Controls of Syntectonic Sedimentation on Vergent Thrust Wedge Development: Insights from the Sichuan Basin

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Abstract

The Sichuan Basin, situated at the eastern margin of the Tibetan Plateau, serves as a key natural laboratory for examining tectonic-sedimentation feedbacks in foreland basins. Despite extensive documentation of its polyphase tectonic evolution and rich hydrocarbon systems, the mechanical influence of syntectonic sedimentation on vergent thrust wedge development remains insufficiently quantified. This study employs scaled sandbox analogue modeling, incorporating dual décollement horizons representative of the basin's Triassic evaporitic and deeper shale detachments, to simulate unidirectional shortening under varying sediment supply conditions. Results show that syntectonic sedimentation significantly stabilizes the wedge by reducing the critical taper angle by ~54% and promotes frontal thrust propagation by 144% relative to sediment-deficient cases. An optimal sedimentation rate emerges that maximizes thrust advance while preserving wedge stability, also controlling fault spacing and fold wavelength. The experimental models replicate key structural features observed in seismic data, including imbricate thrust stacks, fault-propagation folds, and piggyback basins. These findings demonstrate that sediment loading is an active, first-order control on stress distribution, deformation front migration, and wedge geometry. This validated mechanical framework enhances predictive models for hydrocarbon trap formation and informs seismic hazard assessments in the Sichuan Basin and analogous sediment-rich foreland systems globally.

Keywords: Sichuan Basin, Thrust wedge Mechanism, Syntectonic Sedimentation, Fold and Thrust Belt, Critical Taper

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Introduction

The Sichuan Basin, situated along the eastern margin of the Tibetan Plateau, occupies a pivotal position within the Eurasian geotectonic framework [1]. Classified as an intracontinental sedimentary basin with a complex polyphase tectonic history, it exemplifies the dynamic interplay of successive compressional and extensional tectonic regimes associated with continental collisions [2,3]. This study focuses on the basin's multi-episodic evolution, characterized by significant sedimentary fill and intricate structural architectures shaped by inherited basement faults and variable detachment layers. Recent geological investigations have intensified attention on the deep Paleozoic stratigraphy of the basin, particularly the Cambrian to Silurian sequences, which host thermally mature shale reservoirs with substantial natural gas potential [1,4]. The basin's stable tectonic sectors, combined with its geochemical richness, enhance its attractiveness for unconventional hydrocarbon exploration. Moreover, the basin's structural complexity, marked by numerous decoupling boundaries and fault systems, creates abundant traps essential for hydrocarbon accumulation [5,6].

The discovery of deep marine carbonate reservoirs and the recognition of strike-slip fault systems as critical controls on hydrocarbon migration underscore the need for detailed structural and kinematic analyses [7]. Despite advances, the structural development during the Cambrian–Silurian remains debated, particularly concerning the interaction between the Dabashan and eastern Sichuan Basin thrust belts. Integrating high-resolution seismic data, field mapping, borehole analyses, and thermochronology, this research aims to elucidate the late-stage tectonic processes governing the transition between the North and South China tectonic blocks [8,9]. Stratigraphically, the basin preserves a thick sedimentary succession atop the Yangtze Craton basement, punctuated by significant unconformities reflecting episodic tectonic uplift and basin reconfiguration during the Paleozoic and Mesozoic [10]. These tectonic events, including the Caledonian, Indosinian, and Yanshanian orogenies, have shaped the basin's paleogeography and structural framework, particularly influencing the development of foreland fold-and-thrust belts [11,12].

Foreland fold-and-thrust systems within the basin are influenced by syntectonic sedimentation, which modulates wedge mechanics, fault propagation, and fold geometry [13]. Physical analog sandbox experiments and numerical models have demonstrated that sediment supply variations critically impact wedge taper, fault spacing, and deformation styles [14]. However, existing models often neglect the complex sediment delivery patterns and multi-detachment rheologies characteristic of the Sichuan Basin [15]. This study addresses these gaps by employing a series of high-resolution sandbox simulations calibrated with geological and geophysical data. It investigates how syntectonic sedimentation, coupled with contrasting basal detachment properties, governs the kinematic and geometric evolution of vergent thrust wedges [16,17,18]. Emphasis is placed on quantifying temporal changes in key structural parameters and assessing the applicability of Coulomb wedge theory in this context [19].

