Study on Mechanical Mechanism of Kink bands via BEM

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Kink band

Definition:

1.A tabular zone, normally mesoseopic, along which foliation is deflected. (Tectonic Dictionary)

2.An asymmetric, linear zone of deformation characterized by short fold limbs and very small hinge zones. Kink bands commonly occur as conjugate sets (see CONJUGATE FOLD). (Dictionary of Earth Science)

History and usage:

•*Several early authors (e.g., Clough, in Gunn et al., 1897; Dale,*1899; Read, 1934) recognized these structures and described them.

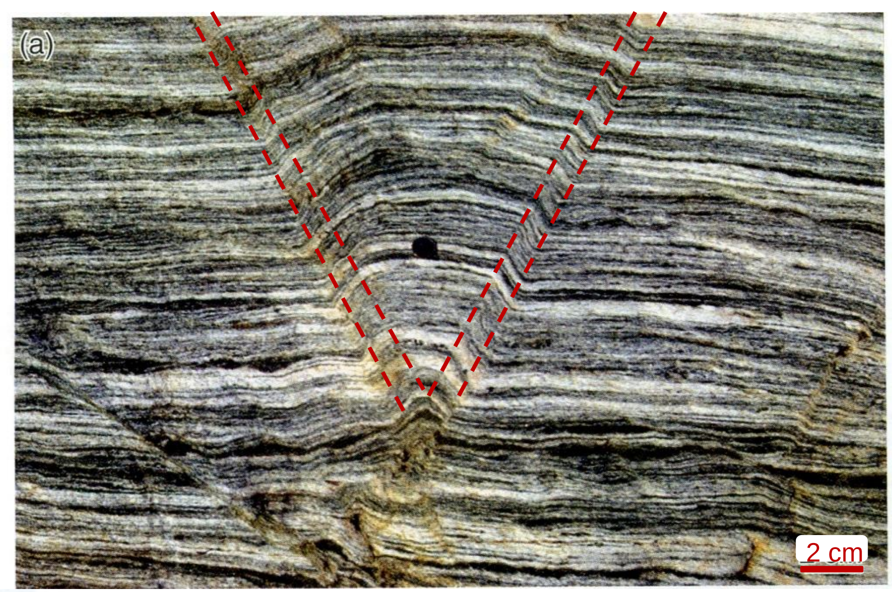
•Analogous structureswere observed in single crystals by Orowan (1942), who named them "kink-bands."

•Voll (1960, p. 548) adopts this term for the corresponding structures in foliated rocks,and this usage continues *(e.g., T. Anderson, 1964).*

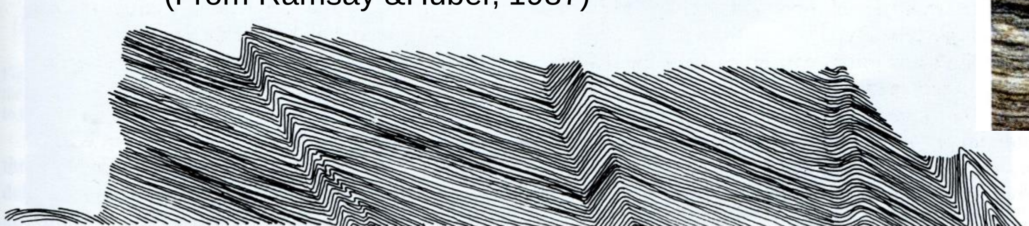
Size scale (in the past): millimeter ~ decameter

(From Ramsay &Huber, 1987)

CONJUGATE FOLD



(Fossen, 2010)

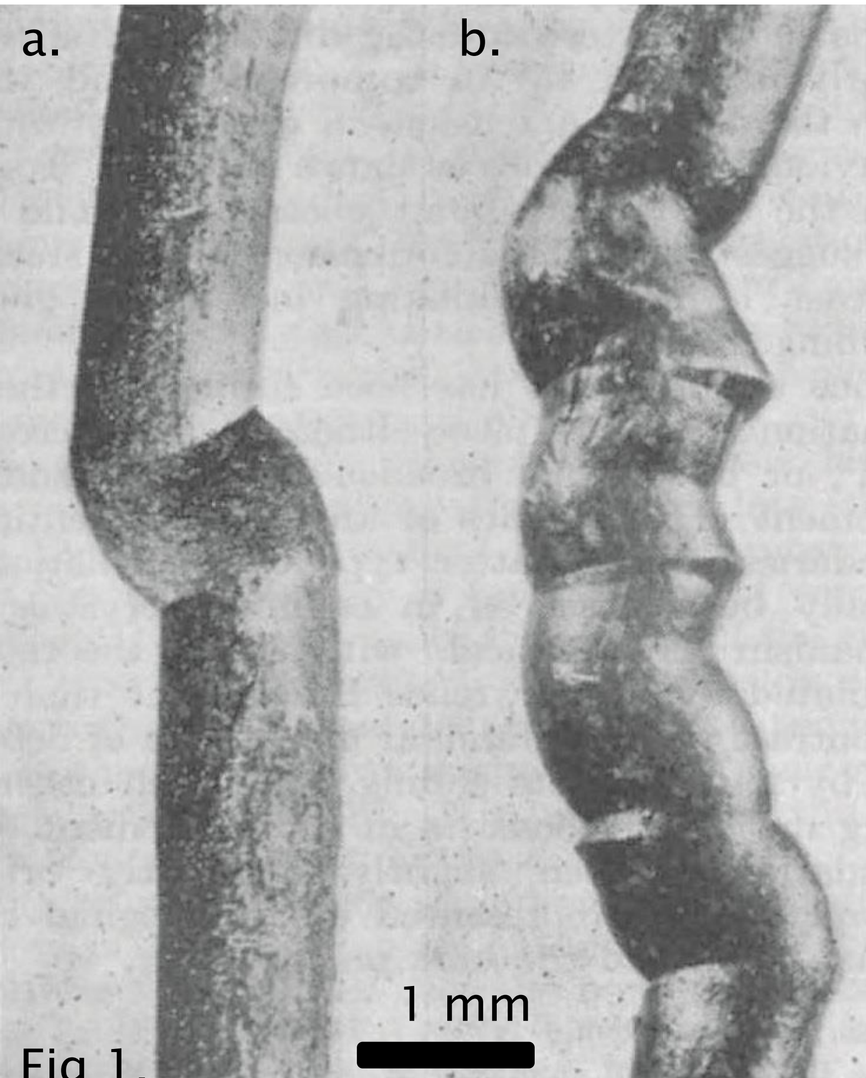


(From Ashwin, 1957)

Some previous studies

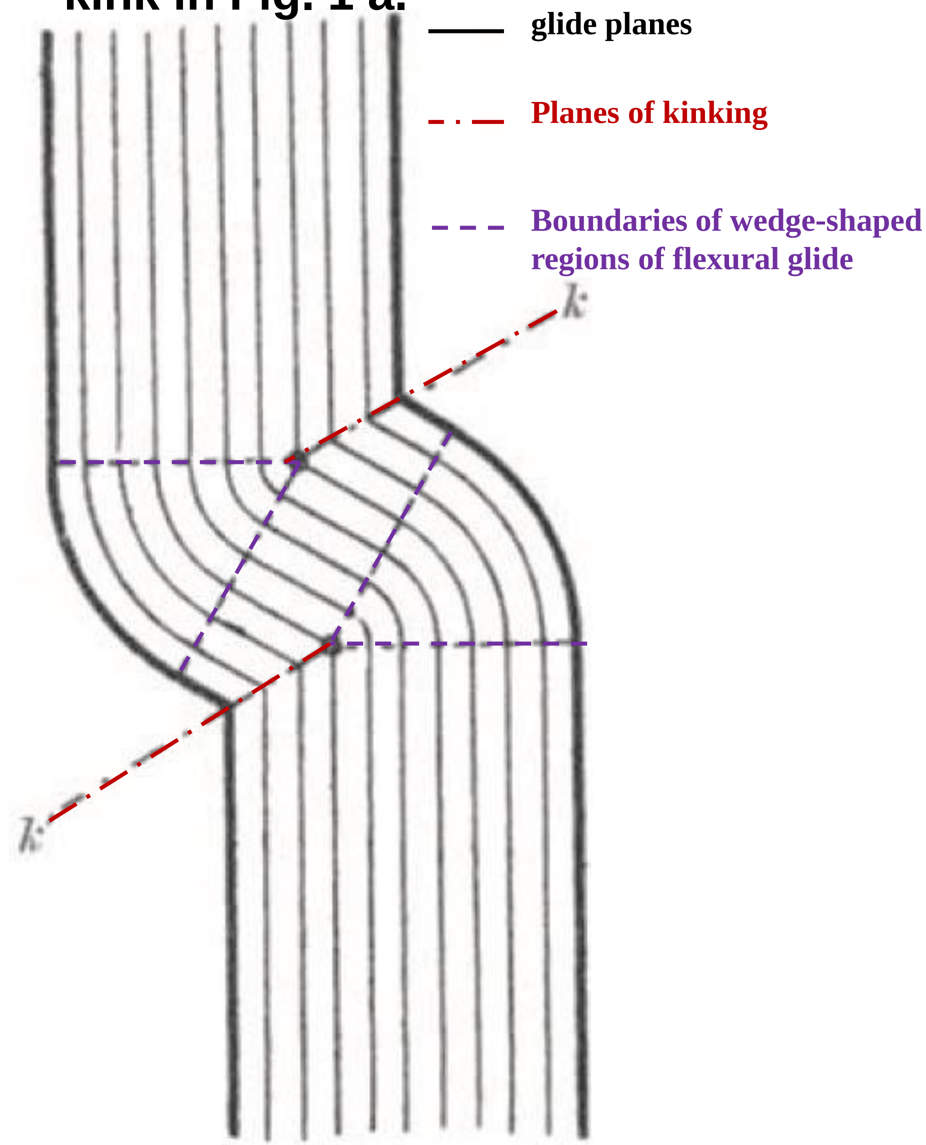
(Orowan, 1942, Nature)

Kink in originally cylindrical cadmium (鎘) single-crystal wires



(Adapted from Orowan, 194

Structure of the kink in Fig. 1 a.



