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Heterogeneous Roughness Properties of Fault Surfaces: New Insights from Laboratory Experiments

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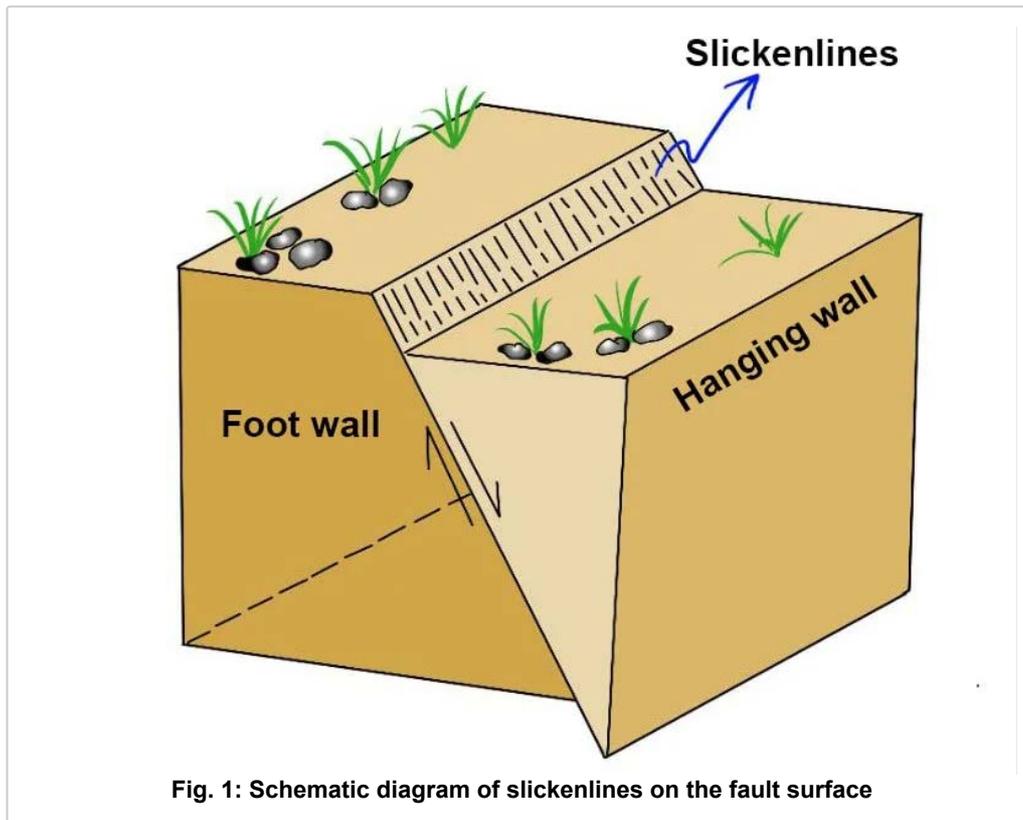
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SCIENCE LEADS THE FUTURE

INTRODUCTION

Slickenlines

- **Linear features** on fault surfaces
- Geometrically defined by **alternate ridge and groove**
- **Reliable indicator of slip**



Genetic types of classical slickenlines

Twiss and Moores (1992) have classified slickenlines broadly into three types:

- **Structural slickenlines** originate from mechanical wearing and ploughing by hard asperities on relatively softer substrates. (*Fig. 2b*)
- **Mineral slickenlines** result from the accumulation of streaks from the smearing out of mineral grains or soft asperities behind hard asperities. (*Fig. 2d*)
- Fault movements often generate locally positive and negative dilation zones in the neighbourhood of geometrical irregularities. At the opening (positive dilation) locale, **slickenfibers** grow, tracking the local displacement vectors. (*Fig. 2e and f*)

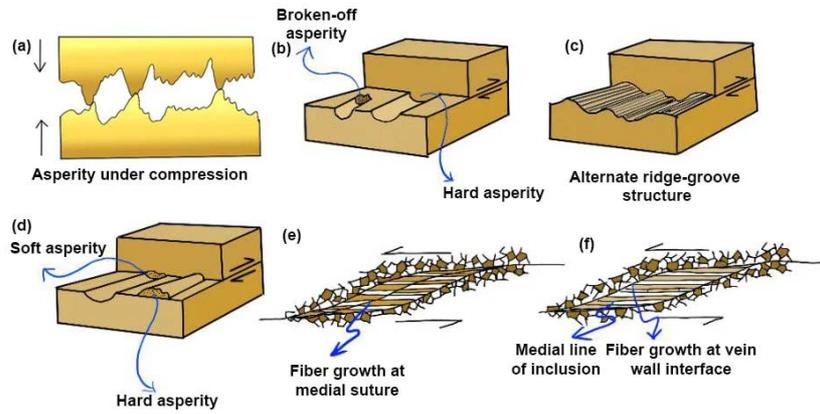


Fig. 2: Schematic diagram of (a) Asperity, (b) Structural slickenlines, (c) Slickenlines defined by alternate ridge and grooves, (d) Mineral slickenlines, (e) Syntaxial fiber slickenlines, (f) Antitaxial fiber growth. (Modified after *Twiss and Moores, 1992*)

EXPERIMENTAL APPROACH

Method

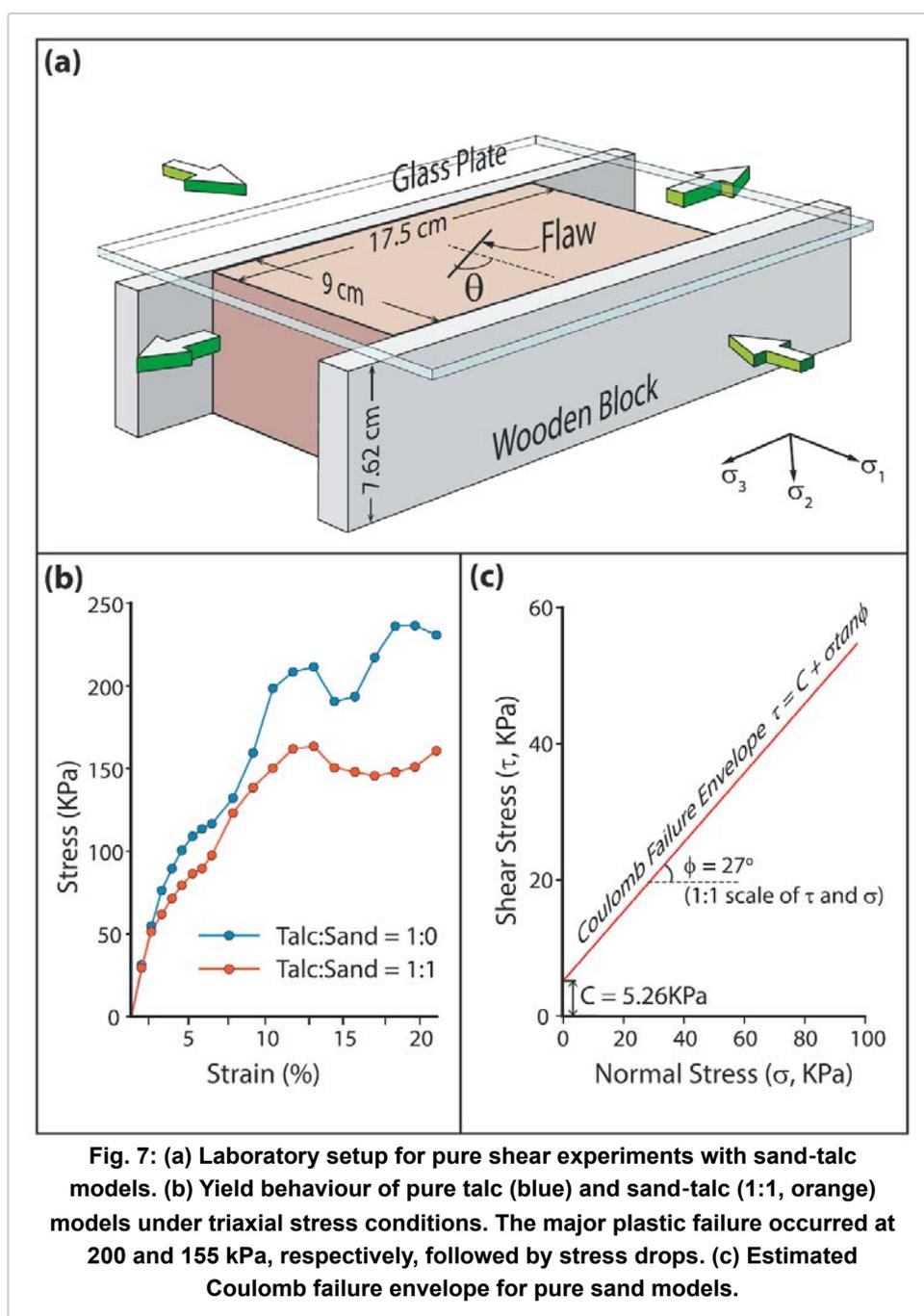
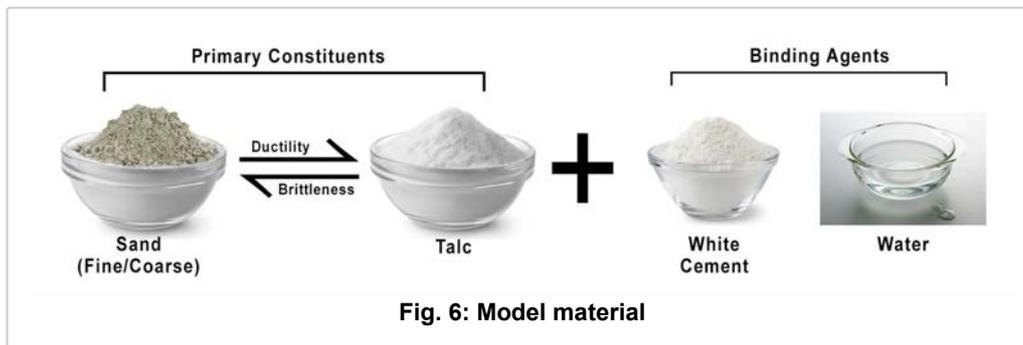
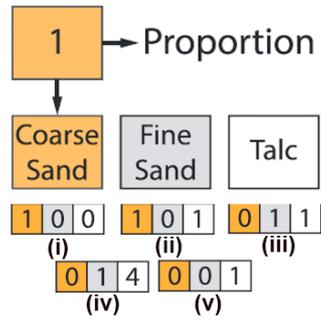


Fig. 7: (a) Laboratory setup for pure shear experiments with sand-talc models. (b) Yield behaviour of pure talc (blue) and sand-talc (1:1, orange) models under triaxial stress conditions. The major plastic failure occurred at 200 and 155 kPa, respectively, followed by stress drops. (c) Estimated Coulomb failure envelope for pure sand models.