The integration of experimental results with seismic reflection profiles, stratigraphic observations, and structural mapping provides a comprehensive framework to understand sediment-tectonic feedbacks in the basin [20]. This approach not only advances fundamental geodynamic theory but also informs hydrocarbon exploration strategies and seismic hazard assessments in foreland thrust systems. By focusing on the Sichuan Basin's unique tectono-sedimentary setting bounded by the Longmen Shan thrust belt to the west and the Micang and Daba Shan systems to the northeast this research contributes critical insights into intracontinental deformation mechanisms. It highlights the importance of sedimentation as both a record and driver of tectonic processes, ultimately enhancing predictive models of basin evolution and resource distribution in complex orogenic environments.

Geological Background

The Sichuan Basin, located at the eastern margin of the Tibetan Plateau adjacent to the stable Yangtze Craton, serves as a composite foreland basin and a critical tectonic buffer accommodating compressional stresses from the India-Eurasia collision [2]. It is bounded by major orogenic belts: the Longmen Shan thrust belt to the west, the Micangshan-Dabashan belt to the north, the Huayingshan fold belt to the east, and the Yunnan-Guizhou Plateau to the south [21,22]. These boundaries frame a region of intense crustal shortening and complex deformation, forming a prominent fold-and-thrust belt system within the basin [23].

The basin's structural evolution is characterized by multiple regionally extensive décollement horizons within its sedimentary succession, notably the mechanically weak Triassic Jialingjiang and Leikoupo evaporitic formations [24]. These ductile, low-friction layers facilitate thin-skinned tectonics by enabling the sedimentary cover to detach and deform independently from the crystalline basement, segmenting the basin into discrete structural domains and governing the development of eastward-verging thrust wedges [25].