(Orowan, 1942, Nature)

Kink bands

Mechanism of Kinking

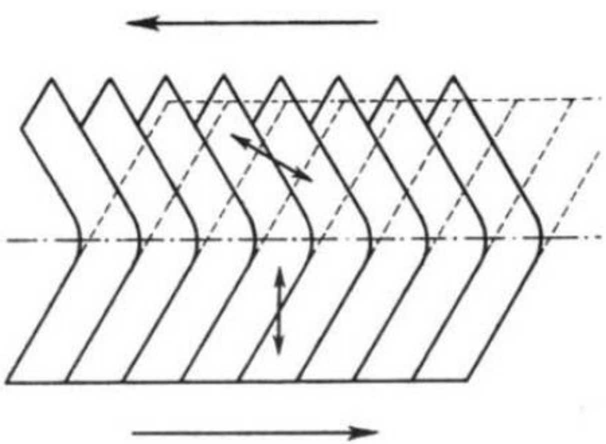


Fig. 3.
MECHANISM OF KINKING.

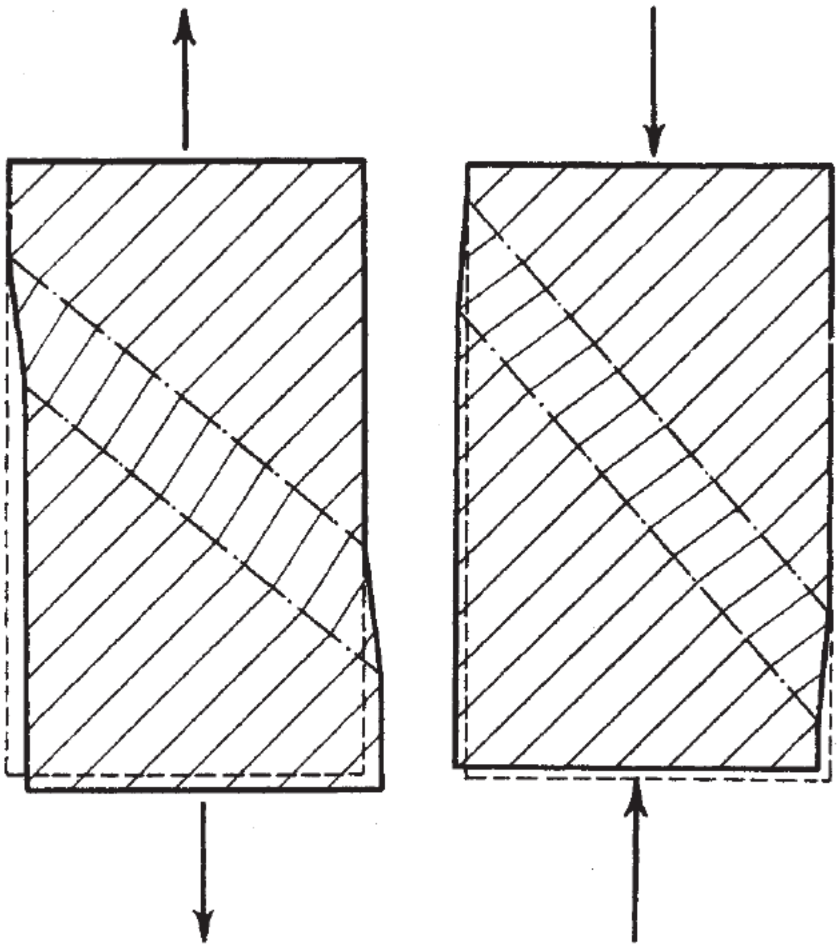
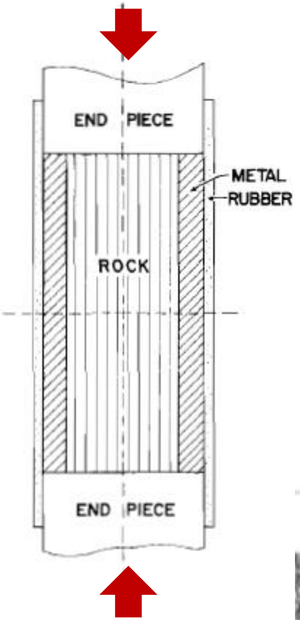


Fig. 5.
EXTENSION AND COMPRESSION OF A CRYSTAL PRODUCED BY KINK BANDS.
Thin parallel lines, glide planes.

(Paterson and Weiss, 1962, Nature; 1966, GSAB)



Foliated rock: Phyllite

Shortening:12%

rubber

Shortening:12%

copper

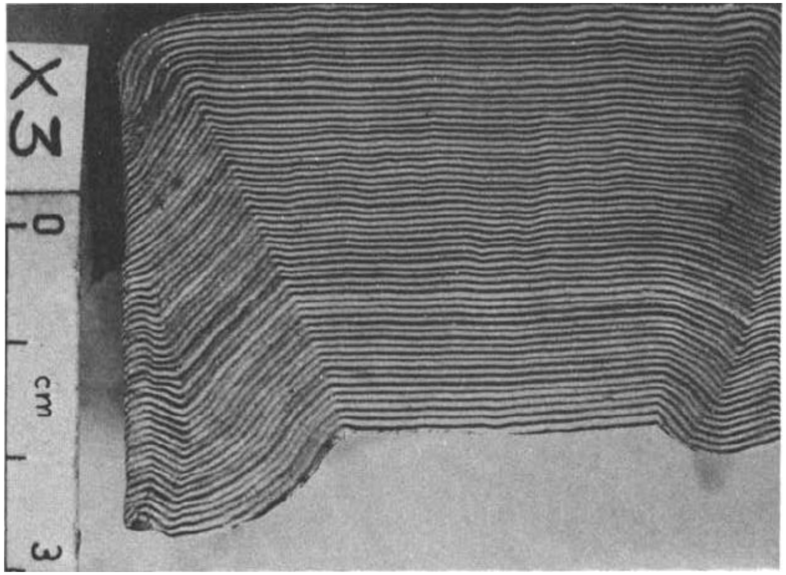
Shortening:13%

brass

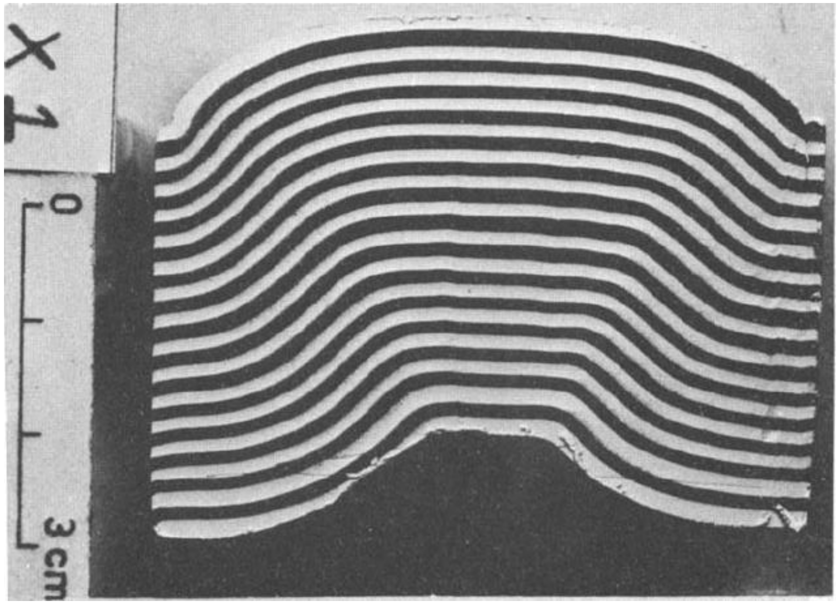
— 1 mm

(Ghosh, 1968, Tectonophysics)

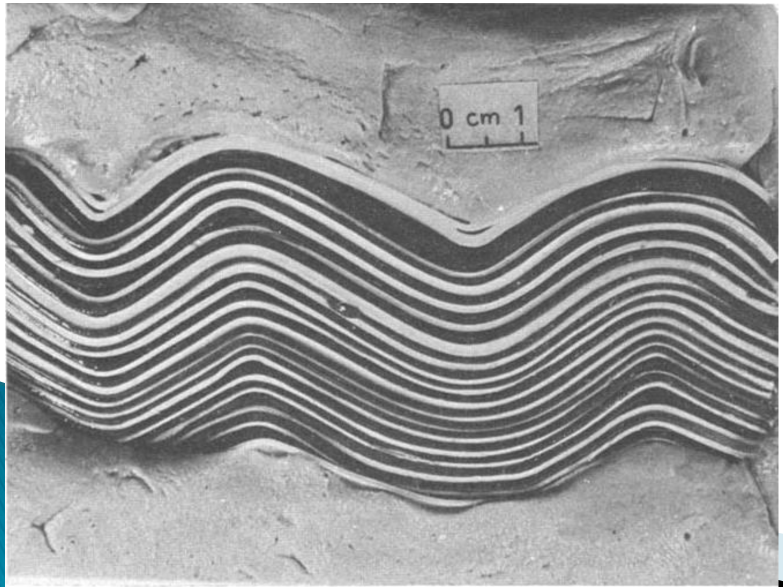
Densely layered with restricted ease of sliding



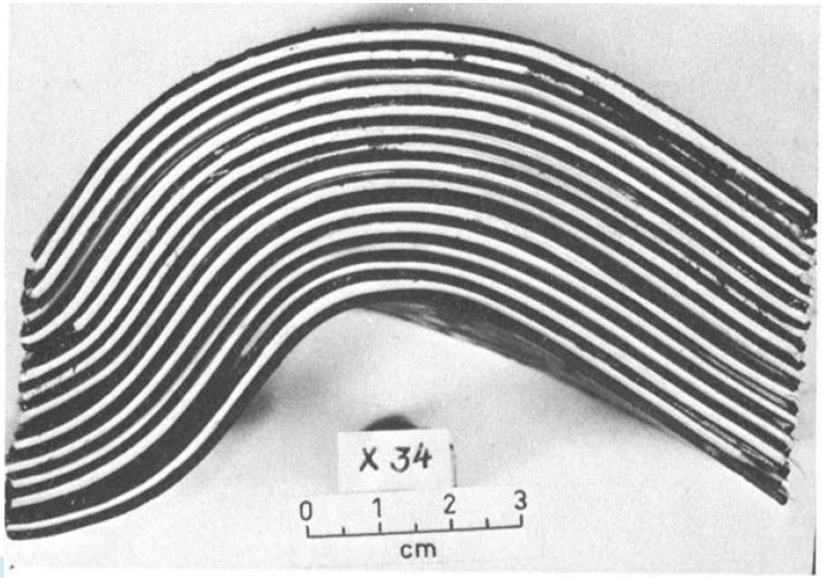
Coarsely layered with restricted ease of sliding