- Type 1 Model:** This experiment had a small initial planar flaw (vertical planar cut with a length of 2 cm) in the middle of the talc-sand block at an angle of 45° to the principal compression direction (σ_1). Type 1 experiments were performed in multiple sets by varying the sand:talc volume ratio-



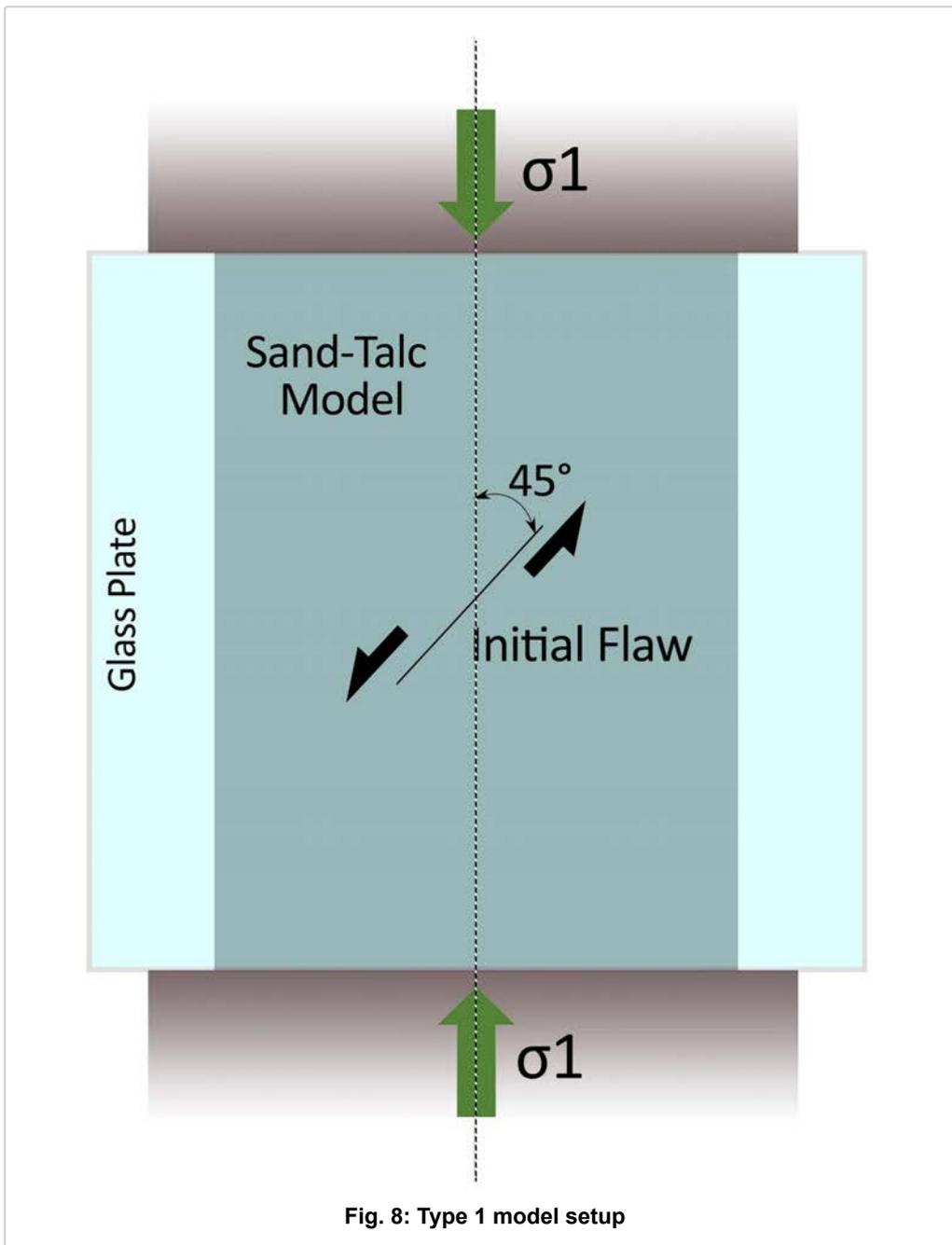
(i) 1:0 (pure coarse sand),

(ii) 1:1 (coarse sand-talc mixture),

(iii) 1:1 (fine sand-talc mixture),

(iv) 1: 4 (fine sand-talc mixture), and

(v) 0:1 (pure talc).



- **Type 2 Model:** The model had a throughgoing cut, which activated to produce a shear fracture during the compression. The model block was prepared by using only talc, added with cement and water. The block was cut into two halves at the desired angle (θ) to the principal compressive stress axis (σ_1).

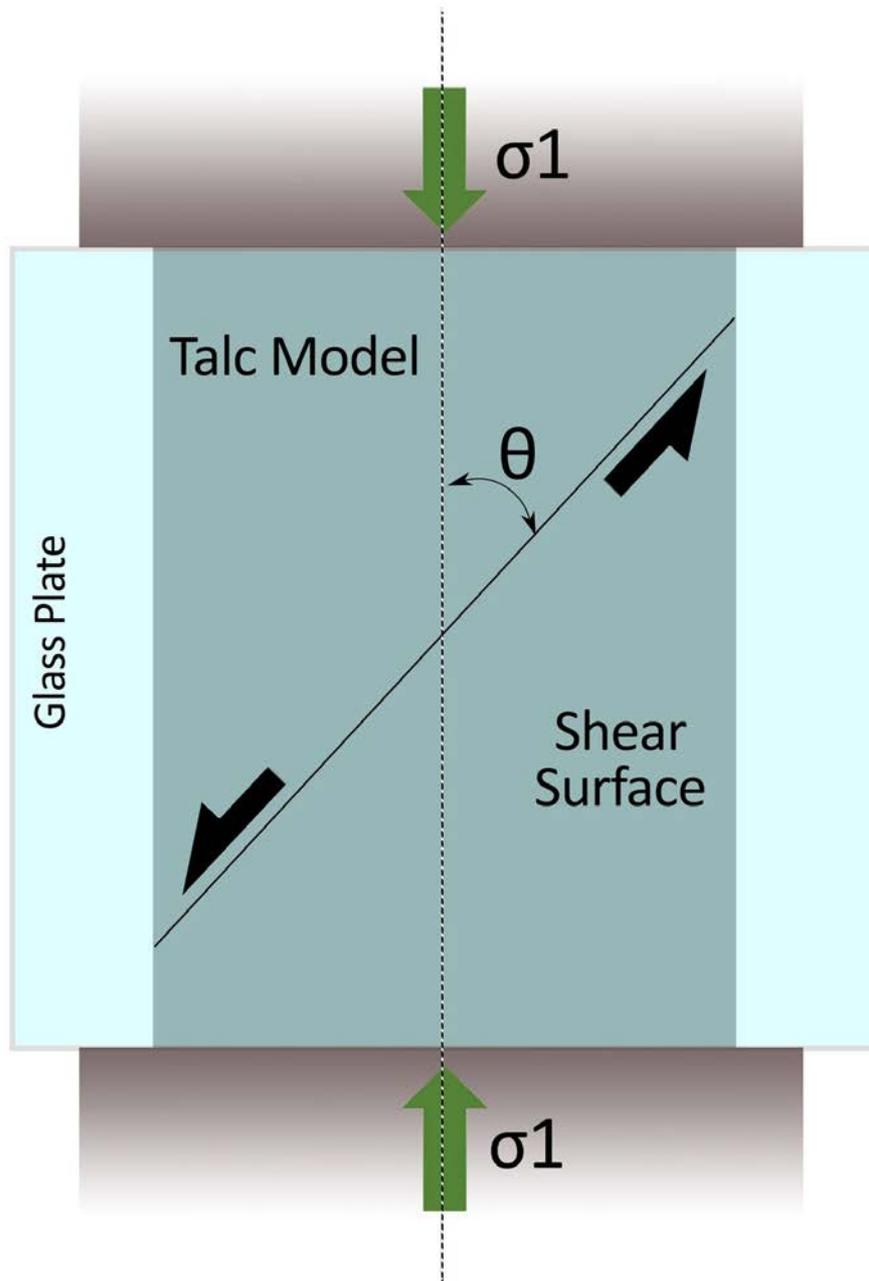
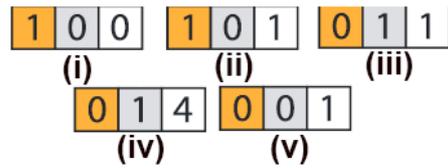