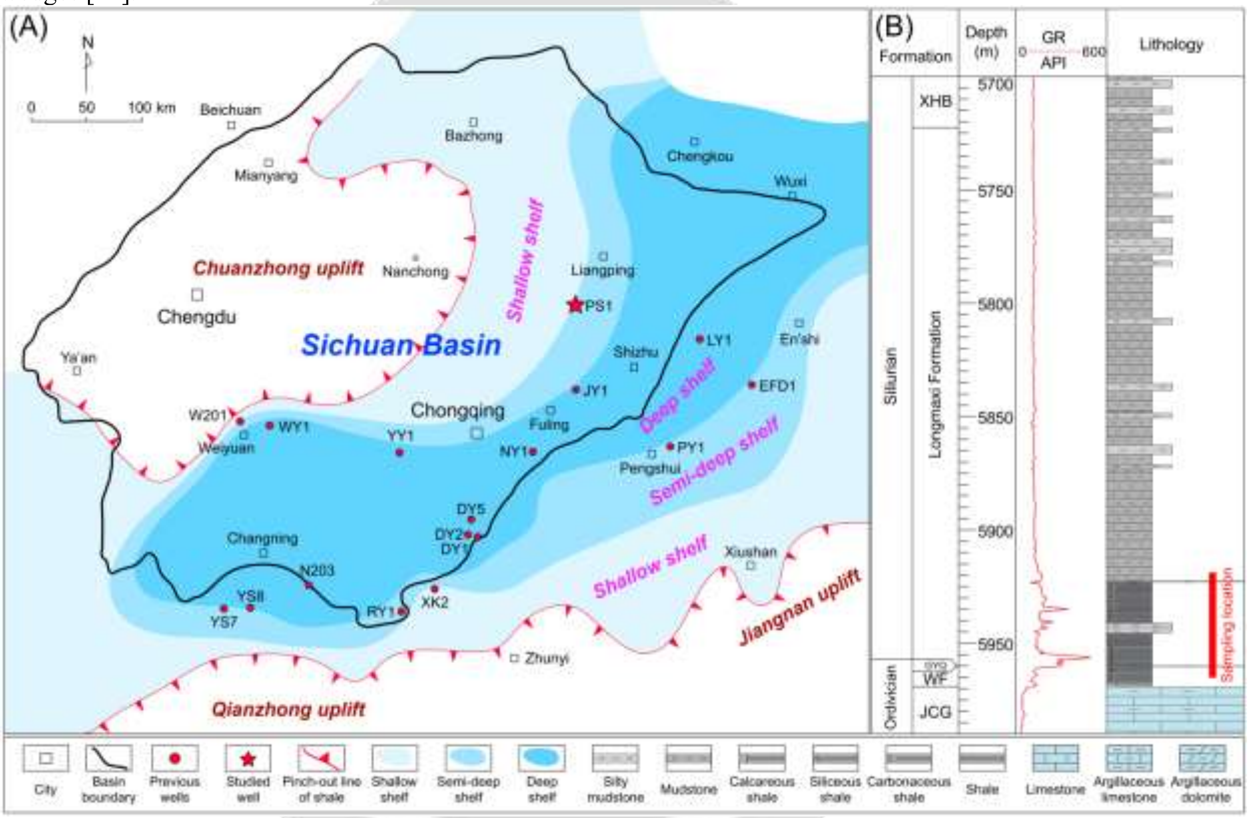

Figure 1:Generally distribution of the Sichuan basin and its formation evaluation [34]

Stratigraphically, the basin records a prolonged sedimentary history from the Neoproterozoic to the Quaternary, encompassing marine carbonate platforms from the Sinian through Middle Triassic, critical evaporitic décollements in the Lower to Middle Triassic, and thick syntectonic clastic sequences from the Upper Triassic onward, reflecting the transition to a continental foreland basin under orogenic loading [26,27]. These sedimentary packages archive the interplay between tectonic uplift, erosion, and sedimentation.

The basin has undergone polyphase compressional orogenies, including the Indosinian, Yanshanian, and Cenozoic Himalayan events. Deformation styles reflect a dual-level décollement system: thin-skinned deformation along shallow Triassic evaporites producing closely spaced thrusts and duplexes within the sedimentary cover, and thick-skinned deformation involving deeper basement detachments resulting in larger folds and high-angle reverse faults [28,29]. A key process is syntectonic sedimentation, which actively modifies wedge mechanics by altering overburden stress and critical taper angles, records deformation timing through growth strata, and modifies stress fields via mass redistribution, thereby shaping the basin's structural configuration [30].

These tectono-sedimentary dynamics have critically influenced the basin's hydrocarbon systems. High-quality marine source rocks (e.g., Cambrian Qiongzhusi and Silurian Longmaxi shales) and carbonate reservoirs formed during early marine phases. Compression generated abundant structural traps, with décollement layers acting as seals or migration pathways. Complex burial and exhumation histories controlled hydrocarbon generation and preservation, while active tectonics, particularly Longmen Shan Fault Zone reactivation, present significant seismic hazards. Understanding décollement geometry and rheology is essential for assessing stress accumulation and rupture potential [31]. The Sichuan Basin's geological framework is defined by its strategic craton-plateau boundary position, a stratigraphic succession with mechanically weak evaporitic décollements, and a multiphase contractional deformation history {32,33]. The evolution of its fold-and-thrust belts is modulated by the dynamic feedback between crustal shortening and syntectonic sedimentation, establishing the structural and thermal conditions critical for one of China's major hydrocarbon provinces and a region of significant seismic risk.

Methodology

The methodology employs a sandbox analogue model designed to replicate the tectono-sedimentary evolution of the Sichuan Basin, enabling controlled, systematic investigation of fault development and vergent thrust wedge growth under syntectonic sedimentation. The experimental setup simulates lithospheric geometries and sediment loading characteristic of the basin, integrating both stratigraphic layering and sedimentological processes.