Embedded with Great ease of sliding



Great ease of sliding



(Honea and Johnson, 1976, Tectonophysics)

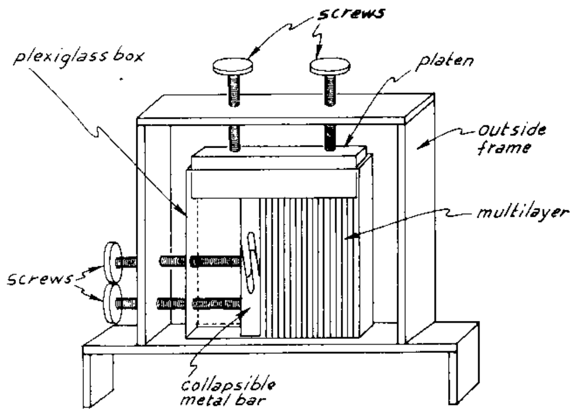
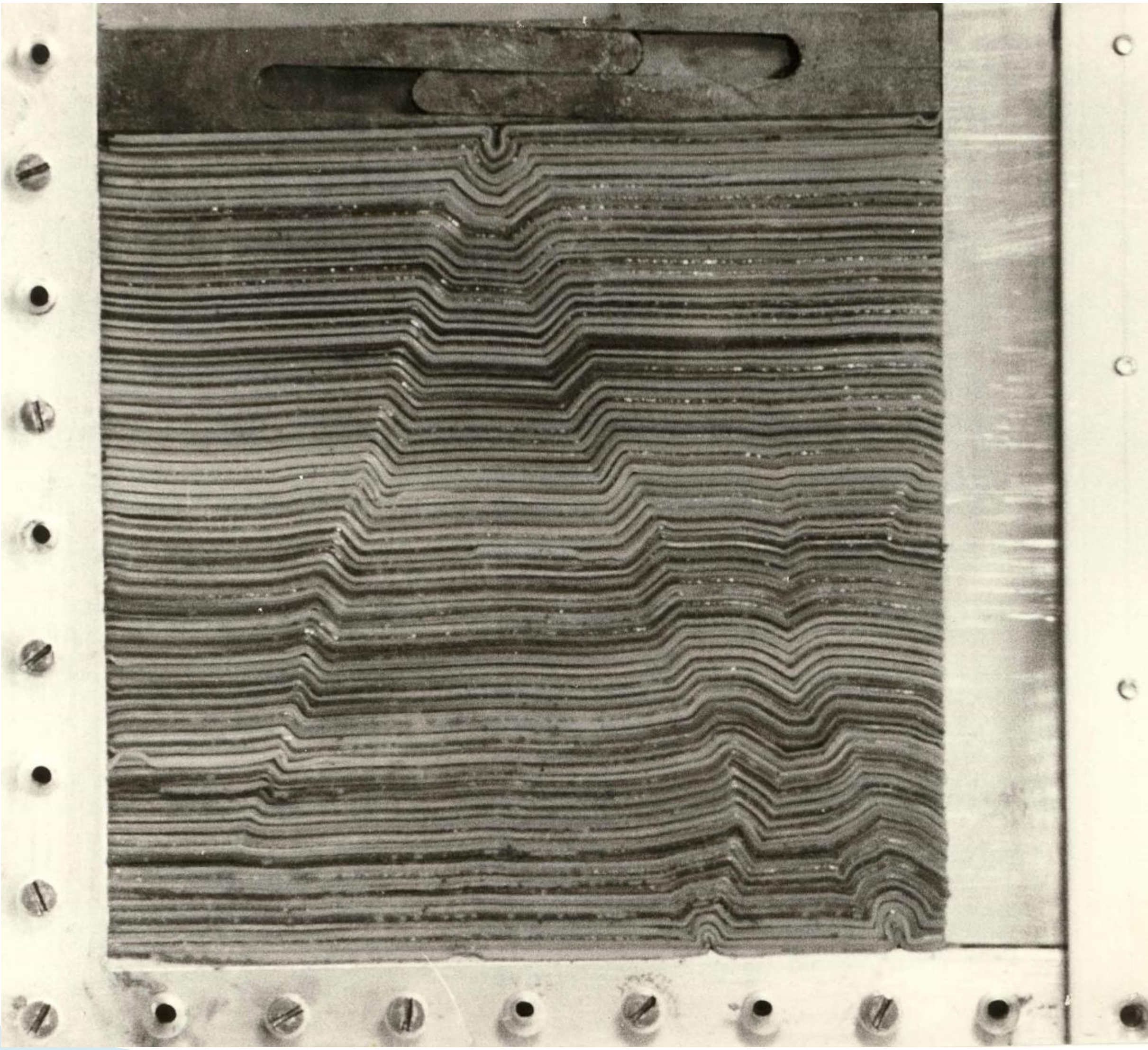
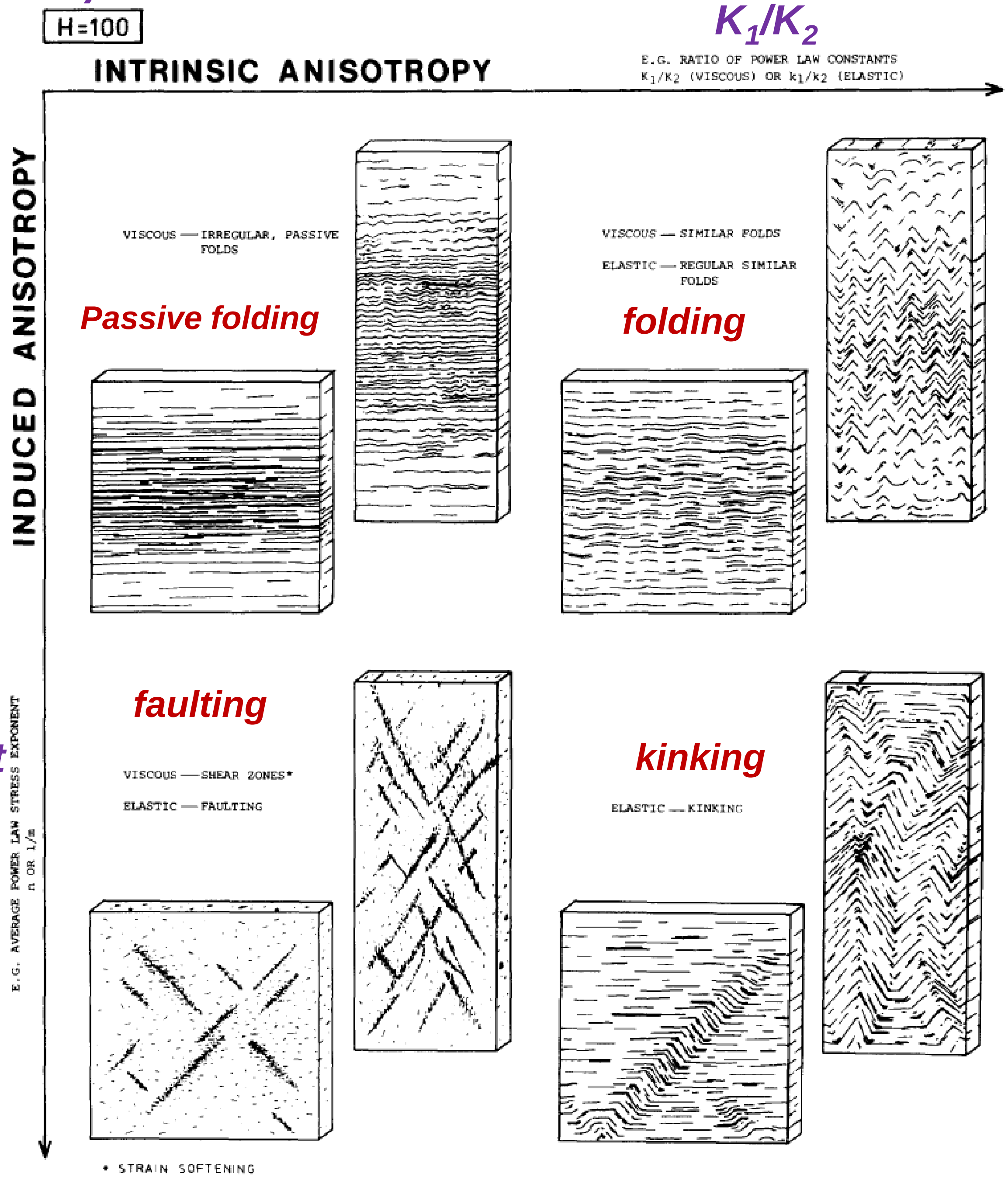


Fig. 1. Apparatus used to deform experimental multilayers.



(Latham, 1985, JSG)