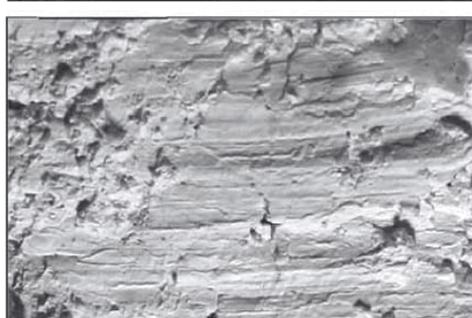
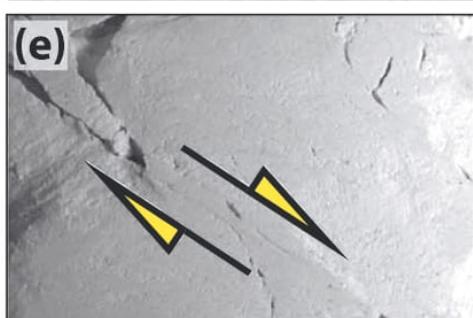
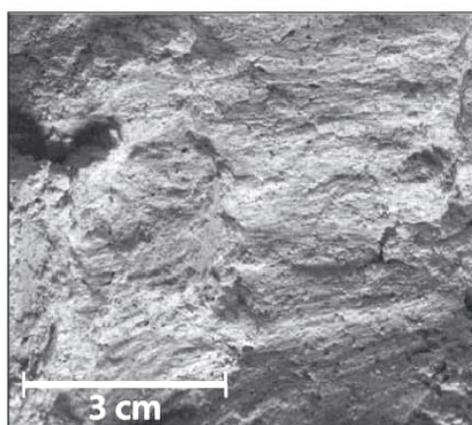
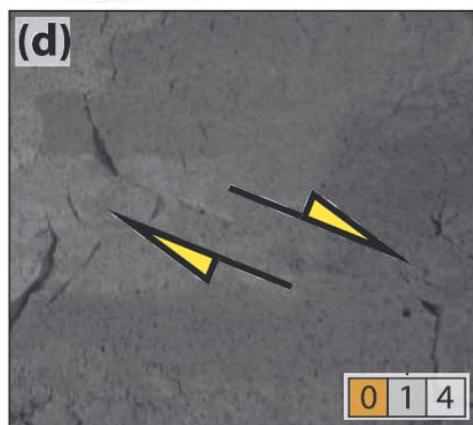
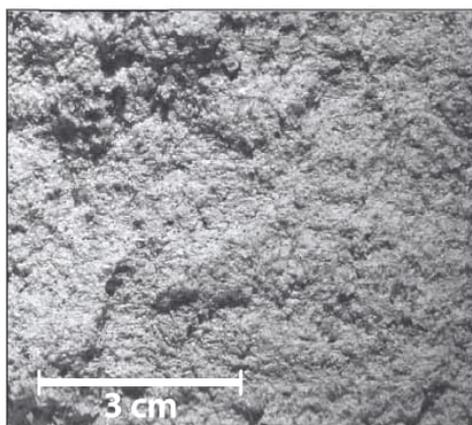
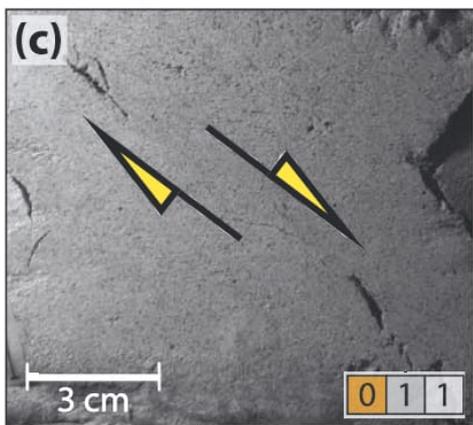
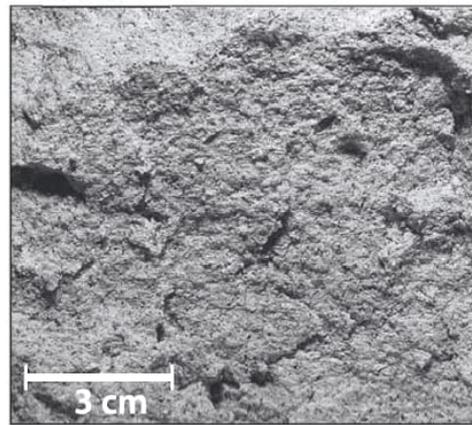
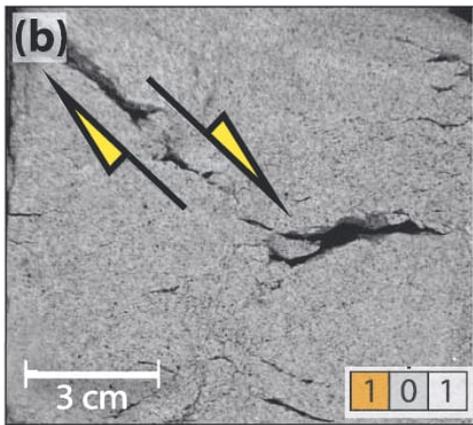
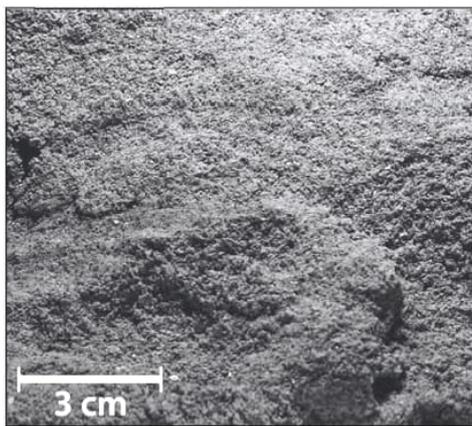
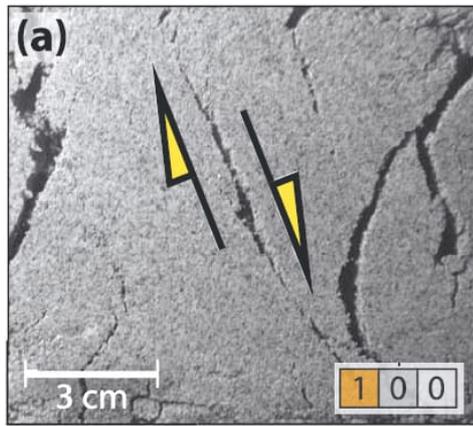
Fig. 9: Type 2 model setup

EXPERIMENTAL FINDINGS

Type 1 Experimental Results



- (i) Produced excellent shear fractures but **without any prominent linear features** on them (*Fig. 10a*).
- (ii) Also did not develop typical slickensides but **showed weak traces of slip motion**, albeit locally on the shear fractures. (*Fig. 10b*).
- (iii) Yielded multiple sets of shear fractures with somewhat **discernible linear irregularities** (*Fig. 10c*).
- (iv) Produced shear fractures **with bold slickenlines**, localized in isolated patches (*Fig. 10d*).
- (v) Produced **excellent one-dimensional irregularities**, giving an appearance of **typical slickensides** (*Fig. 10e*).



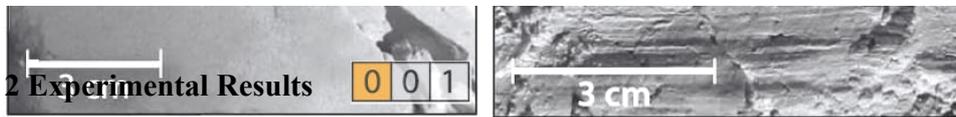


Fig. 10: Formation of shear fractures in Type 1 sand-talc models (left panel) under laboratory conditions (top views). (a) Pure sand, (b) coarse sand-talc (1:1) (c) fine sand-talc (1:1); (d) fine sand-talc (1:4) and (e) pure talc. Their corresponding

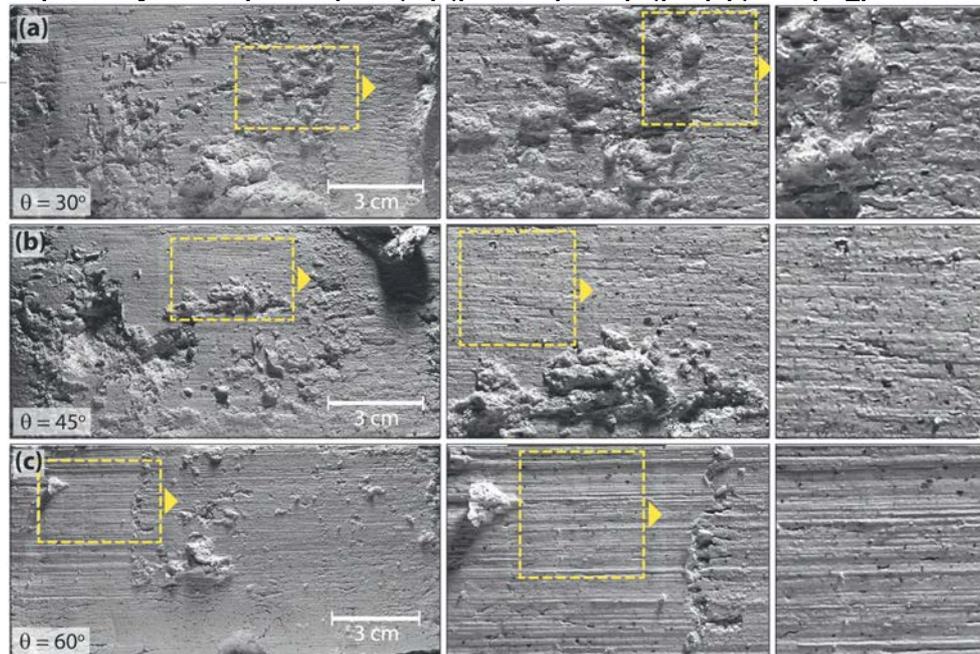


Fig. 11: Variations of the shear fracture roughness in Type 2 pure talc models. The shear fracture angles to the compression direction (θ) were (a) 30° , (b) 45° , and (c) 60° . Notice that the shear surfaces contain relatively smooth domains with prominent lineation (slip zones) and rough domains without any linearity (stuck zones). The latter tends to die out with increasing θ . The yellow boxes show areas of observation with successive magnifications (left to right).