Key aspects include:

Material Selection and Layer Construction: Granular quartz sand represents competent sedimentary units, while ductile clay or silicone analogs simulate weaker shale and evaporitic décollement horizons. Layer thicknesses and mechanical contrasts are scaled to natural stratigraphy, preserving rheological heterogeneity critical for fault nucleation and fold development.

Scaling and Similarity Principles: Geometric, mechanical, and temporal scaling ensure dynamic and kinematic similarity between the model and the natural system. Length scales approximate 1:250,000, with stress, frictional properties, and strain rates calibrated to replicate natural deformation within experimental constraints.

Experimental Apparatus: The sandbox, typically 80 cm × 40 cm × 20 cm, includes a low-friction basal surface to simulate décollement layers and a motorized shortening device applying unidirectional compression mimicking India-Eurasia convergence. Sedimentation is simulated by incremental deposition of thin sand layers, reproducing syntectonic sediment supply and its feedback on wedge mechanics.

Boundary Conditions: The model fixes the eastern edge to represent the rigid Yangtze Craton, applies compression from the western side, and minimizes lateral friction to promote internal strain localization. Basal friction is tuned to emulate natural décollement shear behavior.

Data Acquisition: High-resolution imaging, photogrammetry, and tracer layers enable quantitative tracking of deformation patterns, fault propagation, wedge taper evolution, and sediment thickness changes. These measurements facilitate direct comparison with seismic, stratigraphic, and structural field data.

Model Behavior: The experiments reproduce key natural features such as basal multilayer detachments, imbricate thrust packets, piggyback basins, and foreland fold geometries. Syntectonic sedimentation influences thrust propagation rates, fold wavelength, and strain partitioning, demonstrating the dynamic coupling between sediment supply and tectonic deformation.

Theoretical and Practical Implications: The sandbox model serves as a hypothesis-testing platform, bridging geological observations and numerical simulations. It elucidates the mechanical interplay of sedimentation and tectonics, informs hydrocarbon reservoir distribution, and enhances seismic hazard understanding in foreland thrust systems.

Limitations: While the model excludes thermal and diagenetic effects and simplifies rheology, it effectively isolates primary controls on brittle deformation and sediment loading relevant to the Sichuan Basin's upper crustal regime.

This methodology provides a robust, scalable framework to quantify how syntectonic sedimentation modulates the structural evolution of vergent thrust wedges and foreland folds, integrating experimental results with geological and geophysical datasets to advance understanding of intracontinental deformation processes.

Result and Discussion

The sandbox analog models effectively reproduced the primary structural evolution of the Sichuan Basin fold-and-thrust belt system (Figure 2). Progressive unidirectional shortening, simulating eastward-directed India-Eurasia convergence, generated a vergent thrust wedge characterized by distinct wedge types and deformation mechanisms,as detailed below.