N: power law stress exponent

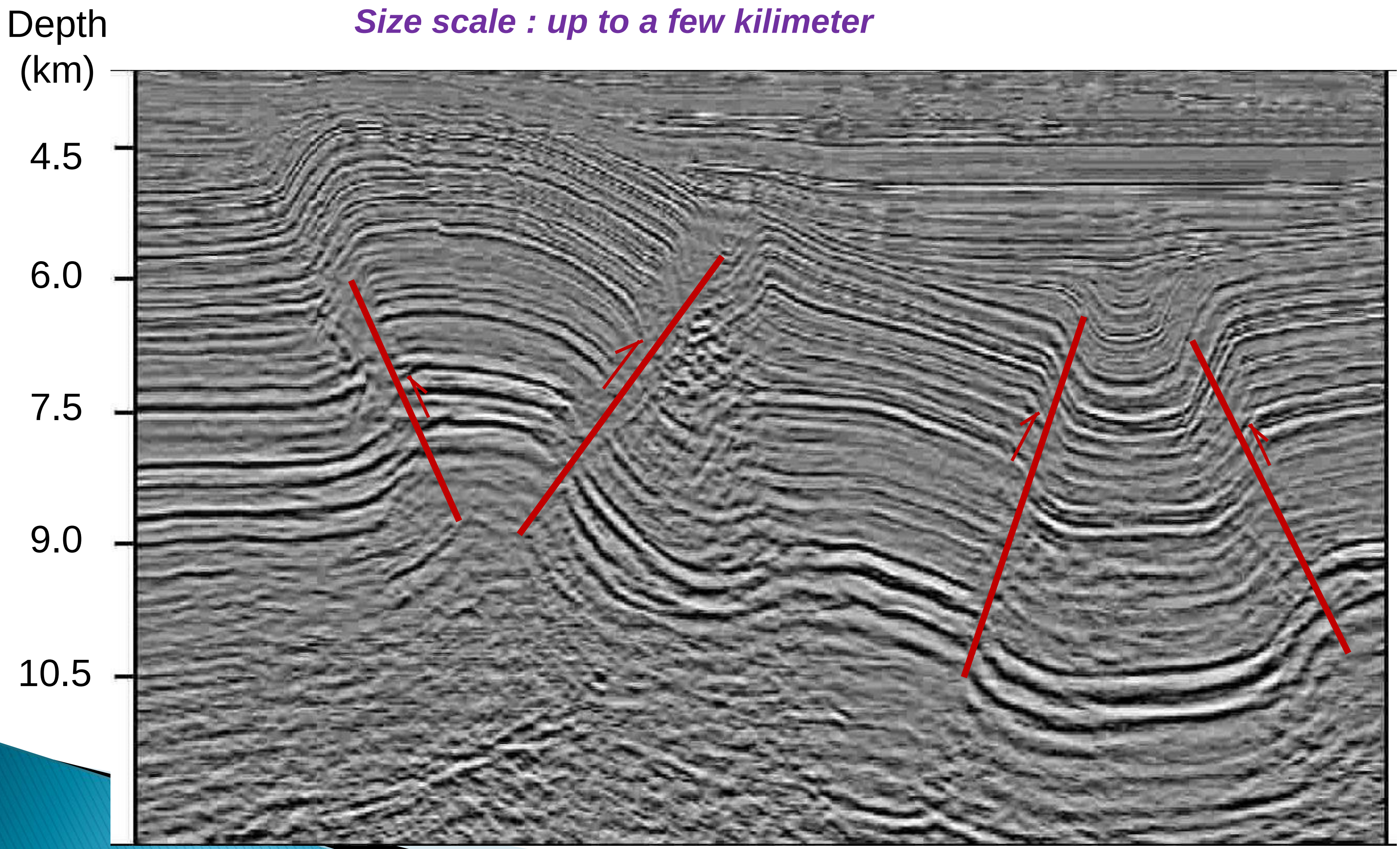


Seismic reflection

(張波等人, 2010,地質探勘)

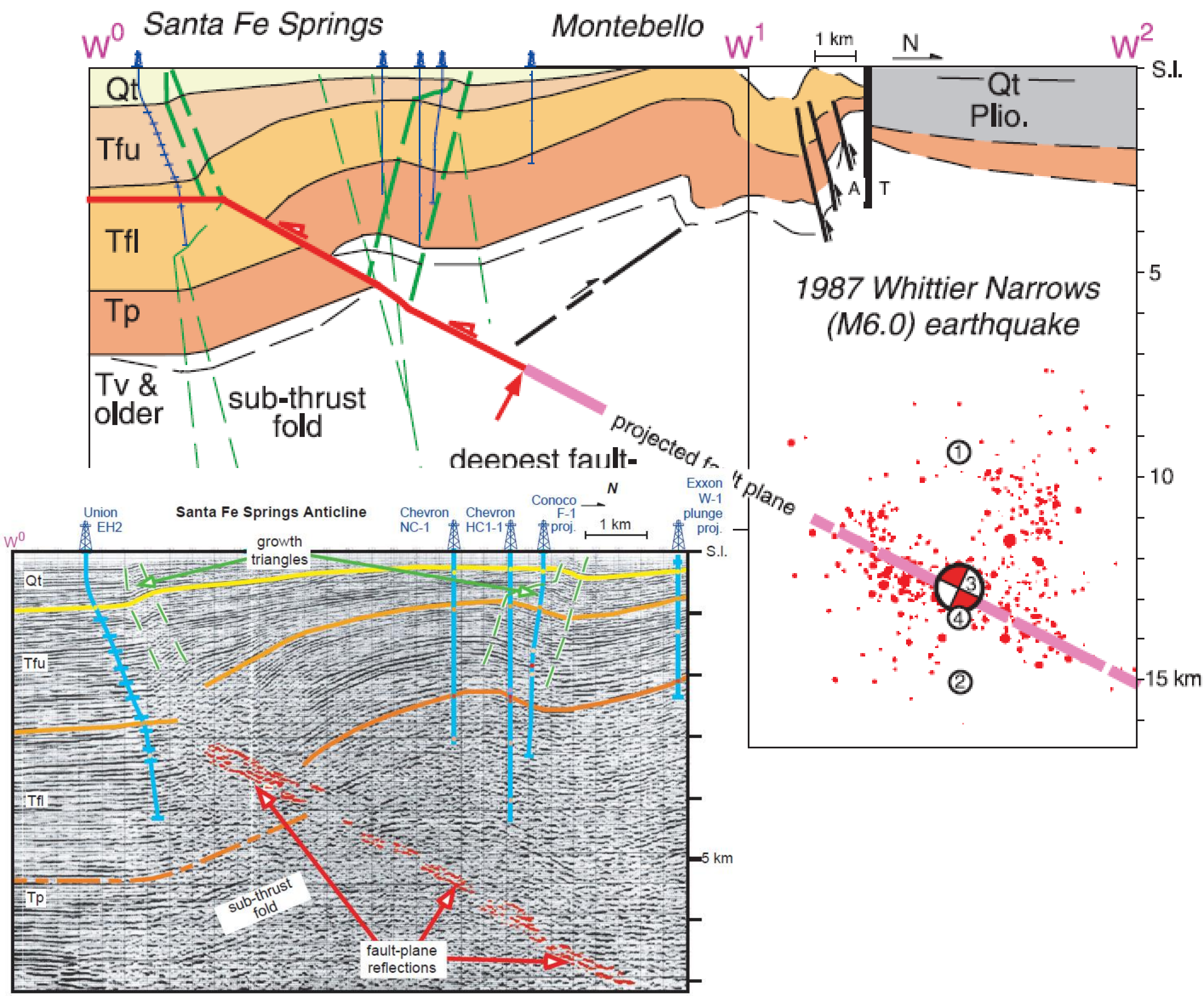
High-angle faults replaced by kink bands

Size scale : up to a few kilimeter



Motivation (Shaw et al., 1999, Nature; 2002, BSSA)

Earthquakes vs. Faulting ? Earthquakes vs. Kinking

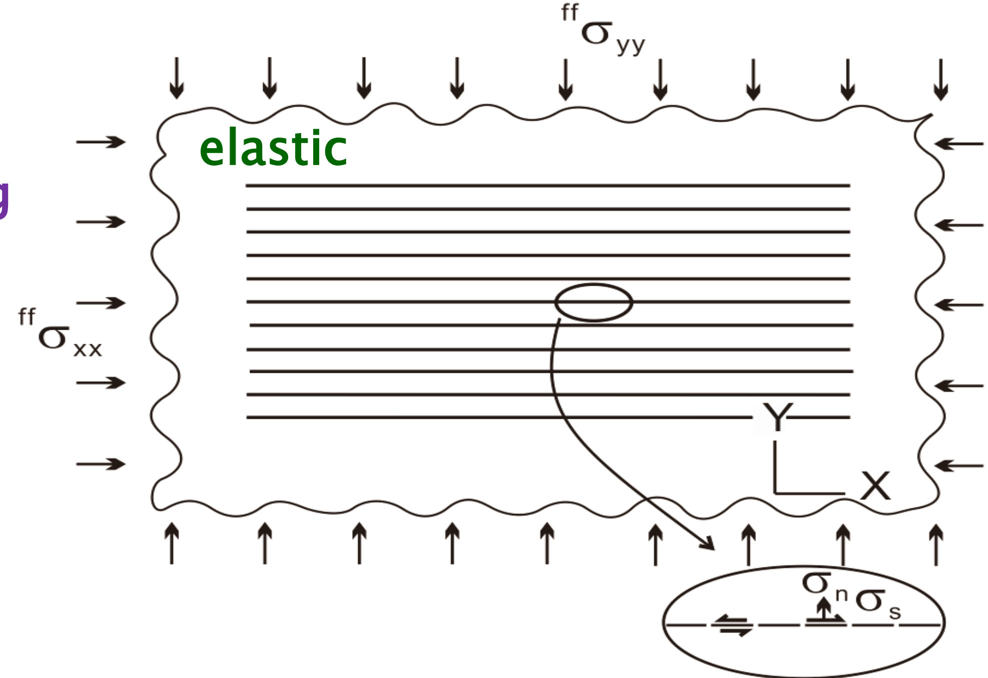


Our BEM model

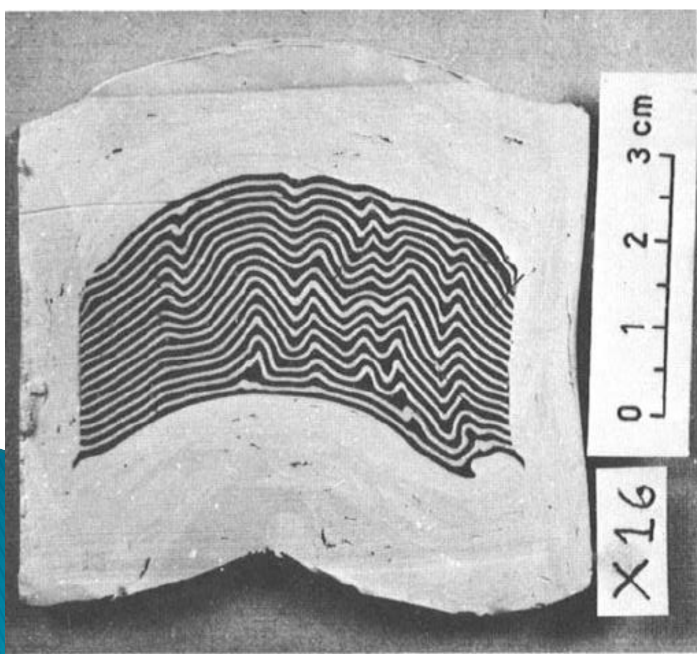
Layers are assumed to slip according to a Coulomb friction law,