ROUGHNESS ANALYSIS

Computational Method

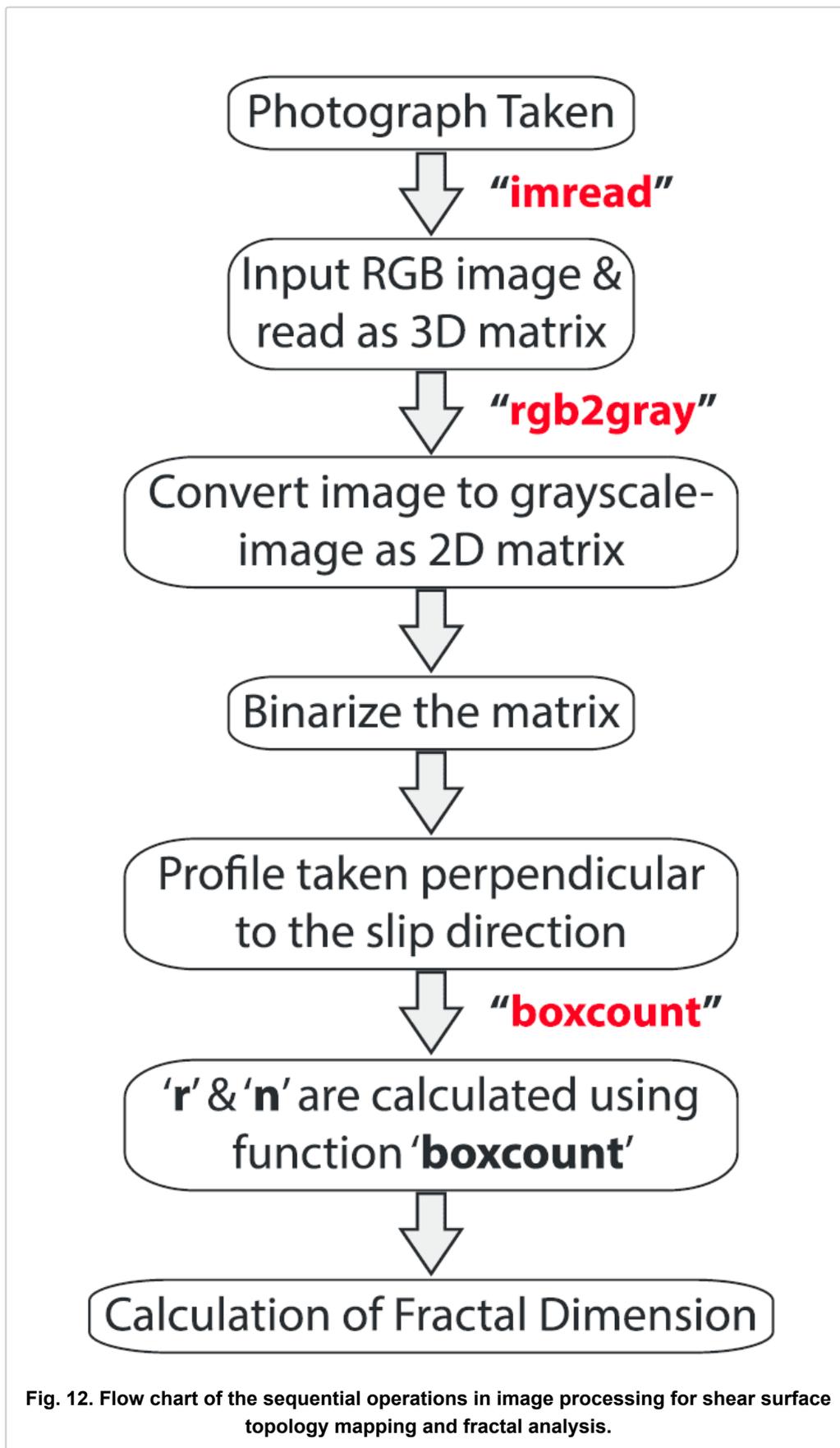
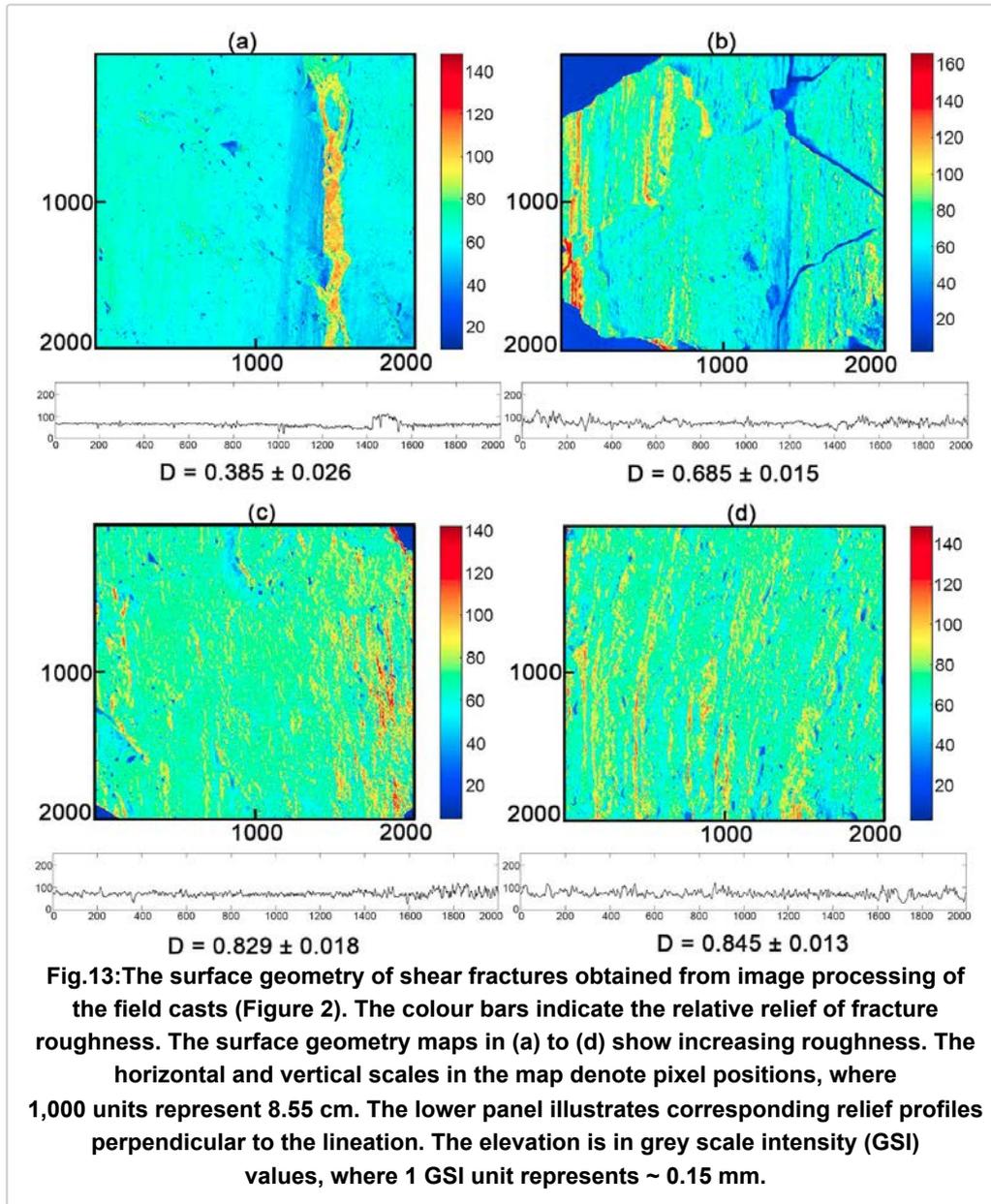


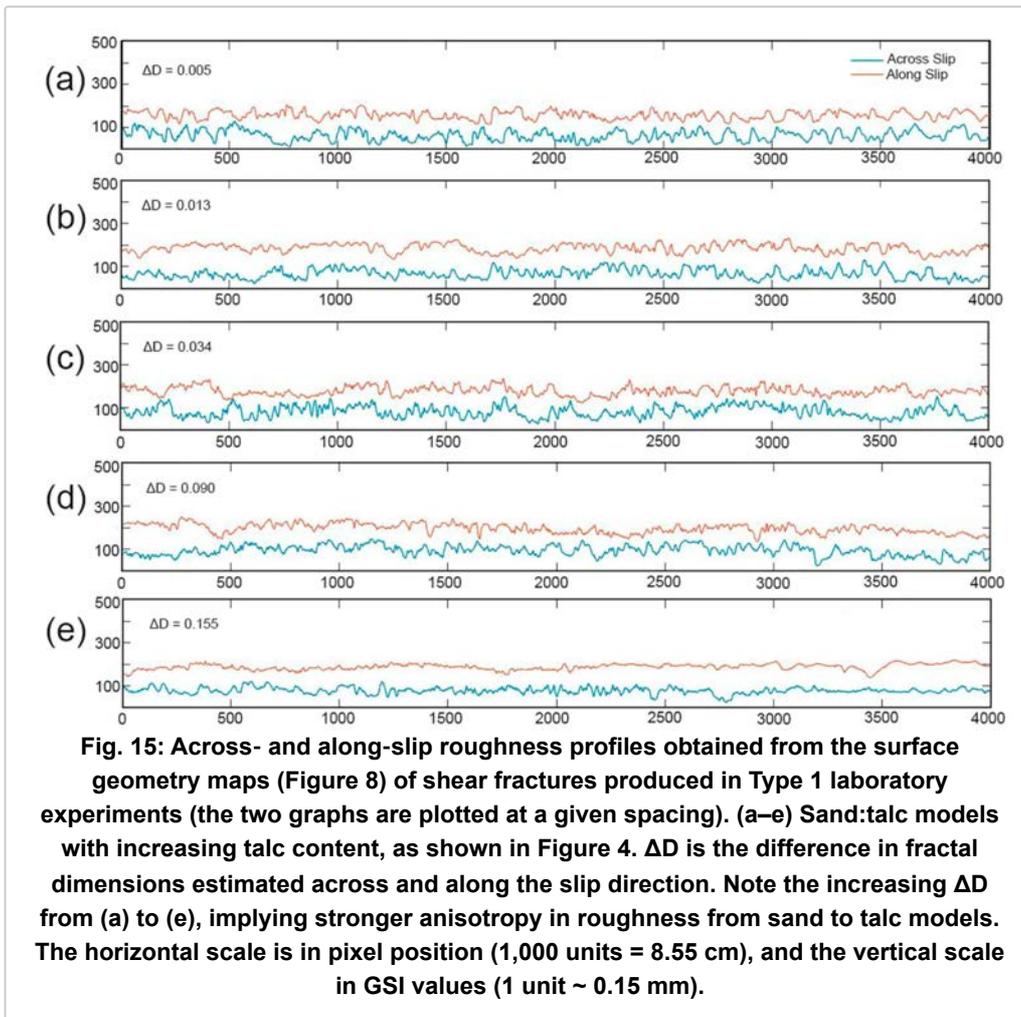
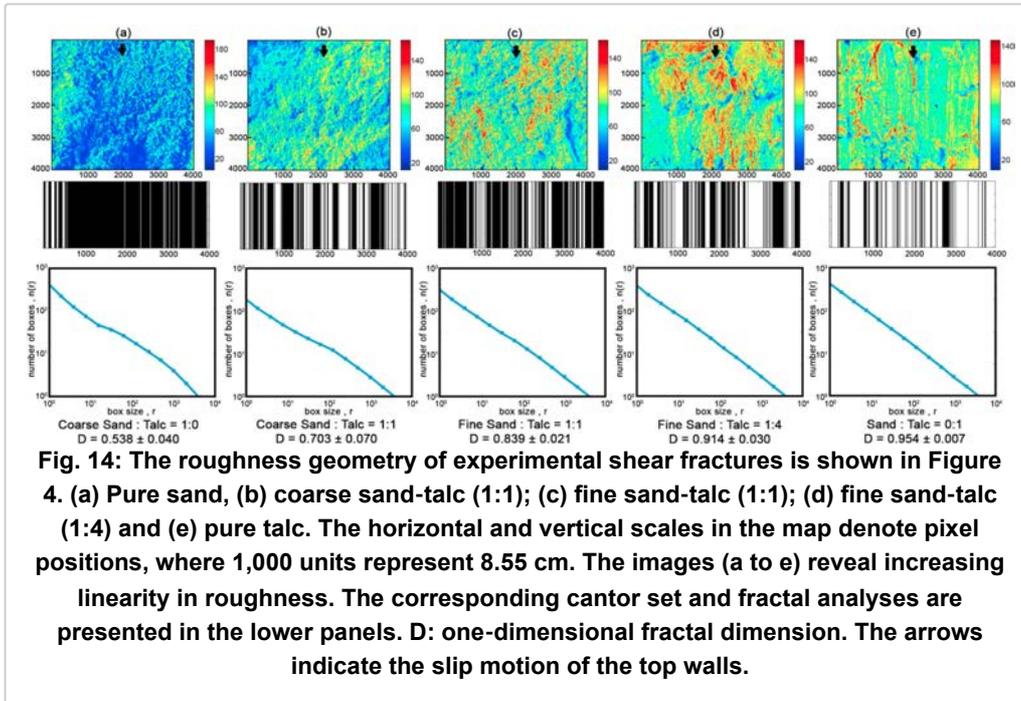
Fig. 12. Flow chart of the sequential operations in image processing for shear surface topology mapping and fractal analysis.