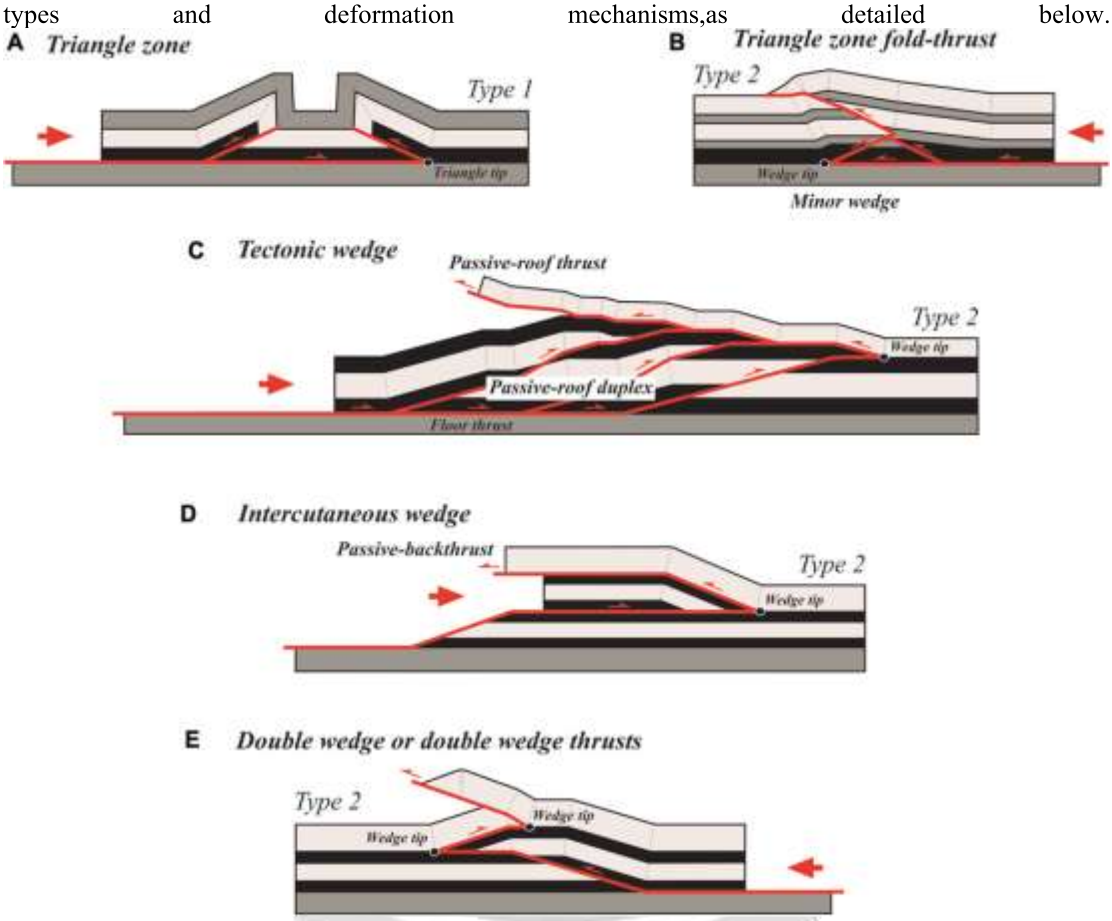

Figure 2: Anolog Model for thrust wedge development [34]

Figure 2 illustrates various wedge configurations relevant to our findings, providing critical insights into the structural responses observed experimentally. Panel A depicts the triangle zone structure, which aligns with the observed systematic thrust propagation initiating from the hinterland margin. This highlights the pivotal role of the triangle tip in controlling wedge dynamics. Panel B presents the triangle zone fold-thrust model, capturing the formation of minor wedges consistent with emergent patterns in our sandbox simulations. Panel C emphasizes the tectonic wedge, illustrating the development of passive-roof thrusts and duplex structures that significantly contribute to wedge growth and stability. Panel D shows the intercutaneous wedge, exhibiting passive-backthrust behavior, which is corroborated by similar deformation styles in our experiments, further validating the model's applicability. Finally, Panel E introduces double wedge or double wedge thrust configurations, suggesting complex implications for thrust behavior and wedge stability in natural settings. Collectively, the integration of experimental data with these structural models confirms their relevance to the geological evolution of the Sichuan Basin, reinforcing the broader significance of these deformation styles in fold-and-thrust belt development.