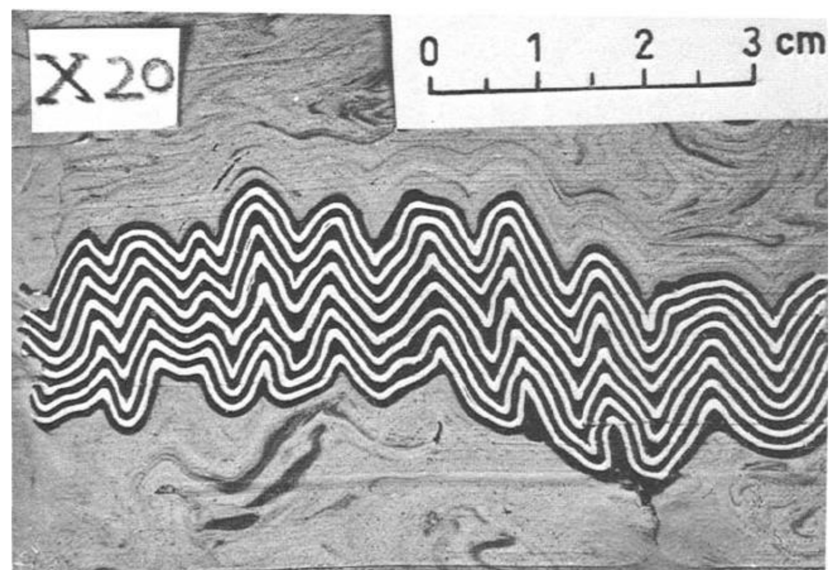
$$|\sigma_s| \leq c + \mu\sigma_n$$

σ: traction
C: cohesion
μ: coefficient of friction



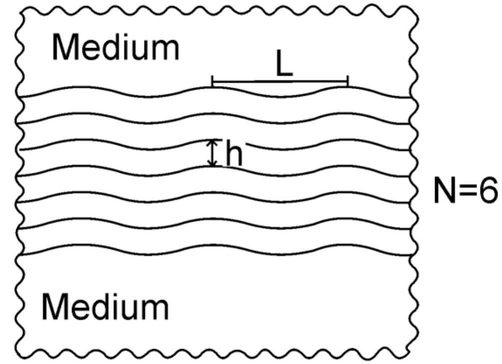
Similar to the experiments (Ghosh, 1968, Tectonophysics)

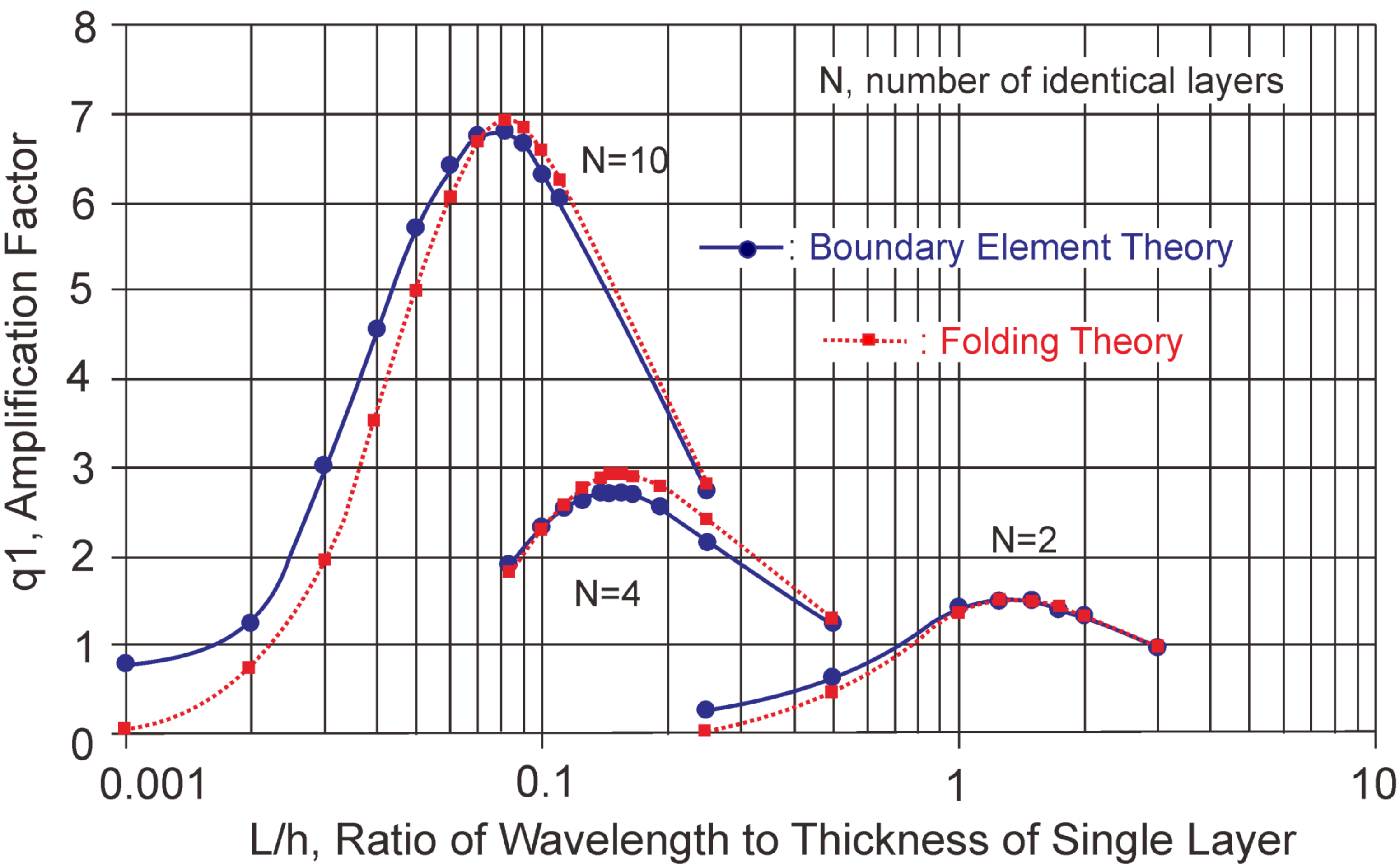




Validation

Illustration of a mulilayer





Research questions

◆ **Are the conditions enumerated below sufficient for the formation of symmetric conjugate kink bands according to our theoretcial analysis?**

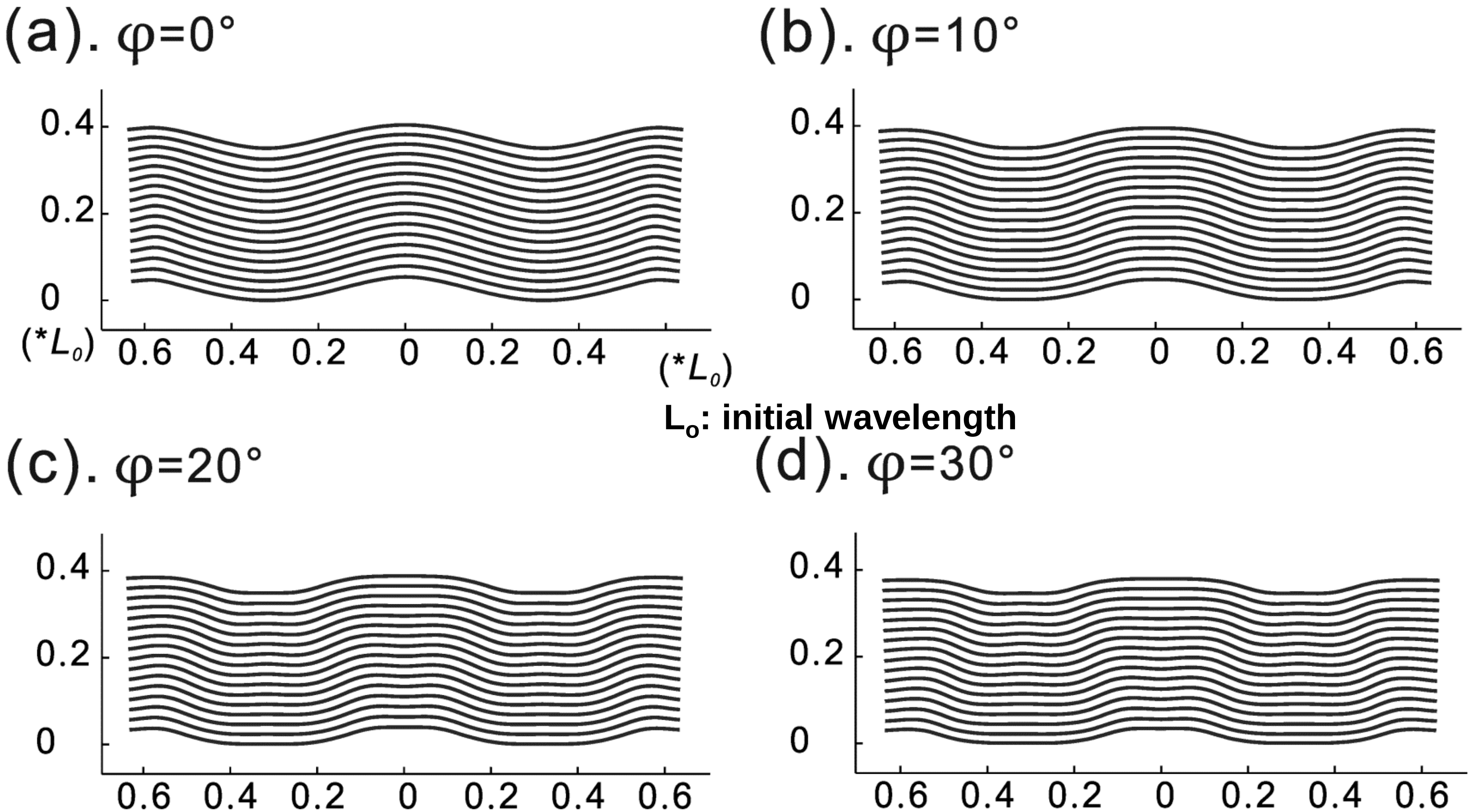
1. **a multilayered material** (bedded stiff layers or interbedded stiff and soft layers),
2. a nonlinear relation, such as **cohesive or frictional strength**, between shear stress and flexural slip **at contacts of layers or within interbeds,**
3. maximum principal compression inclined parellel to the layering in the outer limbs, **Horizntal shortening: 35.9% (this study)**
4. and an initial perturbation of layer orientation. **sinusoidal wave (this study)**

◆**If the answer is yes, then, given certain theoretical properties, can you quantify the states of stress that will produce conjugate kink bands in a multilayer material?**