Analysis Results

Casts Analysis



Type 1 Experiment Analysis



Type 2 Experiment Analysis

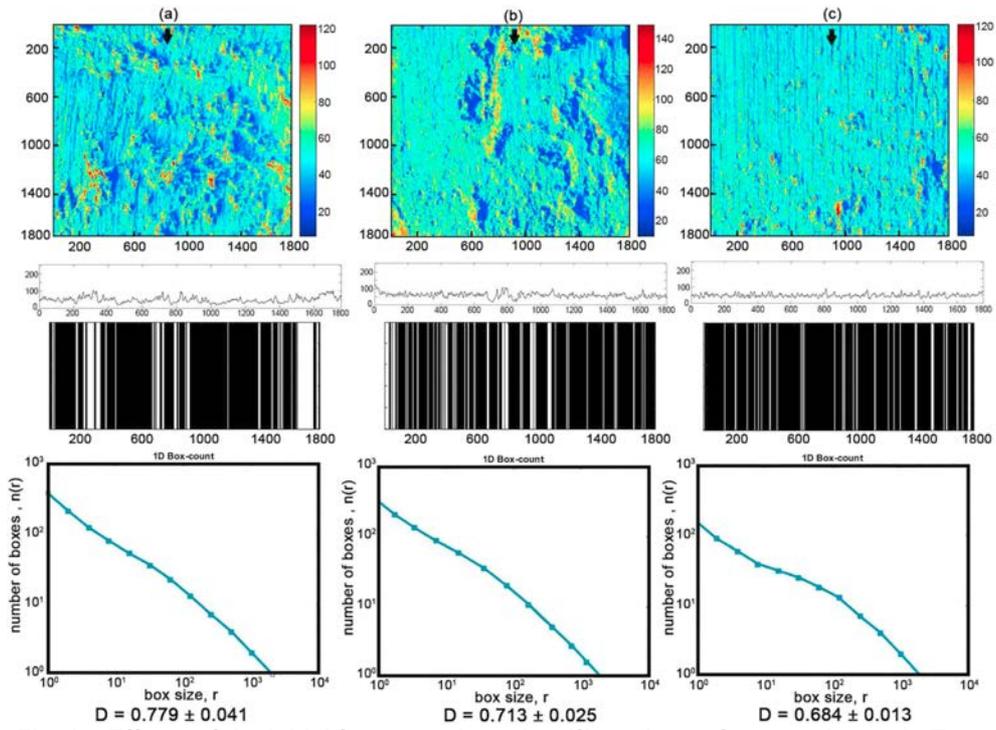
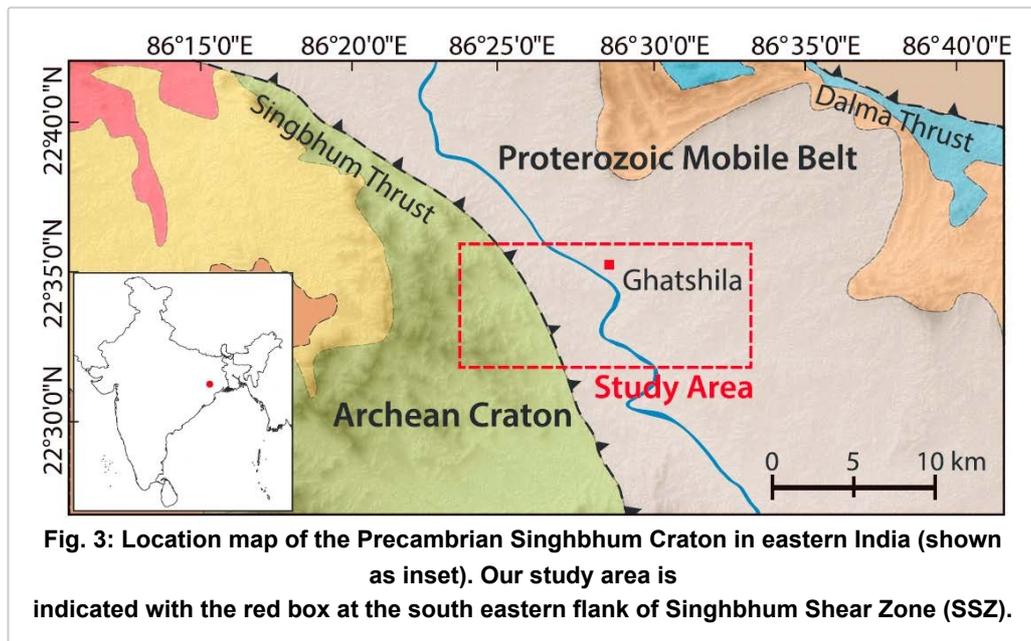


Fig. 16: Effects of the initial fracture orientation (θ) on the surface roughness in Type 2 experiments. $\theta =$ (a) 30° , (b) 45° and (c) 60° . θ : Inclination of the fractures to the principal compression direction. The corresponding across-slip profiles, cantor sets, and fractal analysis are shown below.

FIELD STUDY

Field Area

Southern parts of the **Singhbhum Shear Zone** and some adjoining parts of the Singhbhum Fold Belt on the north of SSZ (*Fig. 3*). Two locations were chosen: (1) Patherogora region near old Surda copper mines and (2) Tentuldanga region. Patherogora is a small village in Purbi Singhbhum district, Jharkhand (22°32'37.911"N, 86°26'31.223"E, altitude: 146 m, accuracy: ±3 m), and falls in the southern part of SSZ.



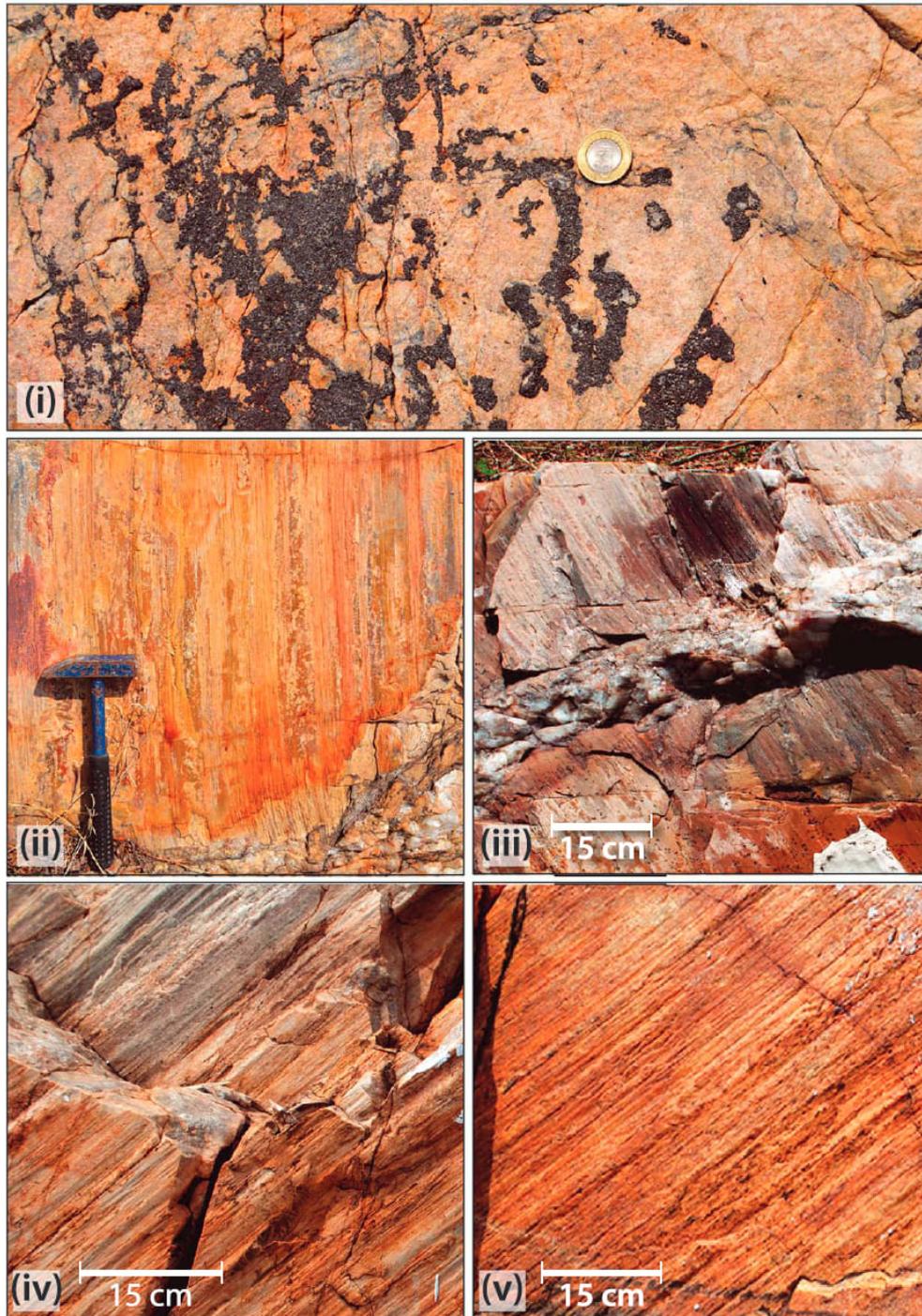


Fig. 4: Three principal types of slickensides observed in the SSZ area. (i) Type 1: Smooth fault surfaces without any discernible linear roughness; (ii and iii) Type 2: slickensides with lineation defined by fine-scale ridges and grooves; and (iv and v) Type 3: slickensides with wavy linear roughness defined by ridges and grooves of varying coarseness. The coin diameter (i) and hammer length (ii) are 2.7 and 30 cm, respectively.

