Unsupervised Machine Learning Delineates the Variability of Turbidites in Unconfined Systems: A Distal Bengal Fan Case Study

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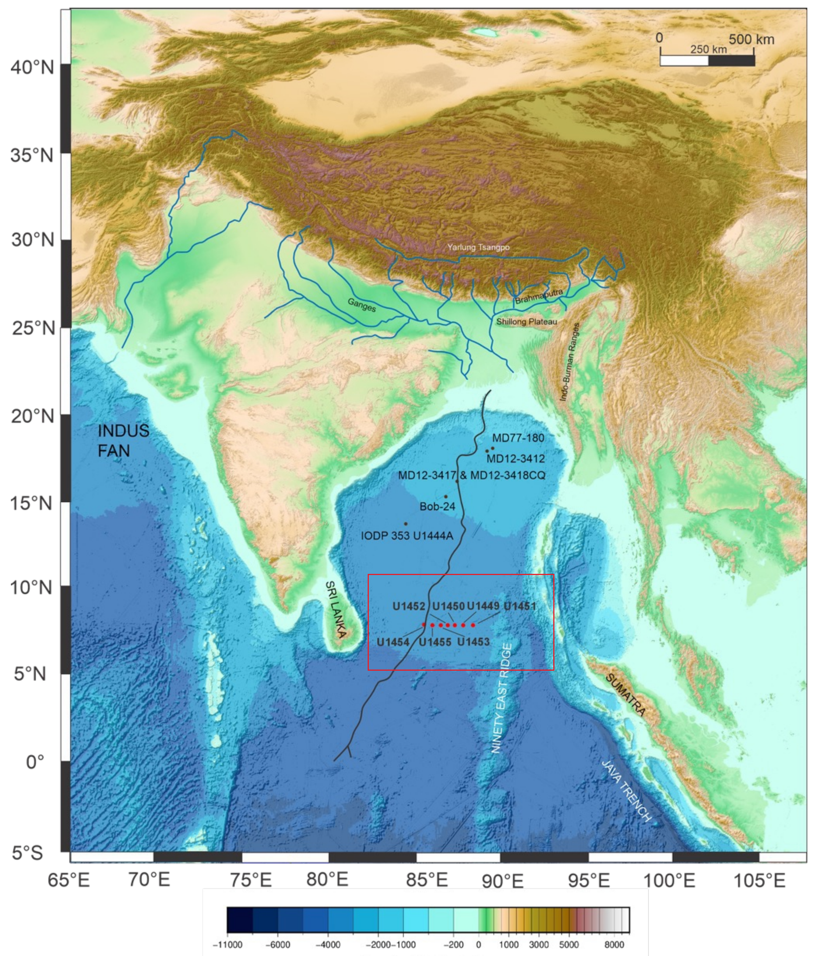
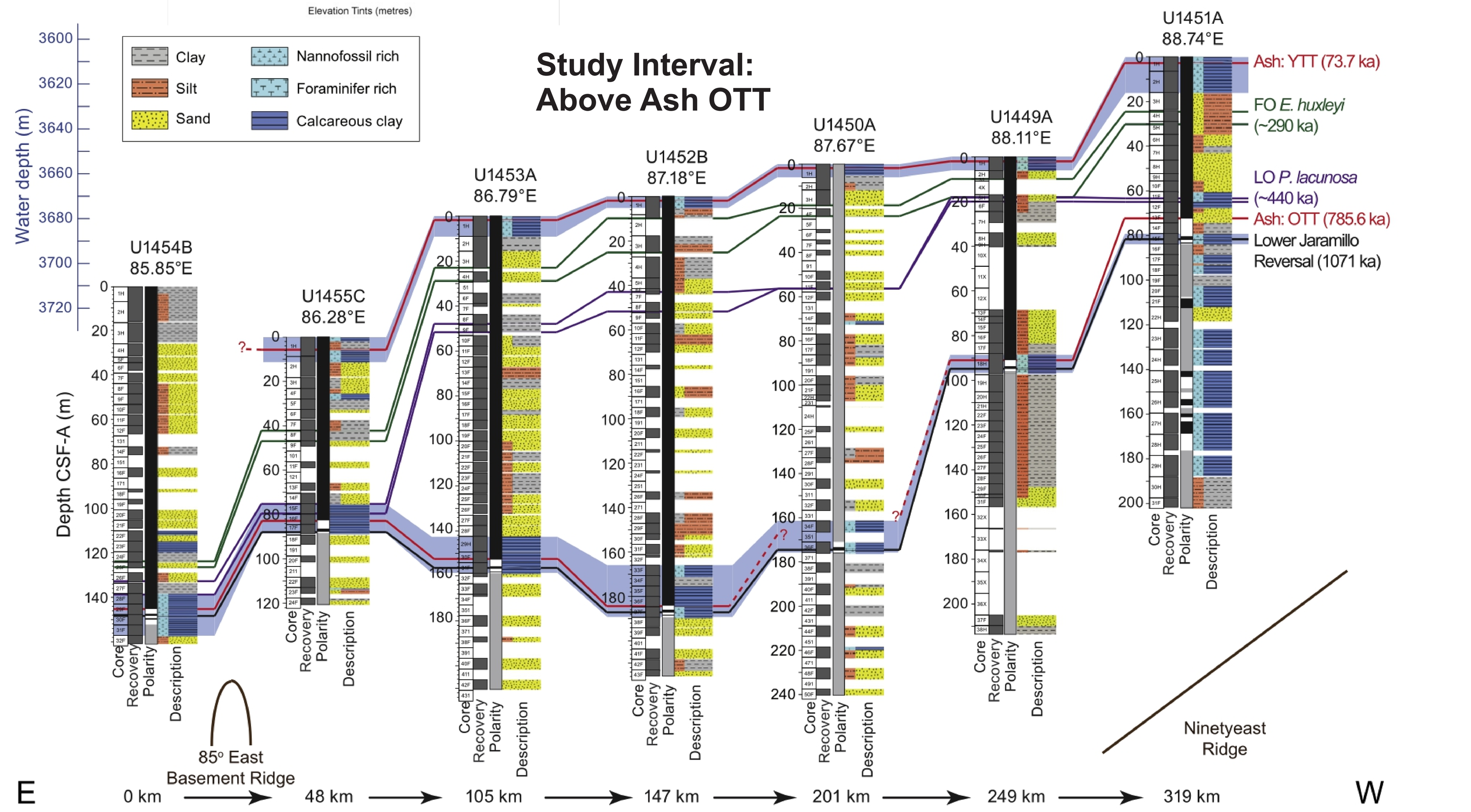
Background