Effect of frictional strength

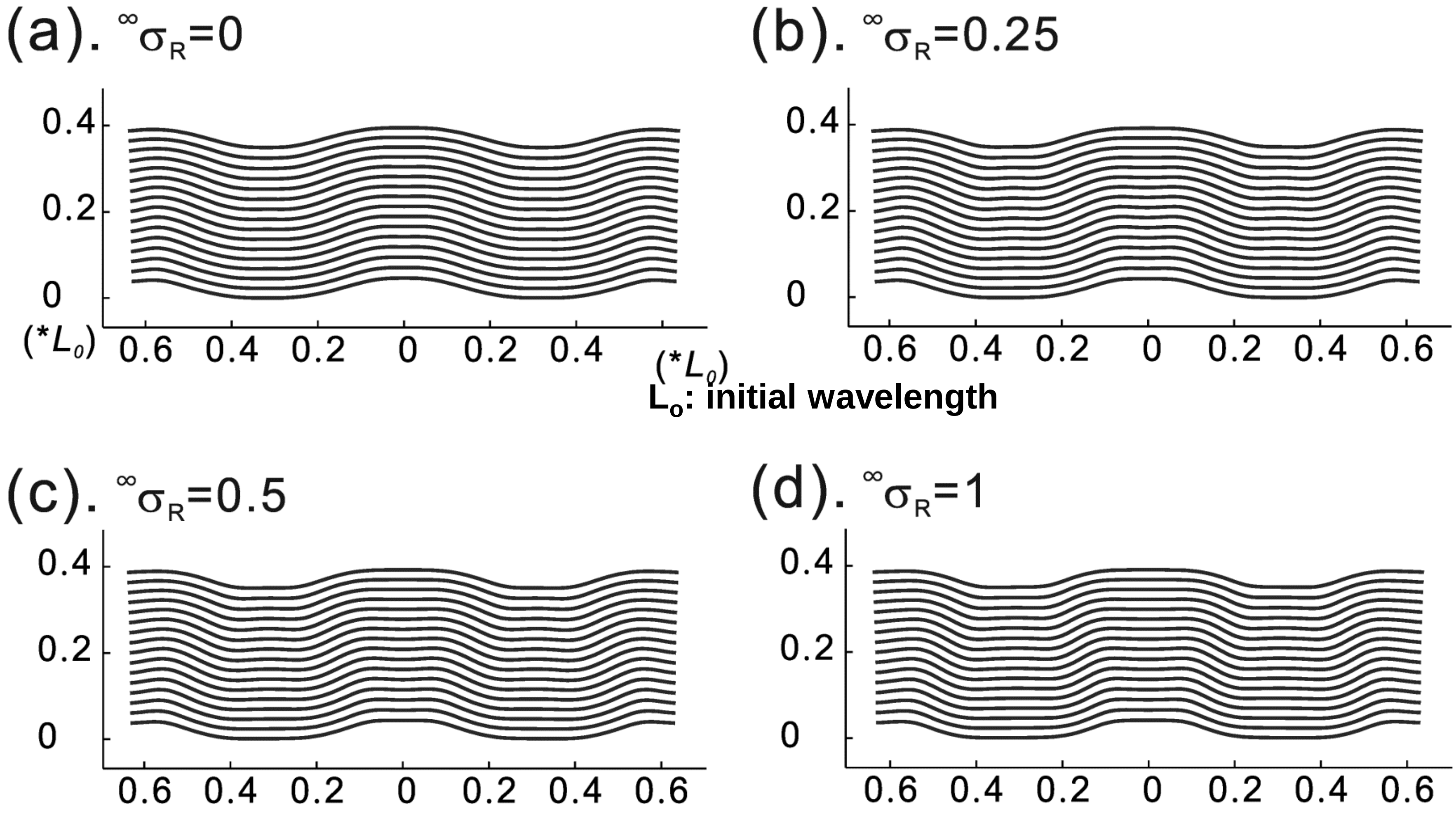
Friction angle, φ

cohesionless (C = 0) for the interfaces without remote vertical stress, i.e. ${}^{ff}\sigma_{yy} = 0$