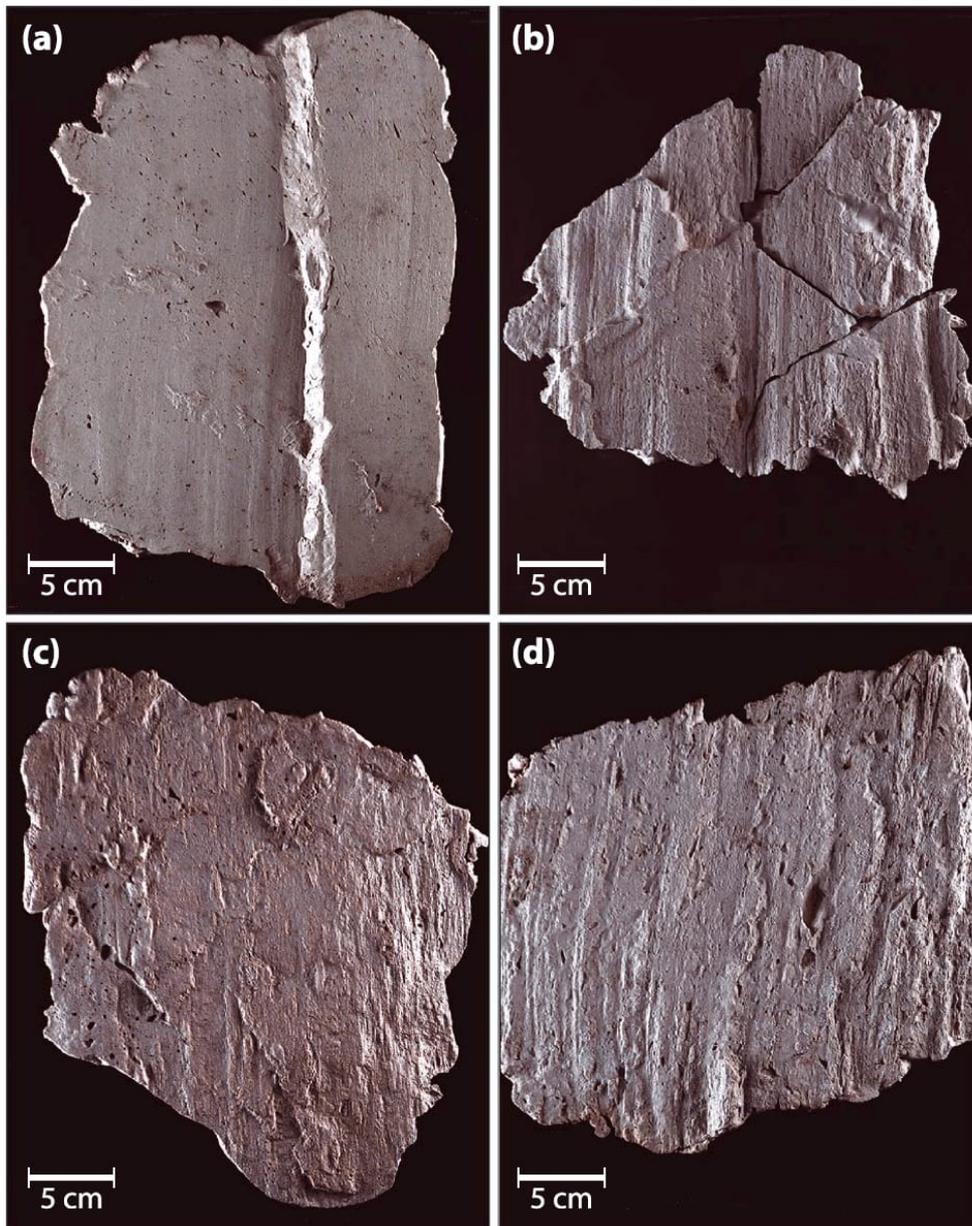
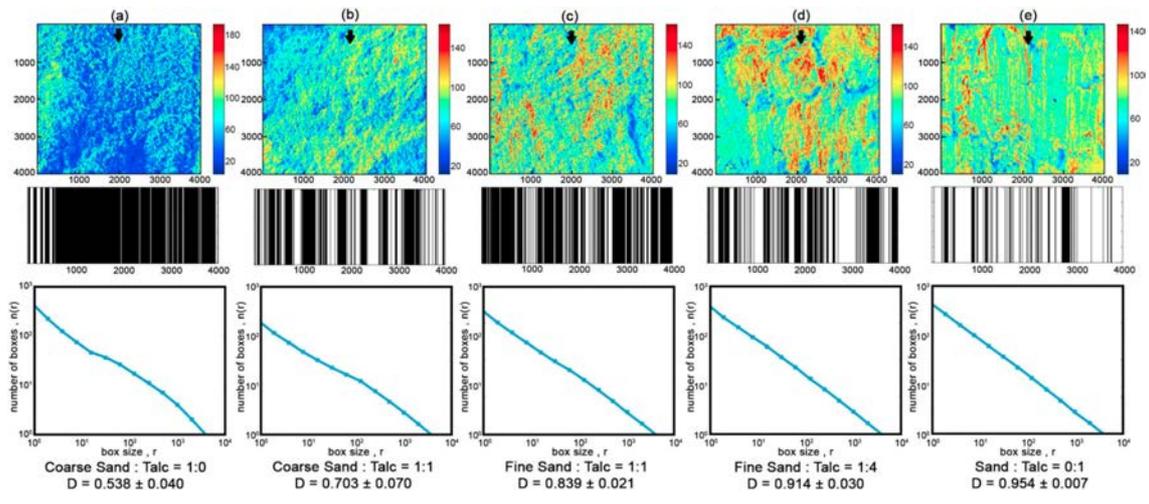
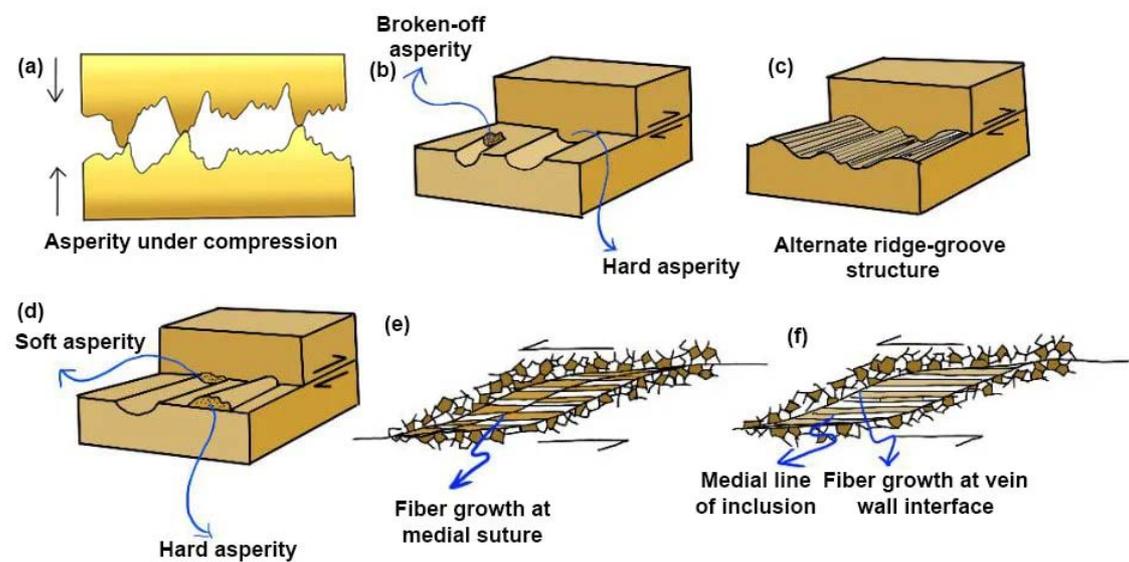
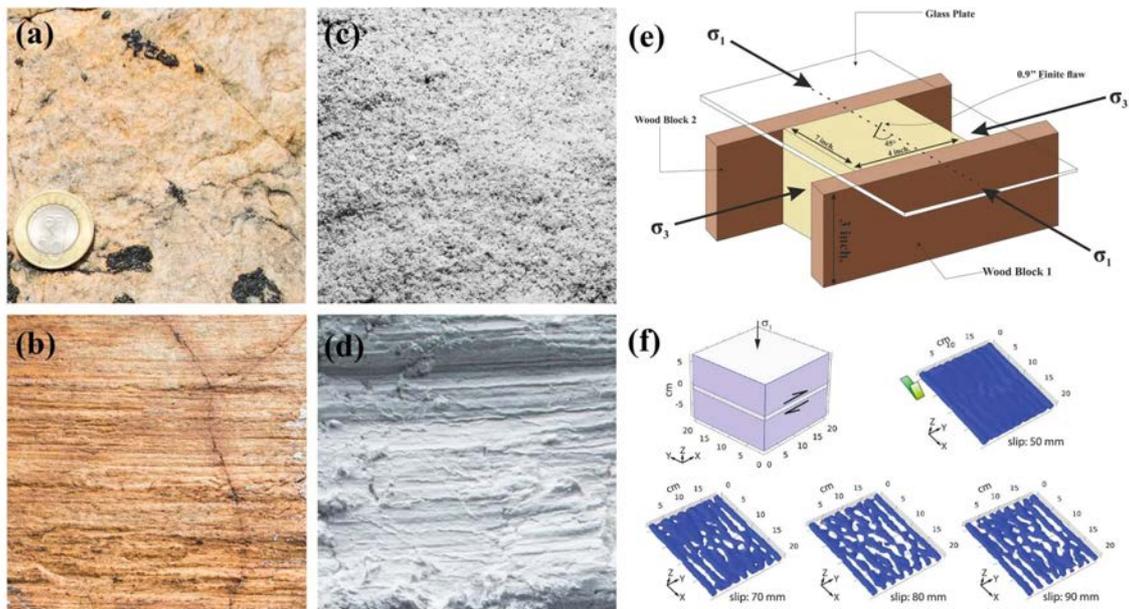
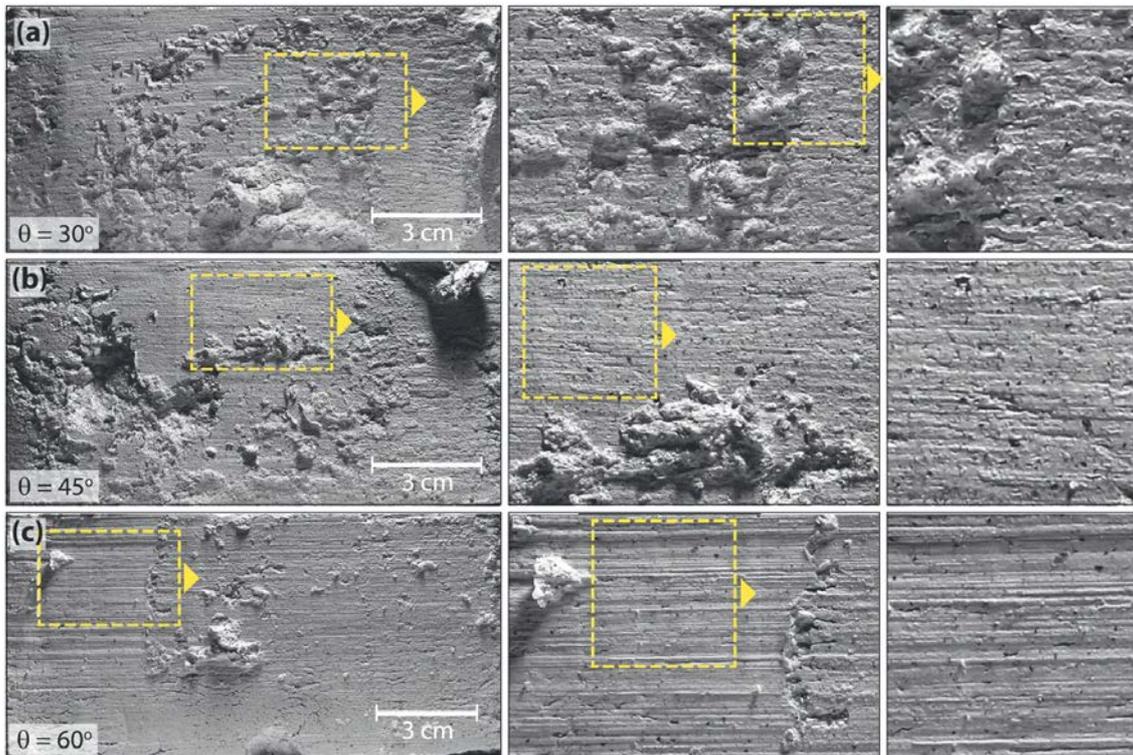