Abstract

This study analyzes over 1000 sediment gravity flow deposits from IODP Expedition 354 in the distal Bengal Fan. Machine learning reveals two scaling endmembers: thin silty beds with proportionally thick caps, and thick sandy beds with proportionally thick caps. Clustering identifies thickness thresholds of 5 cm and 30 cm (basal division) that align with historical classifications. Comparison with the confined Castagnola system demonstrates that basin confinement exerts primary control on internal scaling. Unconfined settings show negative scaling with increasing amalgamation in thicker beds, while confined basins reveal positive scaling. Hybrid event beds display systematically thinner caps and higher cap loss rates than turbidites regardless of setting.



Lithology and correlation of the Middle to Late Pleistocene core transect of the IODP Expedition 354 Bengal Fan at 8°N (Weber and Reilly, 2018).

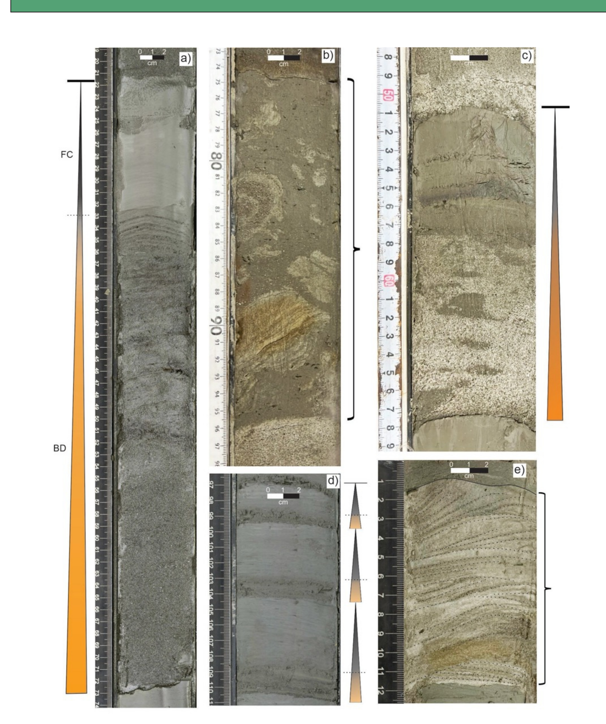
Bengal Fan

- Initiated by the high erosion rate following the uplift of the Himalayas
- Himalayan-Brahmaputra-Ganges-Bengal Fan is the Earth's largest sediment dispersal system