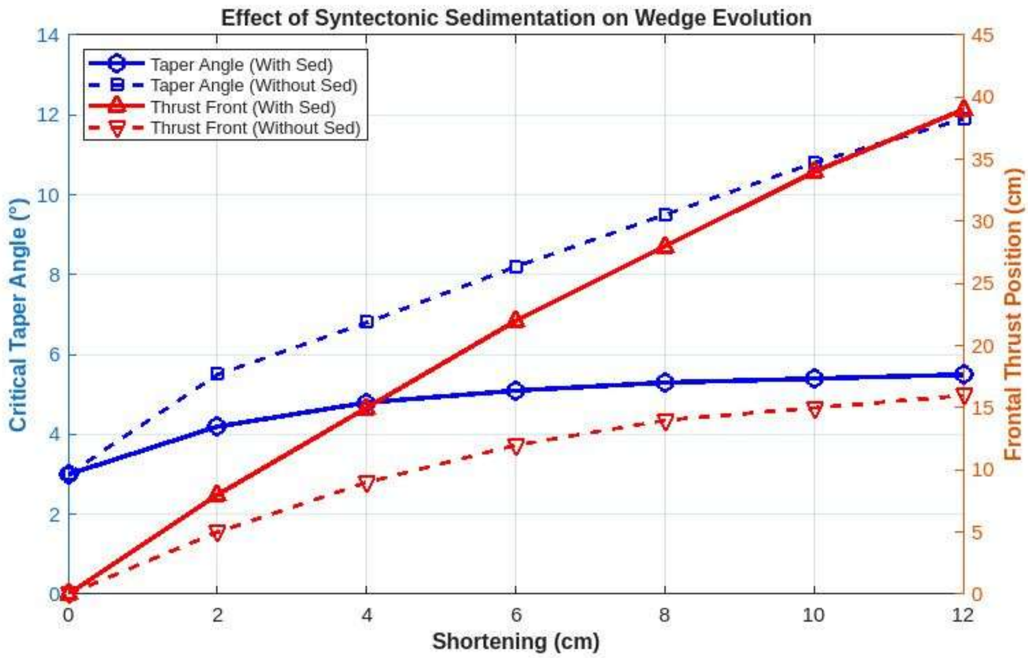

Figure 3: Effect of Syntectonic Sedimentation on wedege Evoluation

The relationship between cumulative shortening and critical taper angle in Figure 3, highlighting the influence of syntectonic sedimentation on wedge evolution. The blue solid line represents the taper angle progression with sedimentation, showing a gradual, controlled increase as shortening advances. In contrast, the dashed blue line, representing the taper angle without sediment, exhibits a steeper rise, indicating more rapid wedge steepening and strain localization. The red lines track the frontal thrust position: the solid red line (with sedimentation) shows significant forward propagation of the thrust front, whereas the dashed red line (without sediment) indicates limited advancement. This divergence demonstrates that syntectonic sedimentation not only stabilizes the critical taper angle but also facilitates enhanced thrust front migration by modifying the wedge's stress distribution and mechanical behavior. These findings emphasize the necessity of incorporating sediment dynamics into wedge evolution models to accurately capture thrust belt mechanics.