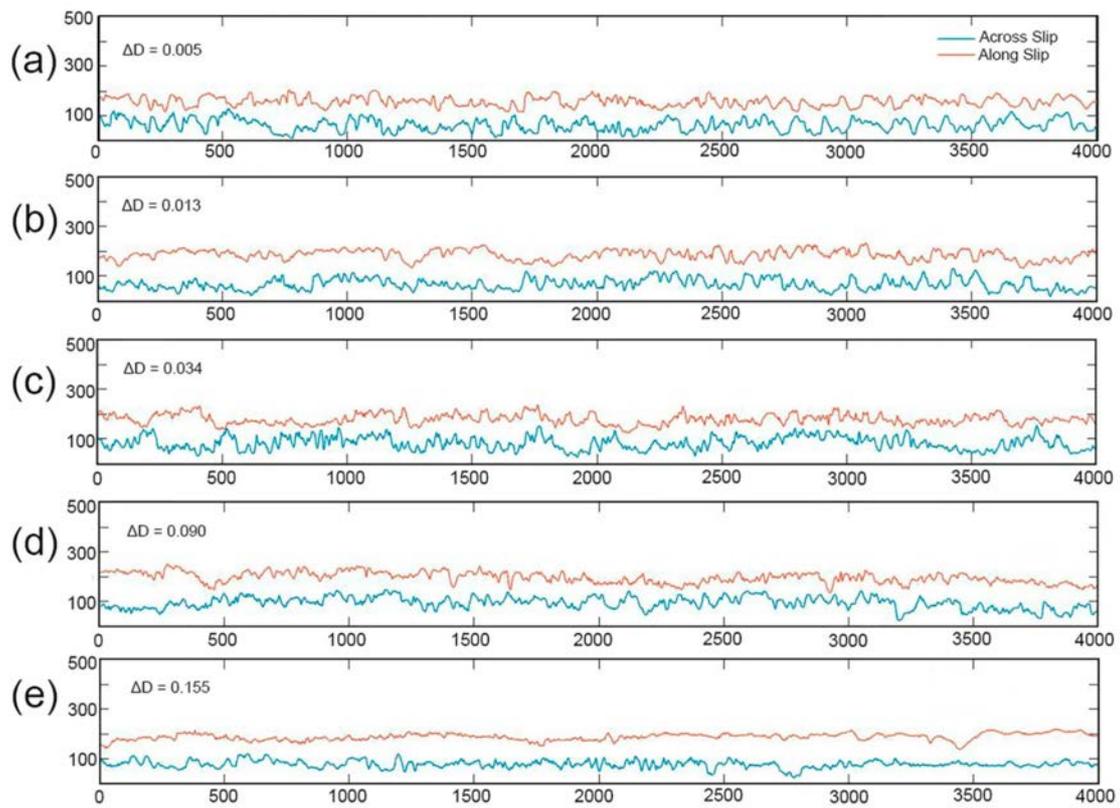
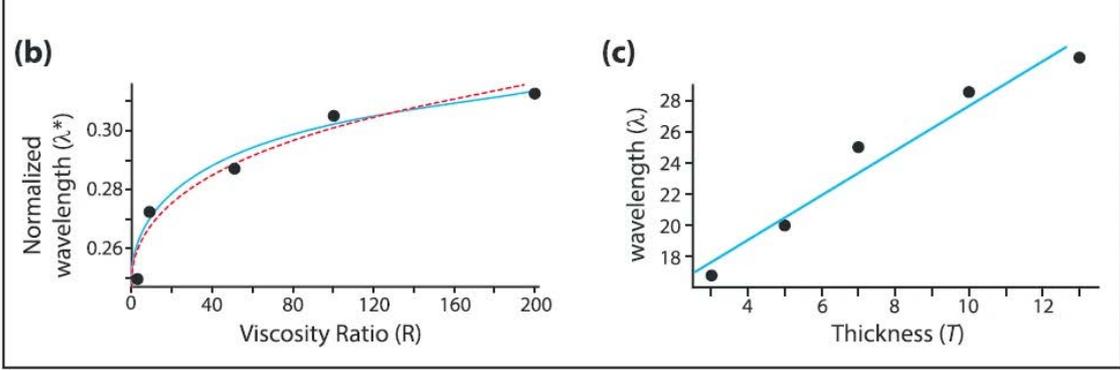
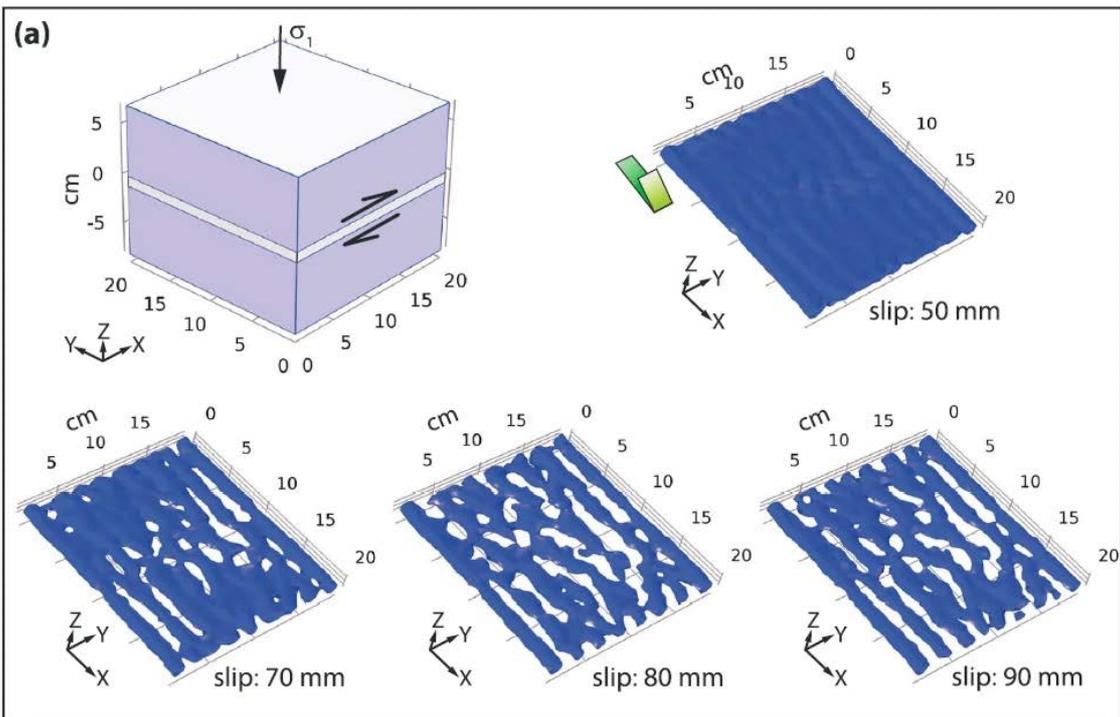
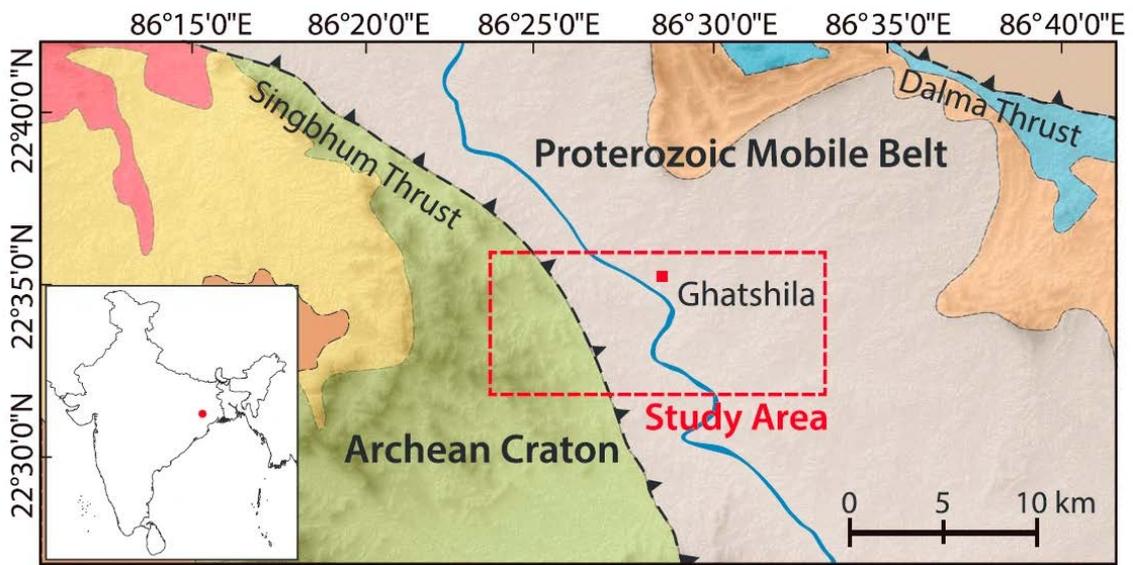