IODP 354

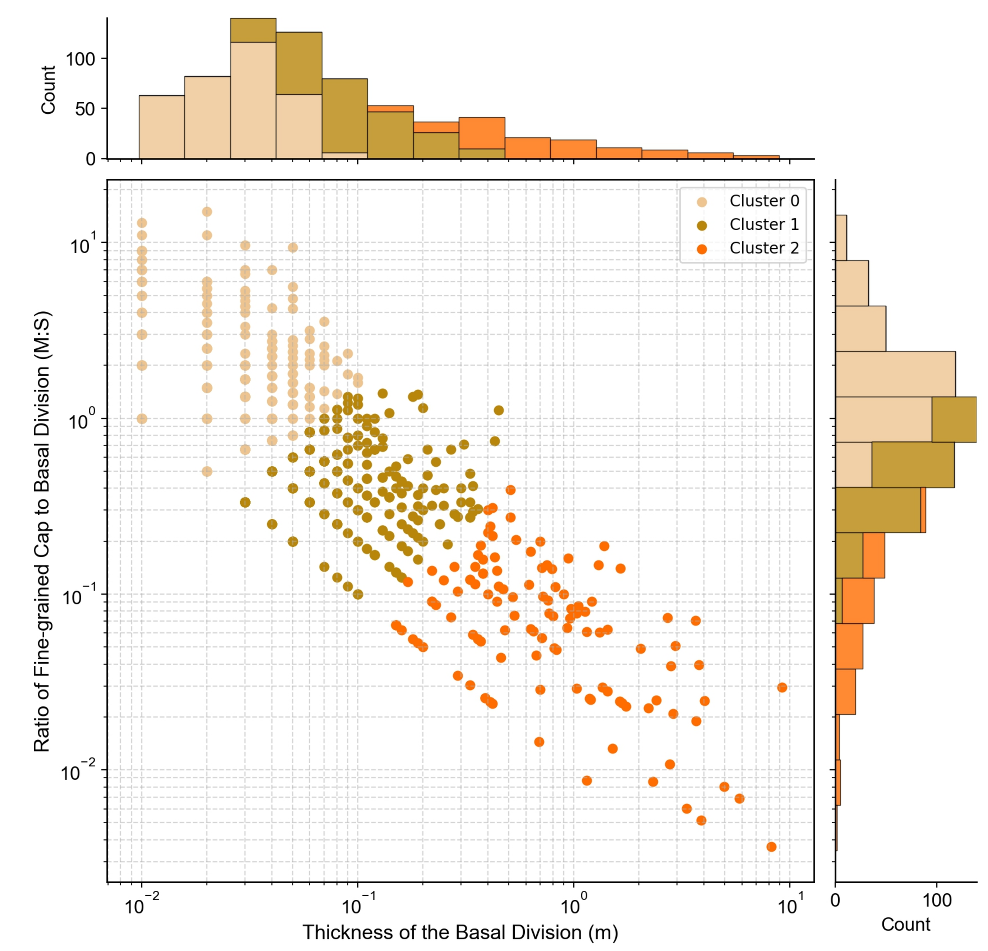
- A transect of seven core sites along 8°N
- From a western active channel to the Ninety East Ridge
- Recovered plenty **sands** and terrestrial organic materials

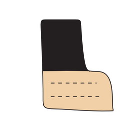
Sediment Gravity Flow Events



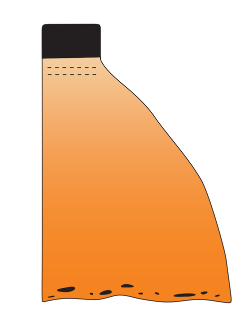
SGF Division	Grain Size	Bouma Sequence	Lowe Sequence	HEB Model (Haughton et al., 200)	Common Terminology	Rheology Interpretation
Basal Division (BD)	Coarse Sand to silt	Ta, Tb, Tc, Td	S3	H1, H2, H3, H4	Sand base, lower division, coarse division, basal division	Continuum of traction-dominated sedimentation reflecting progressive energy decrease from upper flow regime to lower flow regime; deposited by varied mechanisms including rapid suspension fallout, traction carpet development, and bedform migration depending on flow concentration, turbulence intensity, and deceleration rate; may include transitional flow deposits (H2) with banded appearance and a cohesive, matrix-rich component (H3) in hybrid event beds where turbulence is suppressed and clay-induced cohesion dominates (Bouma, 1962; Lowe, 1982; Haughton et al., 2009; Sumner et al., 2012; Talling et al., 2012; Hage et al., 2017)
Fine-grained Cap (FC)	Muddy silt to clay	Te		H5	Upper muddy division, Shale cap, Mud cap, Mud drape	Final suspension fallout from dilute cloud; a dilute turbulent flow in the waning stages of the event; may include subsequent hemipelagic settling (Bouma, 1962; Stow and Shanmugam, 1980)