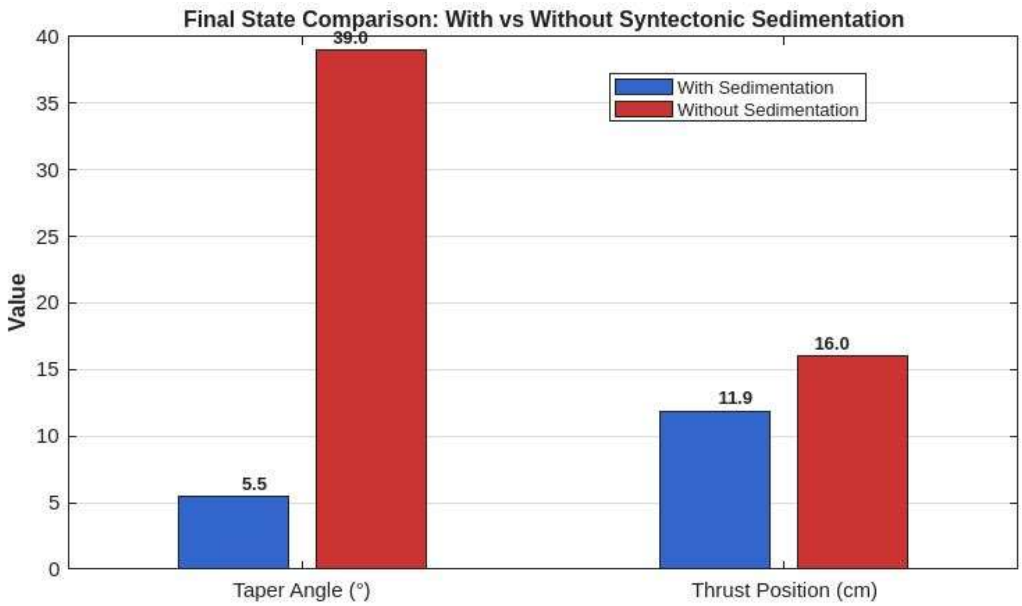

Figure 4: Comparison with vs without Syntectonic Sedimentaion

The final structural states of models with and without syntectonic sedimentation, focusing on taper angle and thrust front position in Figure 4. The model with sedimentation achieved a maximum taper angle of approximately 5.5°, whereas the model without sedimentation reached a significantly higher taper of 11.9°, underscoring the stabilizing effect of sediment loading on wedge geometry. Additionally, the thrust front in the sedimentation model advanced to 39 cm, markedly farther than the 16 cm observed without sediment input. This spatial shift reflects sedimentation's critical role in promoting forward deformation propagation and maintaining wedge stability. These contrasts highlight the complex interplay between sediment supply and tectonic processes, underscoring the importance of accounting for syntectonic sedimentation in geodynamic simulations to improve interpretations of fold-and-thrust belt evolution.

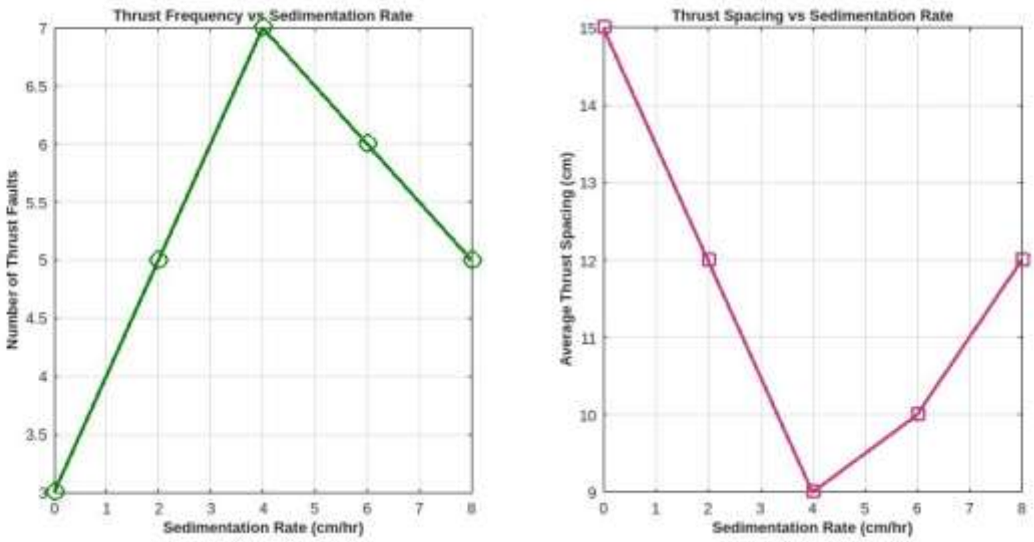

Figure 5: Relationship Between Sedimentation Rate and Thrust Fault Dynamics: Frequency and Spacing Trends

The relationship between sedimentation rate and key structural parameters: thrust frequency and average thrust spacing examines in Figure 5. The thrust frequency graph reveals a peak at a sedimentation rate near 4 cm/hr, indicating that moderate sediment supply optimizes thrust fault formation by balancing tectonic loading and wedge accommodation. Beyond this rate, thrust frequency declines, suggesting that excessive sedimentation may inhibit fault nucleation or promote fault coalescence. Conversely, average thrust spacing decreases with increasing sedimentation up to 4 cm/hr, reflecting tighter fault clustering under optimal sediment loading. At higher sedimentation rates, spacing increases, implying that excessive sediment accumulation disrupts fault interaction efficiency. These patterns highlight the nuanced influence of sedimentation rate on thrust fault dynamics, emphasizing the need for precise sediment flux characterization in tectonic models of active orogenic regions.