Fig. 5: Casts of slickensides with varying roughness from the field.

(a) Smooth shear surfaces, but with down-dipping, low-amplitudes waves, forming a distinct fine scale slickenline structure. (b) Shear surfaces with strongly linear roughness, defined by cylindrical ridges and grooves in different orders. (c) Shear surfaces with heterogeneous linear roughness. There are patchy zones showing weak linearity in the roughness. (d) Shear surface roughness with wavy appearance of long ridges and grooves at varying spacing.



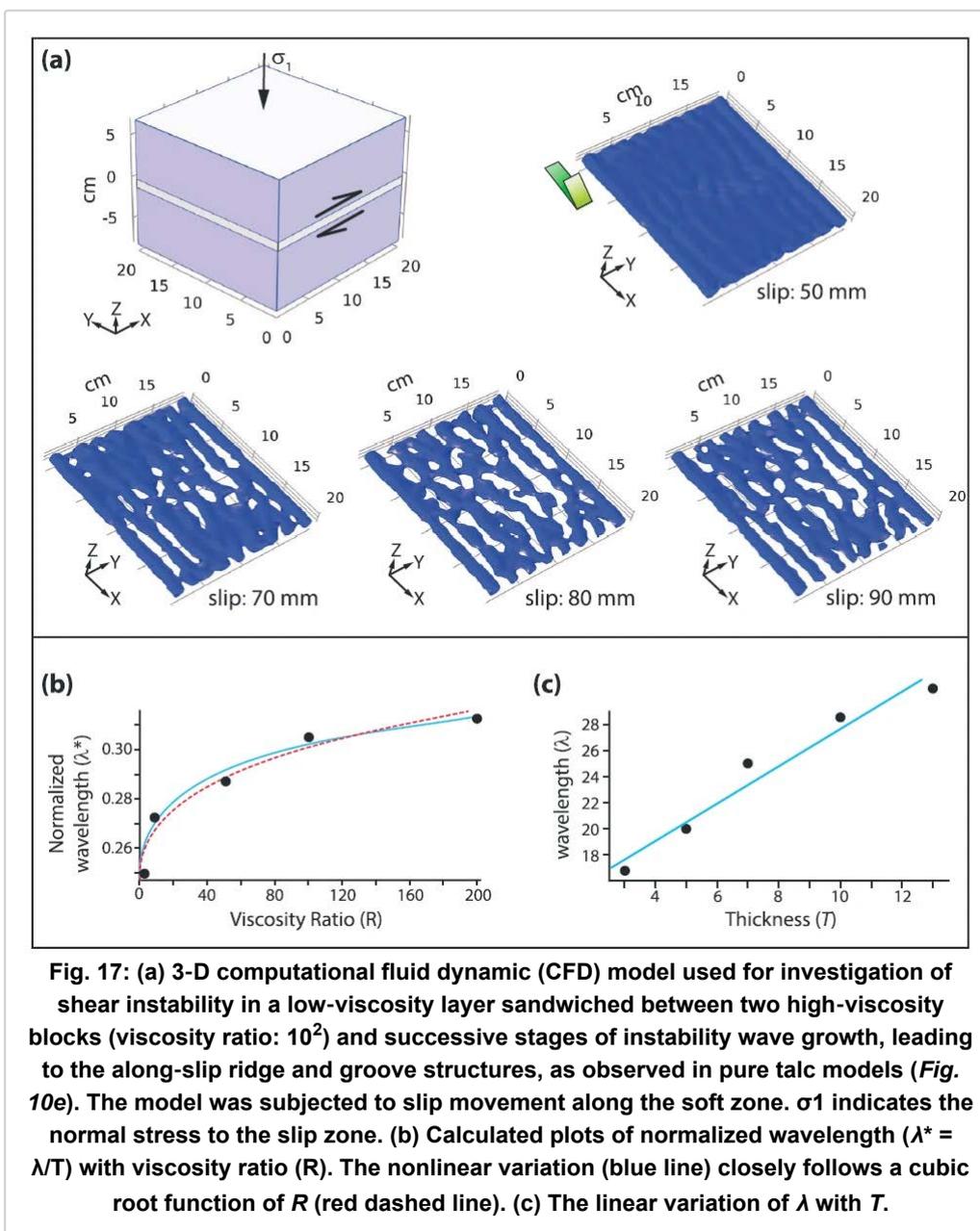


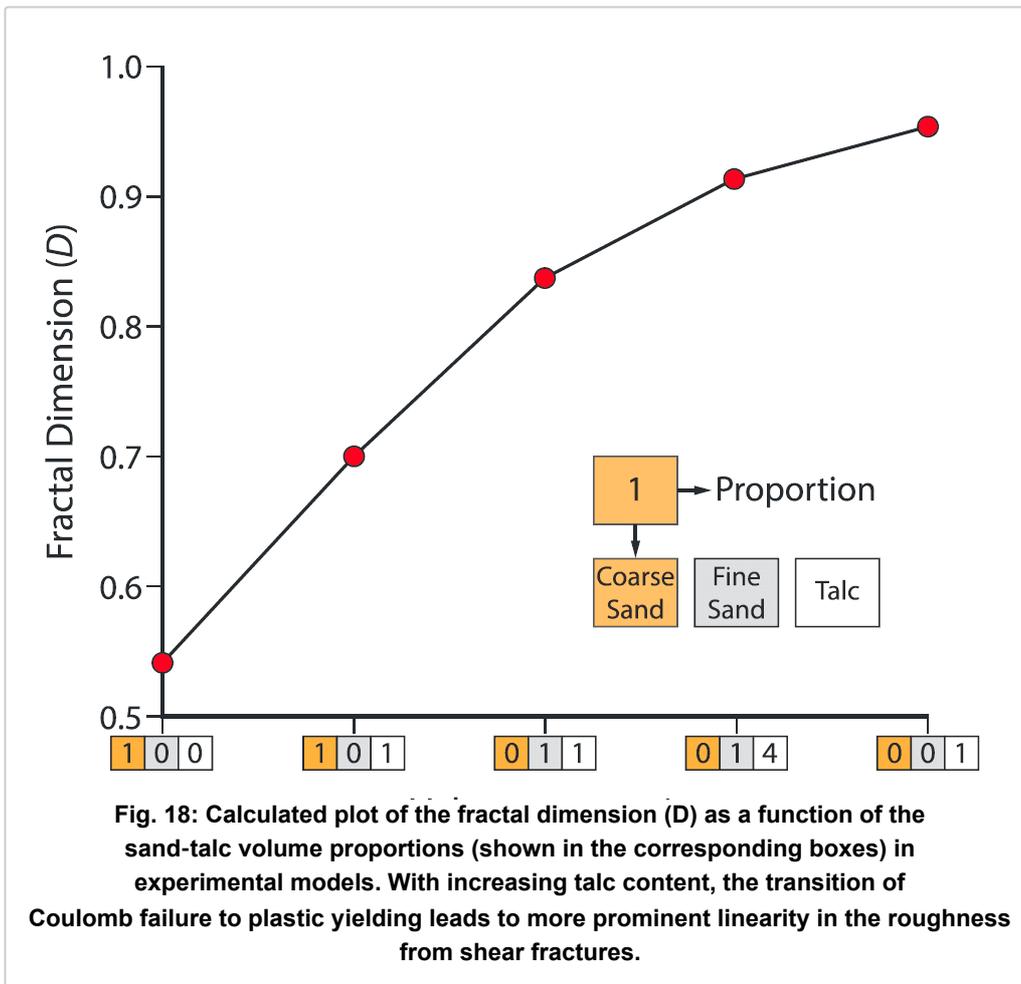


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DISCUSSION AND CONCLUSION





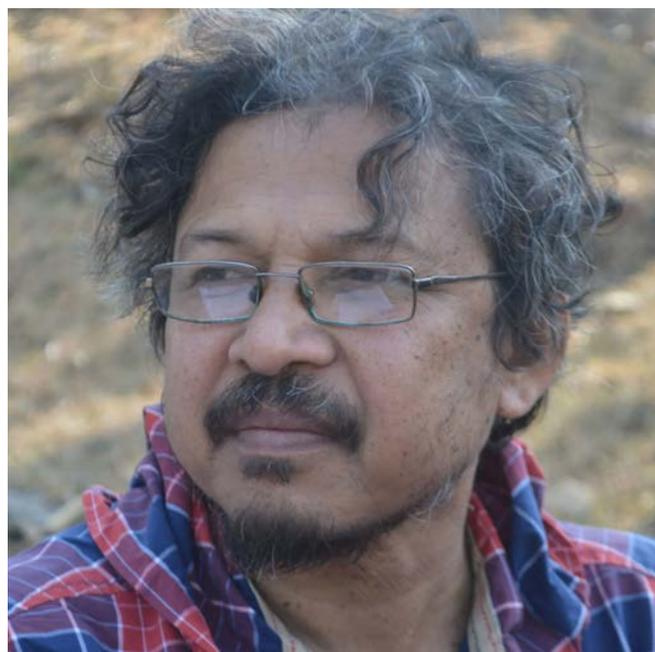
Conclusion

1. Shear surfaces in the field show mainly **three types** of roughness patterns: **Type 1**—smooth surfaces without any distinct linear irregularities, **Type 2**—linear roughness with fine scale ridges of small amplitudes, and **Type 3**—linear roughness with coarse ridges of relative large amplitudes.
 2. **The mode of failure and the initial inclination of fractures to the principal compression direction** are the **potential factors** in controlling the linear roughness of shear surfaces.
 3. **Increase in θ** promotes the formation of **smooth slickenlines** at the cost of rough zones.
 4. Increasing ductility **promotes ΔD values**.
 5. **Mechanical instability** is a potential mechanism for **roughness formation** with marked linearity in the slip zones.
-

AUTHOR INFORMATION



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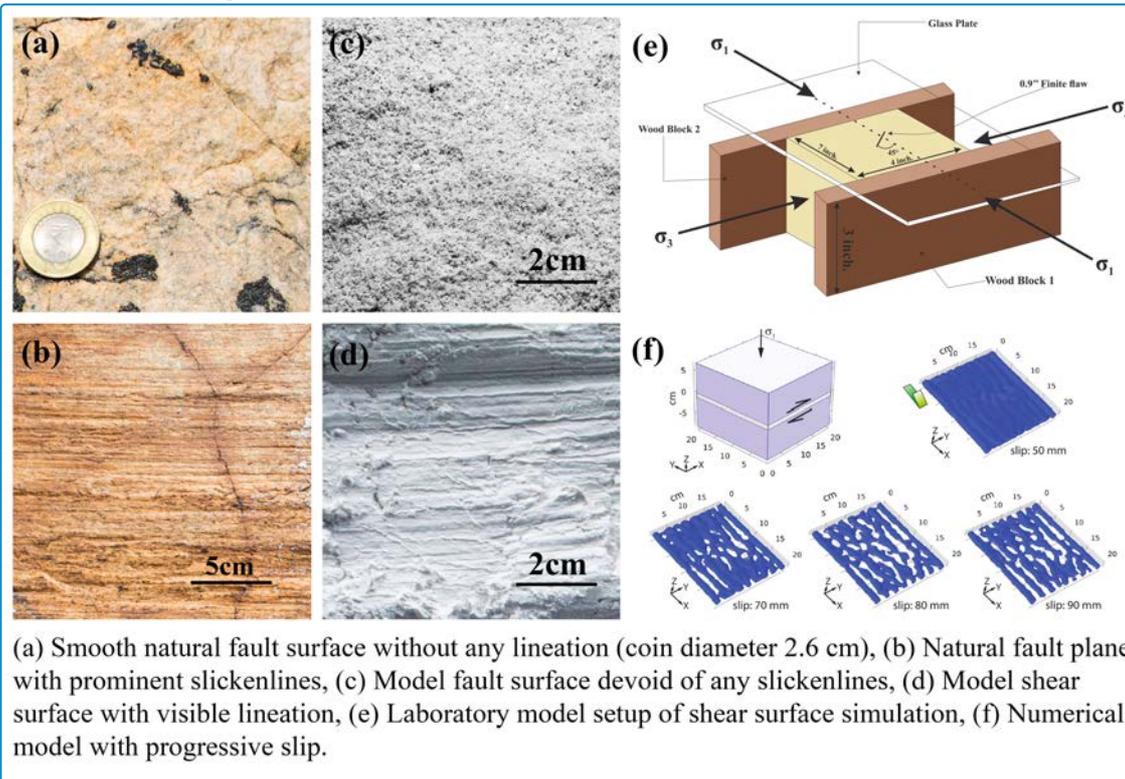
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ABSTRACT

Slickenlines (linear marks) on fault surfaces are the most common indicator of fault slip events. From sheared quartzite in the Singhbhum Shear Zone, eastern India, this study reports varying slip surface roughness (smooth without lineation to strongly rough with intense lineation) imparted by slickenlines. Analogue experiments with sand-talc models suggest that the modes (brittle versus ductile) of shear failure and the inclination of pre-existing slip planes to principal stress direction (θ) largely control the roughness characteristics of a fault surface. Coulomb failure in pure sand models in the brittle regime produces a smooth fault surface with little or no slickenlines roughness features. On the other hand, increasing talc content in the models resulted in a transition from brittle to ductile shear failure, and slip surfaces produced prominent slickenlines in the slip direction that becomes strong with increasing $\theta = 30^\circ$ to 60° . This study provides a roughness analysis of the laboratory models and field casts in terms of 1D fractal dimension (D) using the box-counting method and the image processing technique. The directionality in D , measured as ΔD (difference in D across and along the slip direction), is evaluated to show the degree of roughness anisotropy on slip surfaces. The present work also sheds light upon the origin of slickenlines. Previous workers hypothesized them as a product of ploughing action by asperities, directional deposition of the abraded asperities, and syn-kinematic growth of secondary minerals. This study introduces a new interpretation, showing slip-induced wave instability as a possible mechanism of slickenlines formation.



(https://agu.confex.com/data/abstract/agu/fm22/7/6/Paper_1054167_abstract_955126_0.jpg)

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