Clustering Analysis of Turbidite Spectrum

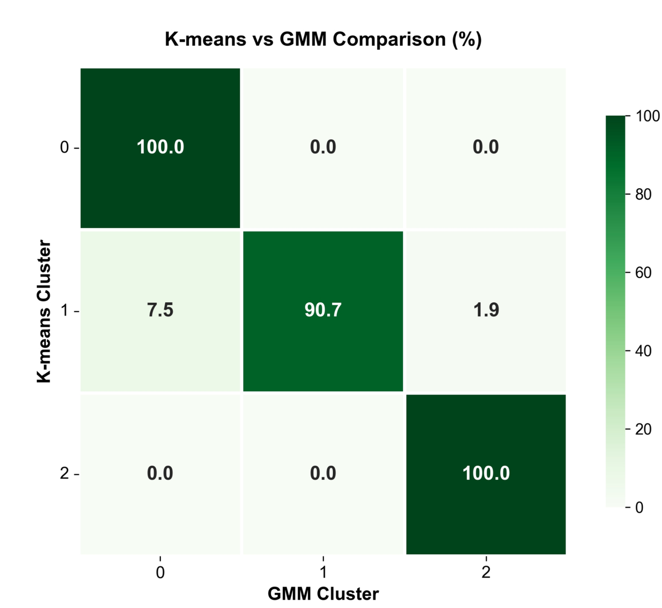




Cluster 0:
Thin, silty basal divsion with relatively thick fine-grained cap endmember

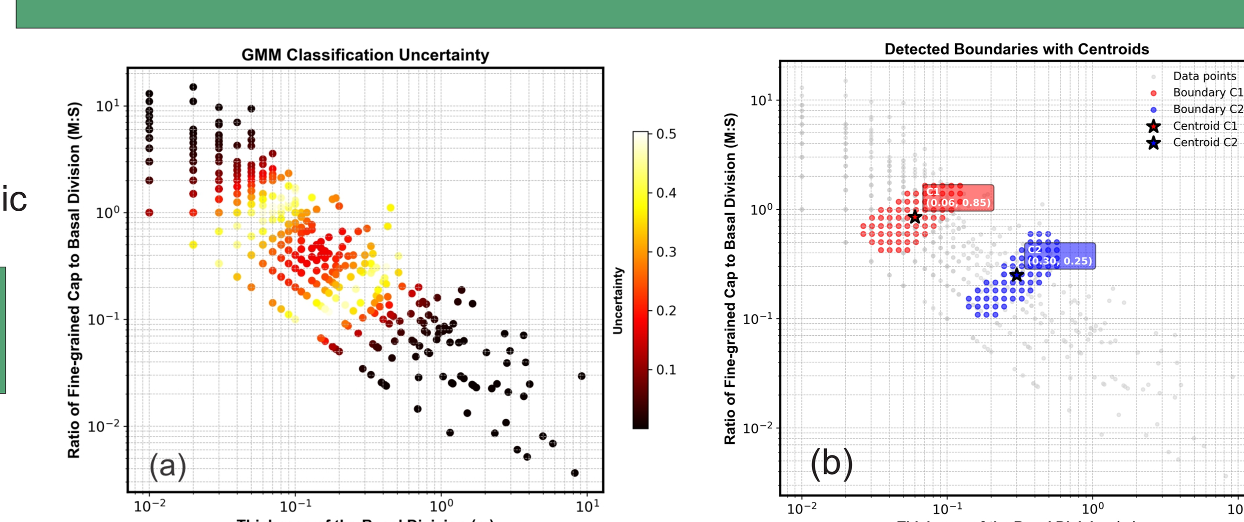


Cluster 2:
Thick, sandy basal divsion
with relatively thin fine-grained cap endmember