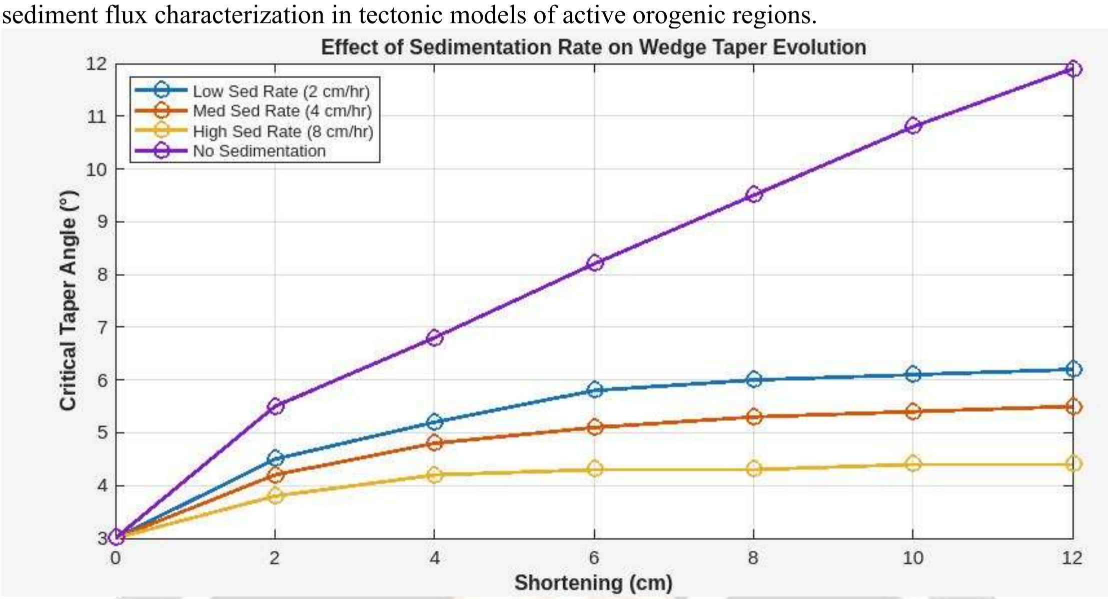

Figure 6: Effect of Sedimentation rate on wedge taper Evolution

The evolution of critical taper angle under varying sedimentation rates during progressive shortening is illustrates in Figure 6. Four scenarios are presented: no sedimentation, low (2 cm/hr), medium (4 cm/hr), and high (8 cm/hr) sedimentation rates. All scenarios show an increase in taper angle with shortening; however, the magnitude and rate differ. The medium and high sedimentation rates exhibit more pronounced taper increases, particularly at advanced shortening stages, indicating that sediment accumulation enhances wedge steepening and potentially wedge stability. The low sedimentation rate shows a more gradual taper increase, while the no-sedimentation model presents moderate taper growth but with less stability. These results demonstrate that sedimentation rate critically modulates wedge mechanical evolution, reinforcing the importance of integrating sediment dynamics into geomechanical models for accurate representation of fold-and-thrust belt development.

Conclusion

This study conclusively demonstrates the pivotal influence of sedimentation rates on the critical taper angle and mechanical evolution of thrust wedges under progressive shortening. The experimental results reveal that sediment accumulation significantly modulates wedge geometry, with higher sedimentation rates promoting steeper and more stable taper angles. This effect underscores sedimentation as a key factor in controlling wedge stability, strain distribution, and deformation front propagation. The marked differences in taper angle evolution and thrust migration between sediment-laden and sediment-free scenarios highlight the necessity of incorporating syntectonic sediment dynamics into geomechanical and tectonic models. Such integration enhances the predictive accuracy of wedge behavior across diverse geological environments, informing interpretations of fold-and-thrust belt development, sedimentary basin evolution, and associated resource potential. Beyond advancing theoretical frameworks, these findings carry practical implications for geological hazard assessment, hydrocarbon exploration, and basin management by elucidating how sediment supply interacts with tectonic forces to shape structural architectures. Future investigations should aim to refine these models by accounting for variable sediment properties, depositional rates, and coupled tectono-sedimentary feedbacks, thereby improving our capacity to anticipate structural responses under complex natural conditions.

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