Effect of frictional strength under remote vertical stresses

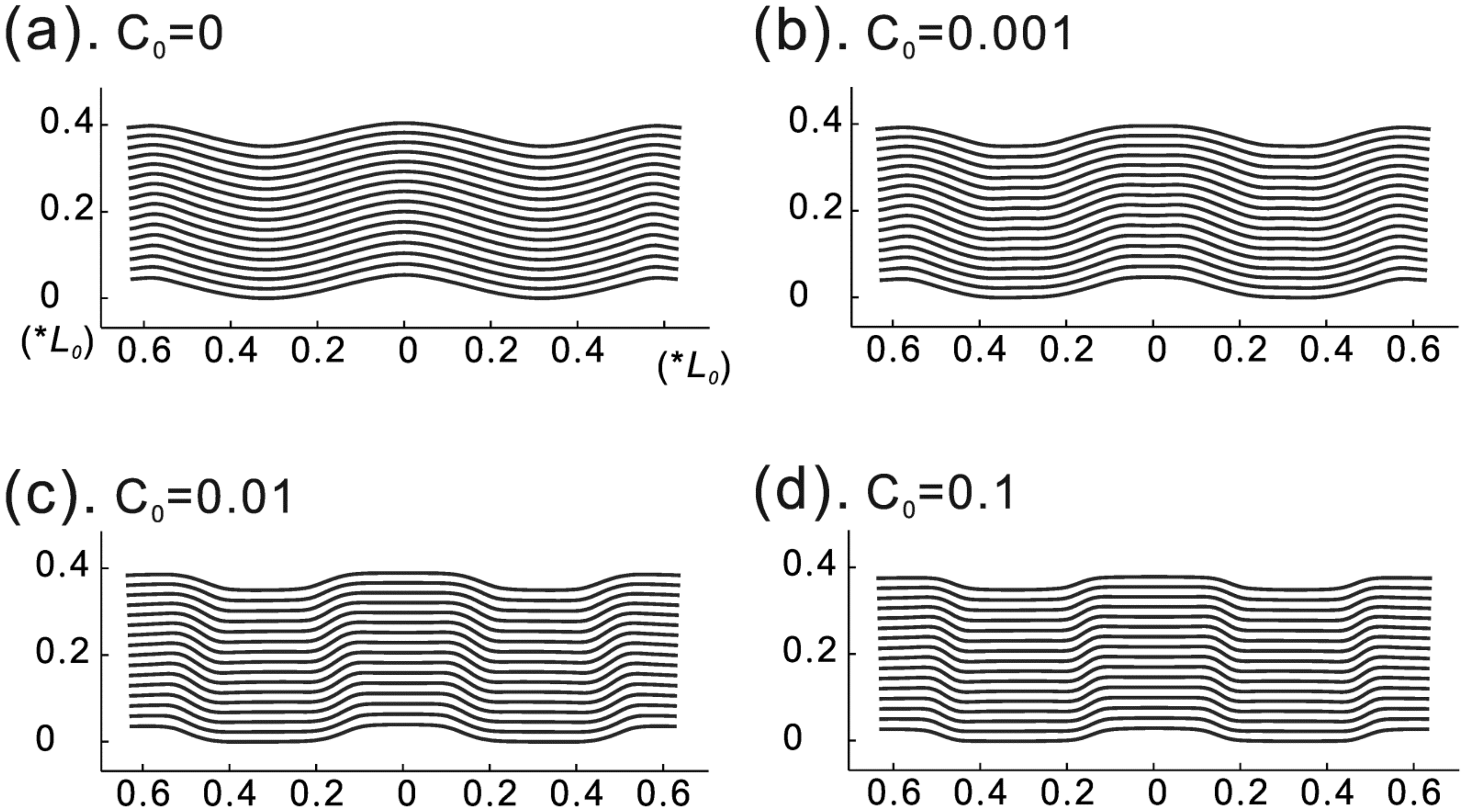
Friction angle, φ, of 10 °



Effect of cohesive strength

C_0 : cohesion normalized by Young's modulus

frictionless

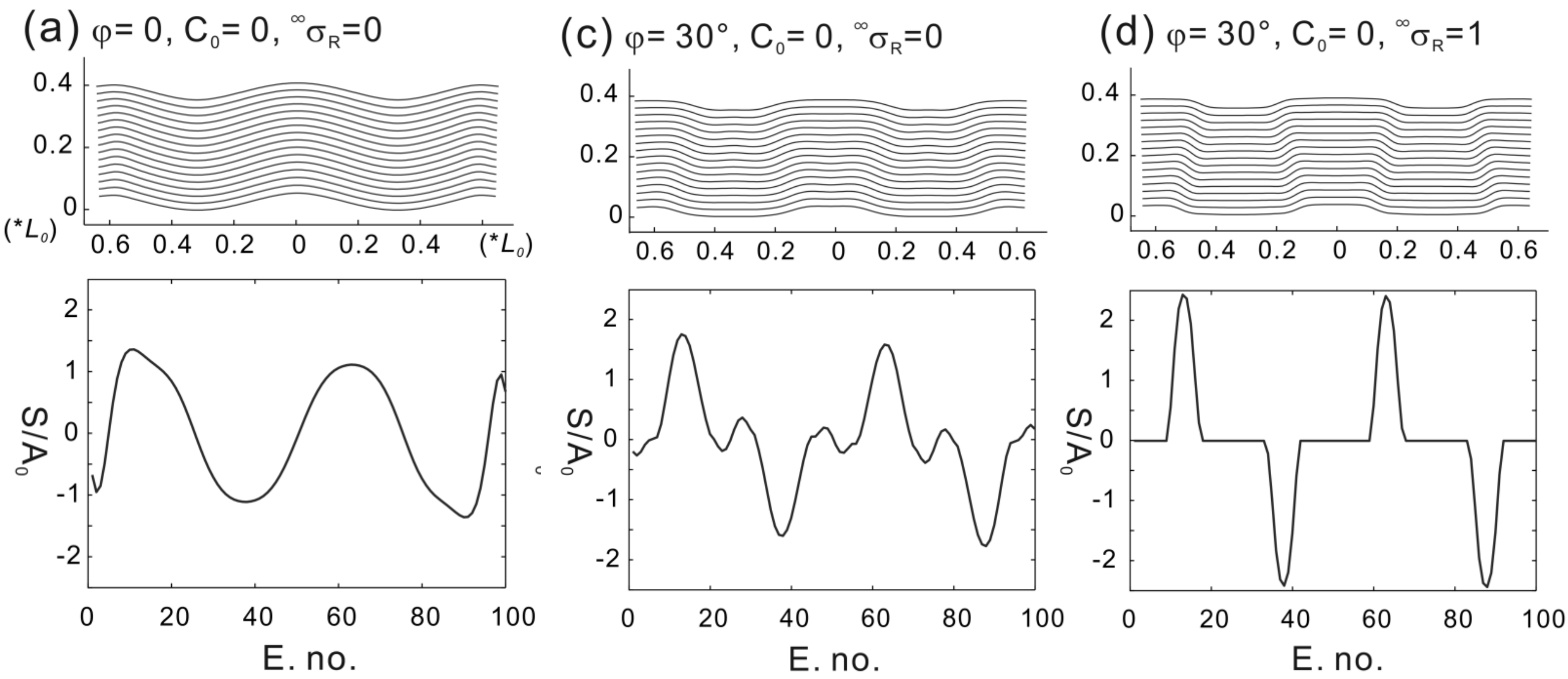


Accumulative slip pattern

Frictionless and cohesiveless

Frictional without remote vertical stress

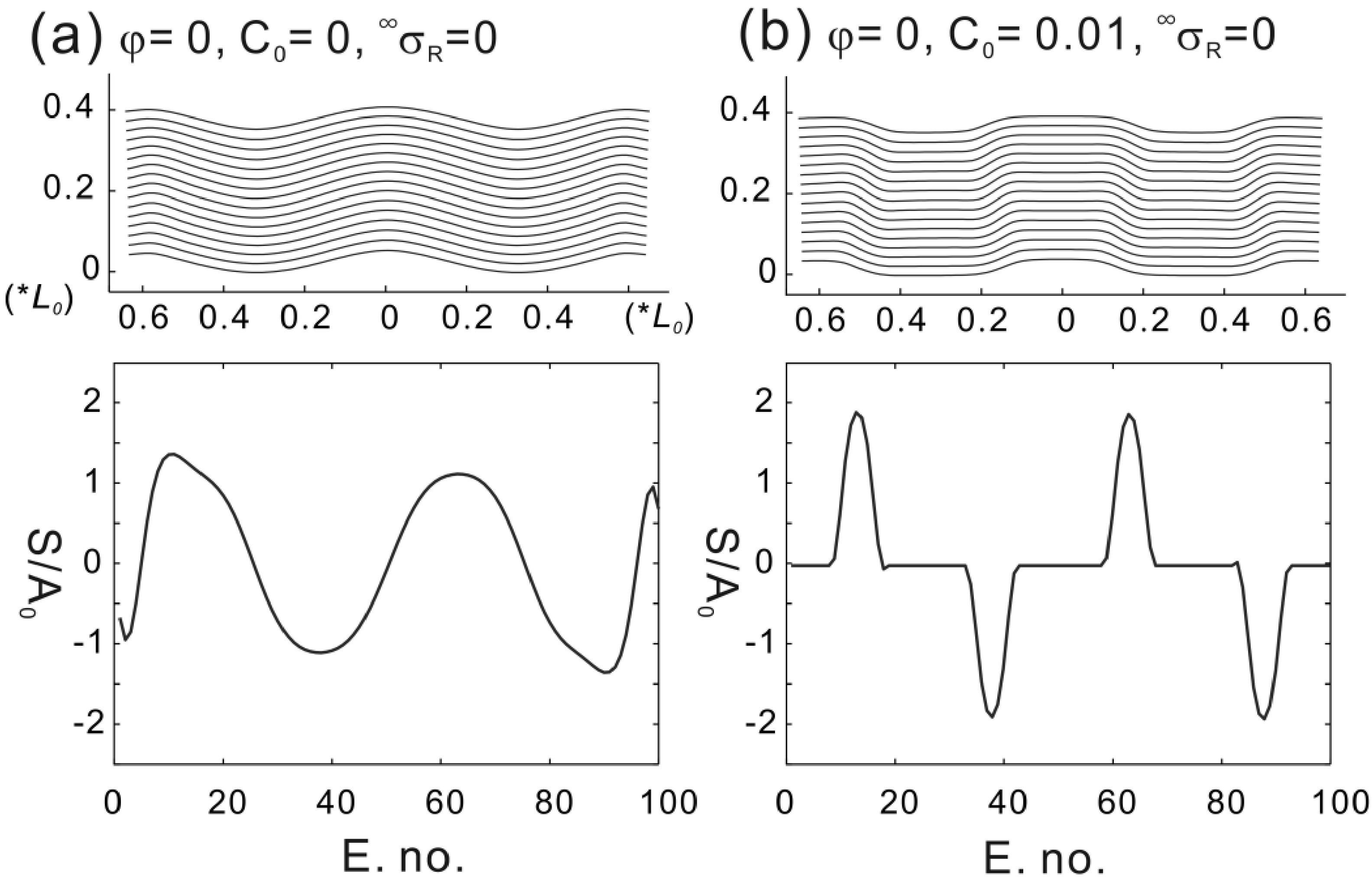
Frictional with remote vertical stress



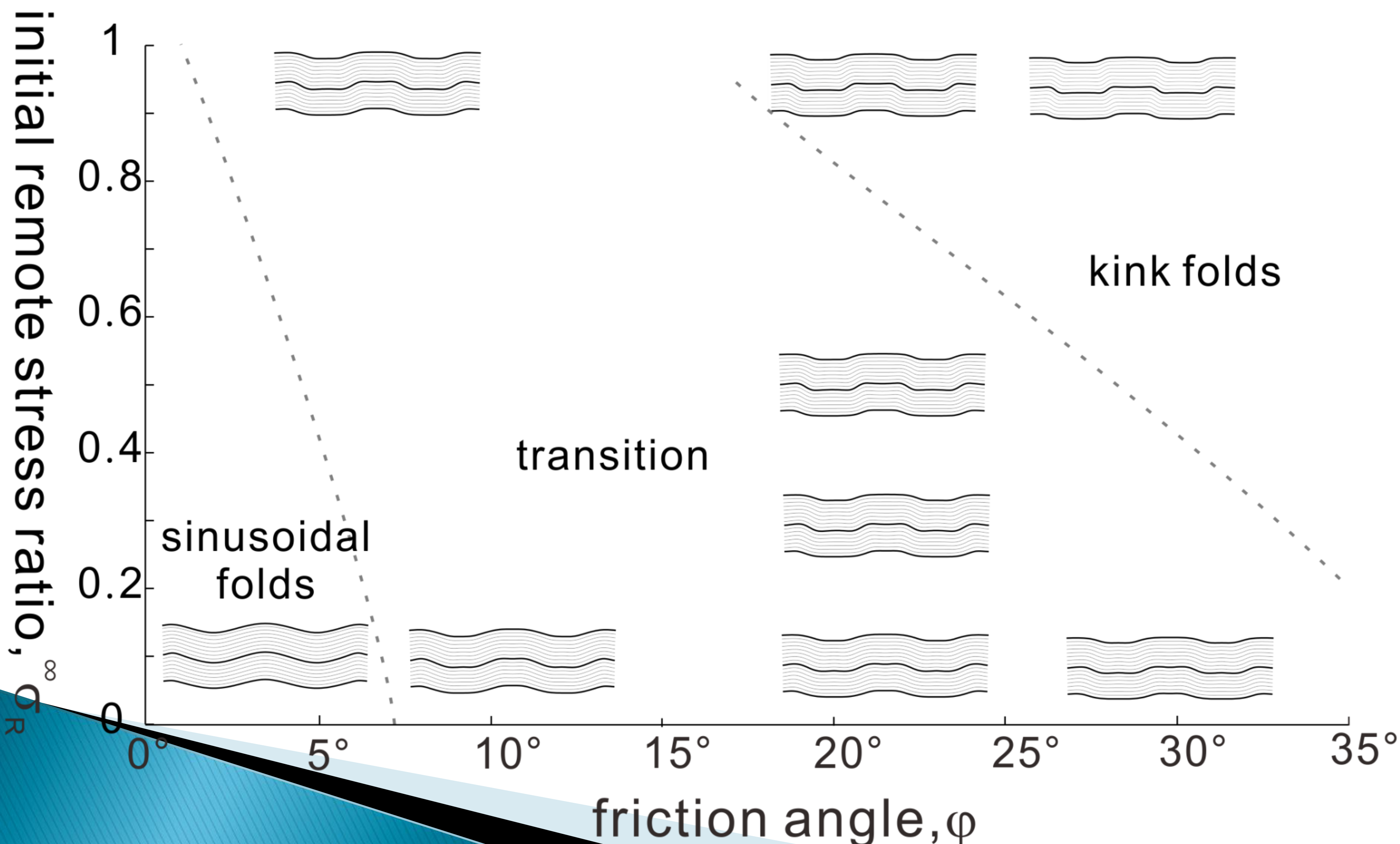
Accumulative slip pattern

frictionless and cohesiveless

cohesive but frictionless

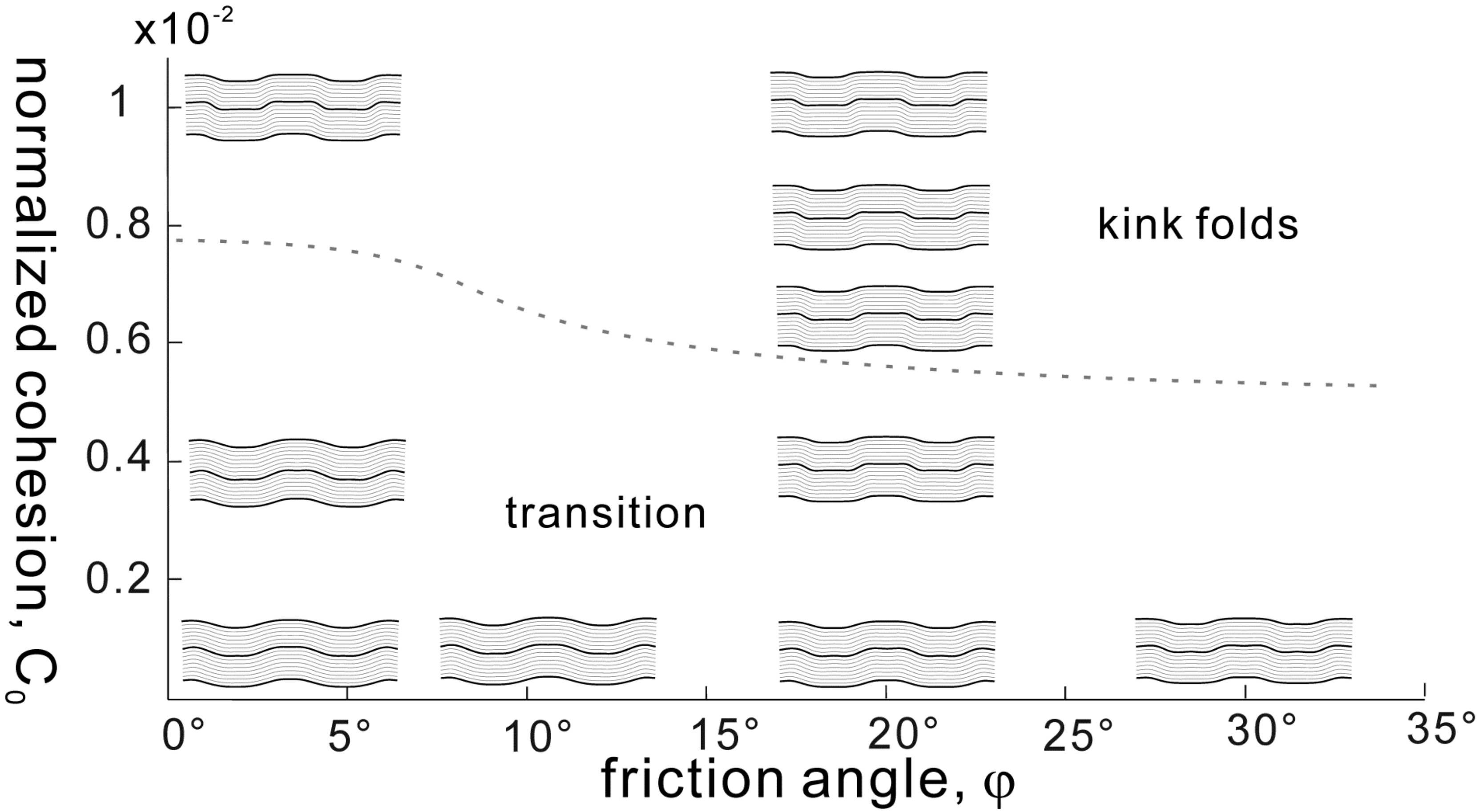


Result for effect of frictional strength under varying initial vertical stress



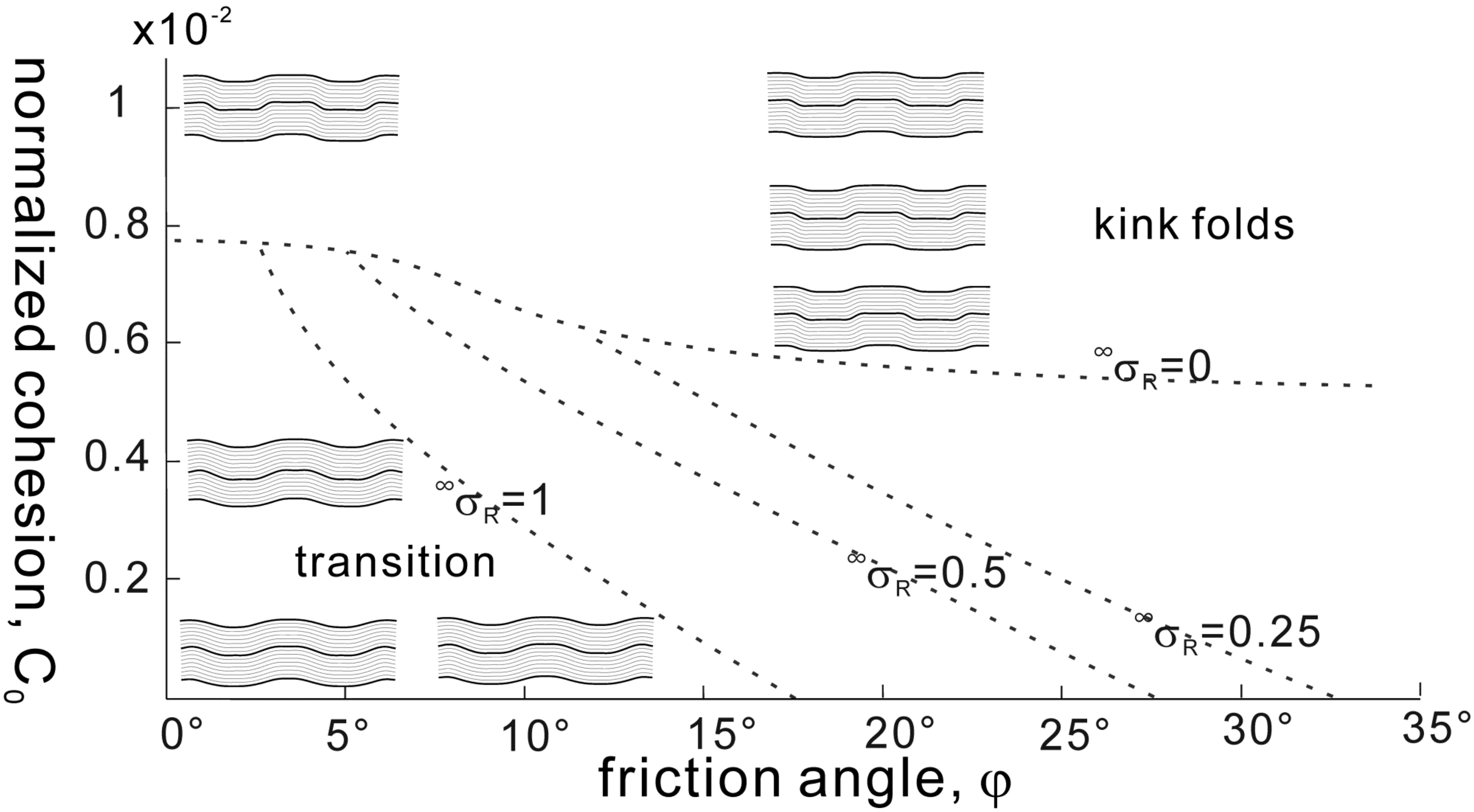
Result for combined effect of frictional vs. cohesive strength

without remote vertical stress, ${}^{\infty}\sigma_R = 0$



Result for combined effect of frictional vs. cohesive strength

With varying remote vertical stress



Discussion

Our BEM elastic model