- Two independent clustering tests: K-means and Gaussian Mixture Model (GMM), which show high agreement (96.3%), supporting that the identified patterns represent genuine geological populations and confirming the integrity of the input data.
- GMM was ultimately selected due to its superior suitability with the elongated distribution geometry and its ability to provide uncertainty analysis

Thickness Based Classification: Data-driven Thresholds and Literature Context



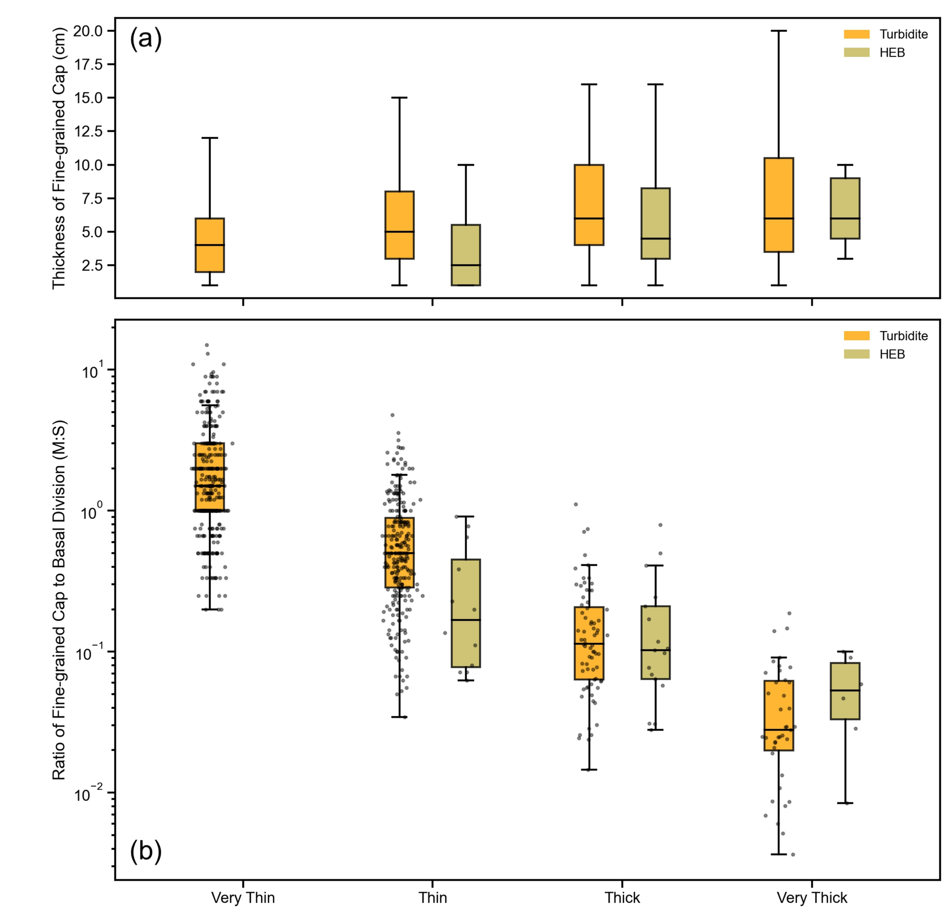
- Classification **uncertainty** was calculated as 1 minus the maximum probability score
- High uncertainty regions were identified as boundary zones and clustered using DBSCAN to locate coherent transition regions between adjacent clusters
- Geometric centroids of boundary clusters yielded thickness thresholds at 0.06 m and 0.3 m, rounded to 0.05 m (5 cm) and 0.3 m (30 cm) for practical classification

Classification	Ingram 1954	McKee and Weir 1953
Very thin	1-3cm	1-5cm
Thin	3-10	5-60
Medium	10-30	NaN
Thick	30-100	60-120
very thick	>100	>120

Classification Thresholds Based on Basal Division (BD) Thickness from this Study

- Very thin: 0 < BD ≤ 5 cm
- Thin: 5 < BD ≤ 30 cm
- Thick: 30 < BD ≤ 100 cm
- Very thick: BD > 100cm

Influence of Flow Properties on Scaling - Turbidite vs HEB



Thickness Group	Turbidite Count	HEB Count	Turbidite Amalgamation Rate	HEB Cap Loss Rate
Very Thin	428	1	1%	0%
Thin	363	26	7%	27%
Thick	108	33	13%	30%
Very Thick	84	7	21%	29%

