

This research was supported by the Science and Technology Foundation of Mongolia. The authors gratefully acknowledge the institutional and financial support from the Mongolian Academy of Sciences and the Institute of Astronomy and Geophysics.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Vol. 66 No 01(257) 2026
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