Consistent Absolute and Relative Scaling Trends in Both HEBs and Turbidites

- Absolute cap thickness generally increases with basal division thickness
- However, relative scaling (M:S ratio) decreases with basal division thickness
- Cap growth rate is slower than basal division growth rate

Distinct Internal Scaling Between HEBs and Turbidites

- HEBs have thinner fine-grained caps than turbidites of comparable thickness
- HEBs show higher cap loss rates (M:S = 0)
- Interpretation: HEBs have lower clay fractionation efficiency due to mud internalization within linked debrites

Comparison with Confined Case Study

Data Observation

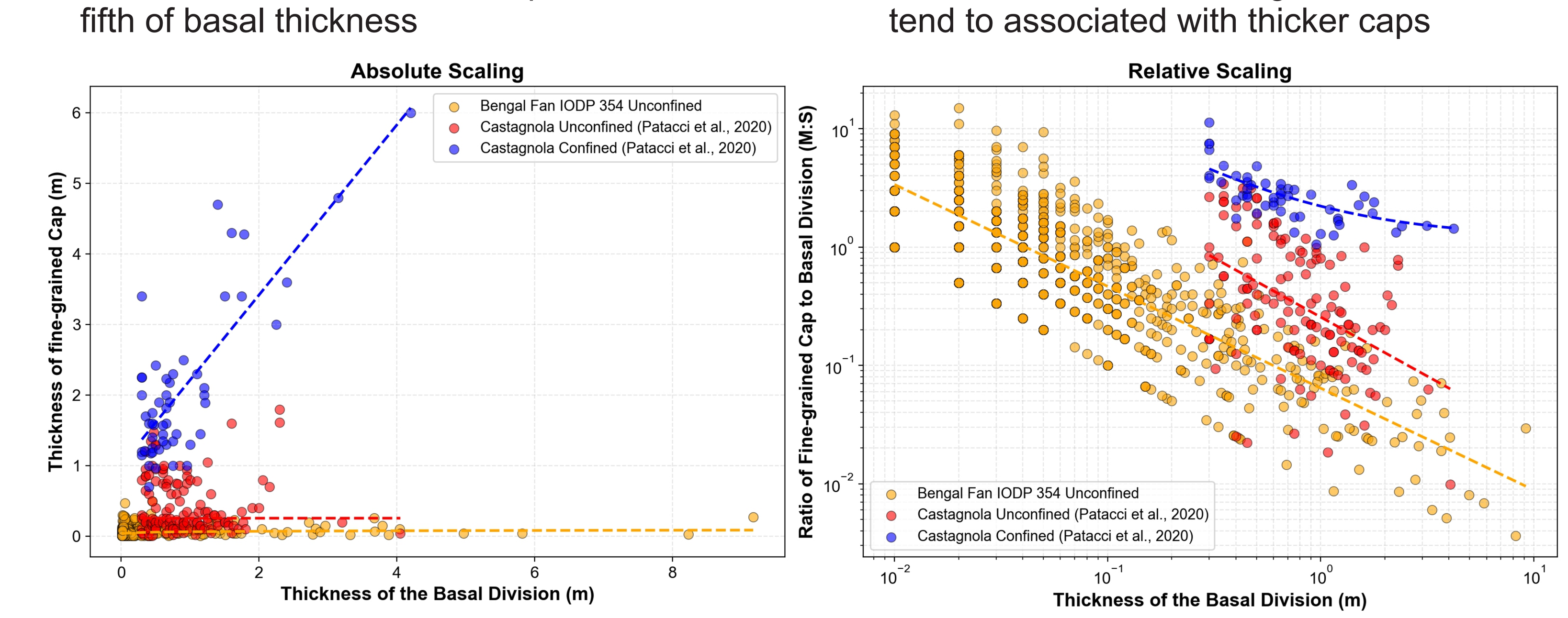
Unconfined Distal Bengal Fan:

- Weak absolute scaling trends but strong negative relative scaling (power-law)
- Thick beds (>1 m basal thickness) consistently show M:S ratios <0.2, with caps less than one fifth of basal thickness

Data Observation

Confined Portion of Castagnola System (Patacci et al., 2020)

- Confined portion of Castagnola shows strong positive absolute scaling
- In terms of relative scaling, thick basal beds tend to associated with thicker caps



Generalized Interpretation

Basin confinement exerts primary control on fine-grained partitioning, which manifests as distinct internal scaling patterns: confined basin settings force flow deceleration and local fine trapping, while unconfined settings allow continued bypass.

Key References

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