$$\text{Fold form} = f(A_0, L_0, h, N, C_0, \psi, {}^{\infty}\sigma^i, {}^{\infty}\varepsilon^L_{xx}, {}^{\infty}\varepsilon^L_{xy})$$

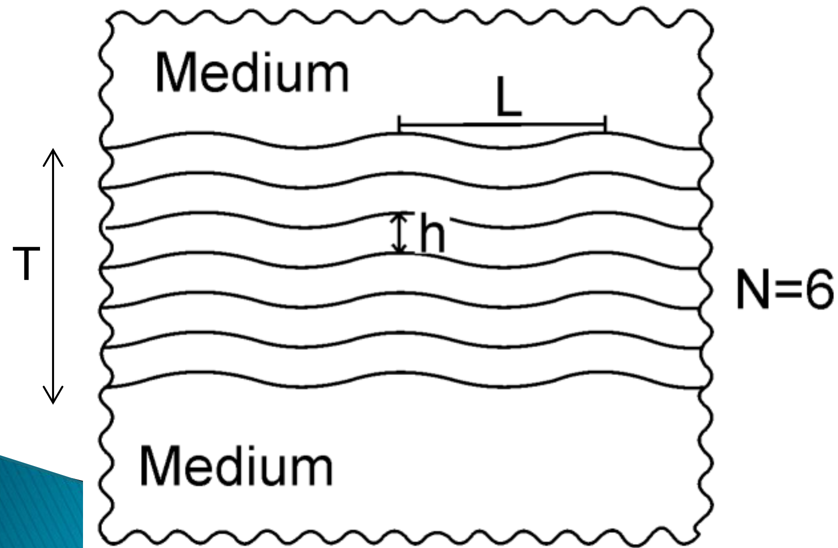
Fixed values 15

0

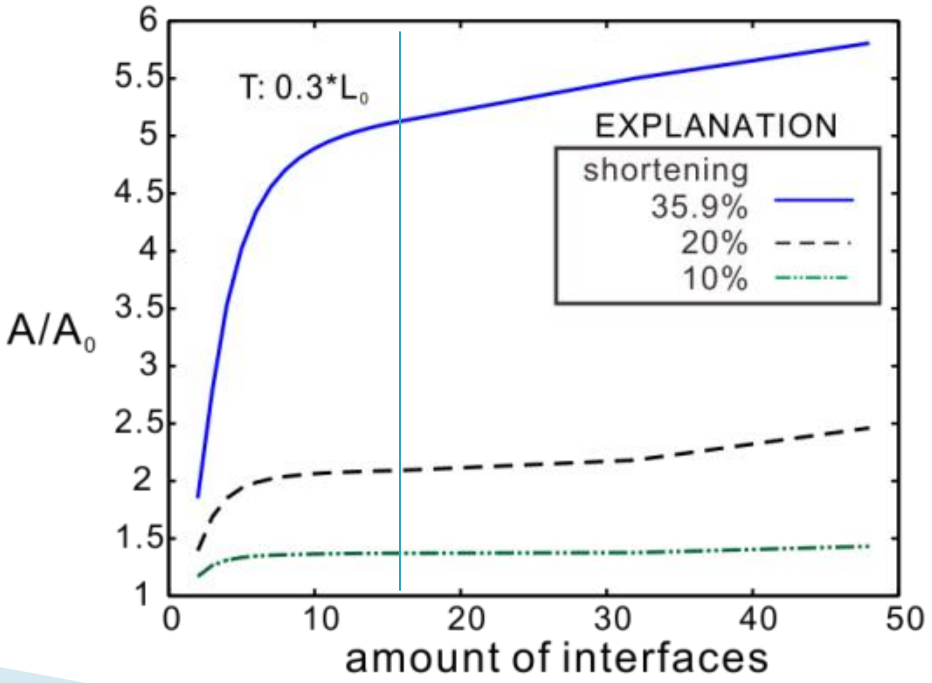
$$\text{Conjugate fold} = f(A_0, L_0, h, N, C_0, \psi, {}^{\infty}\sigma^i, {}^{\infty}\varepsilon^L_{xx}, {}^{\infty}\varepsilon^L_{xy})$$

A_0: initial amplitude

Illustration of a mulilayer of 6 layers



Growth of fold amplitude, A, vs. number of interfaces, N,



Conclusions

◆ **Are the conditions enumerated below sufficient for the formation of symmetric conjugate kink bands according to our theoretcial analysis?**

1. **a multilayered material** (bedded stiff layers or interbedded stiff and soft layers),
2. a nonlinear relation, such as **cohesive or frictional strength**, between shear stress and flexural slip **at contacts of layers or within interbeds,**
3. maximum principal compression inclined parellel to the layering in the outer limbs,
4. and an initial perturbation of layer orientation.

Ans: Yes.

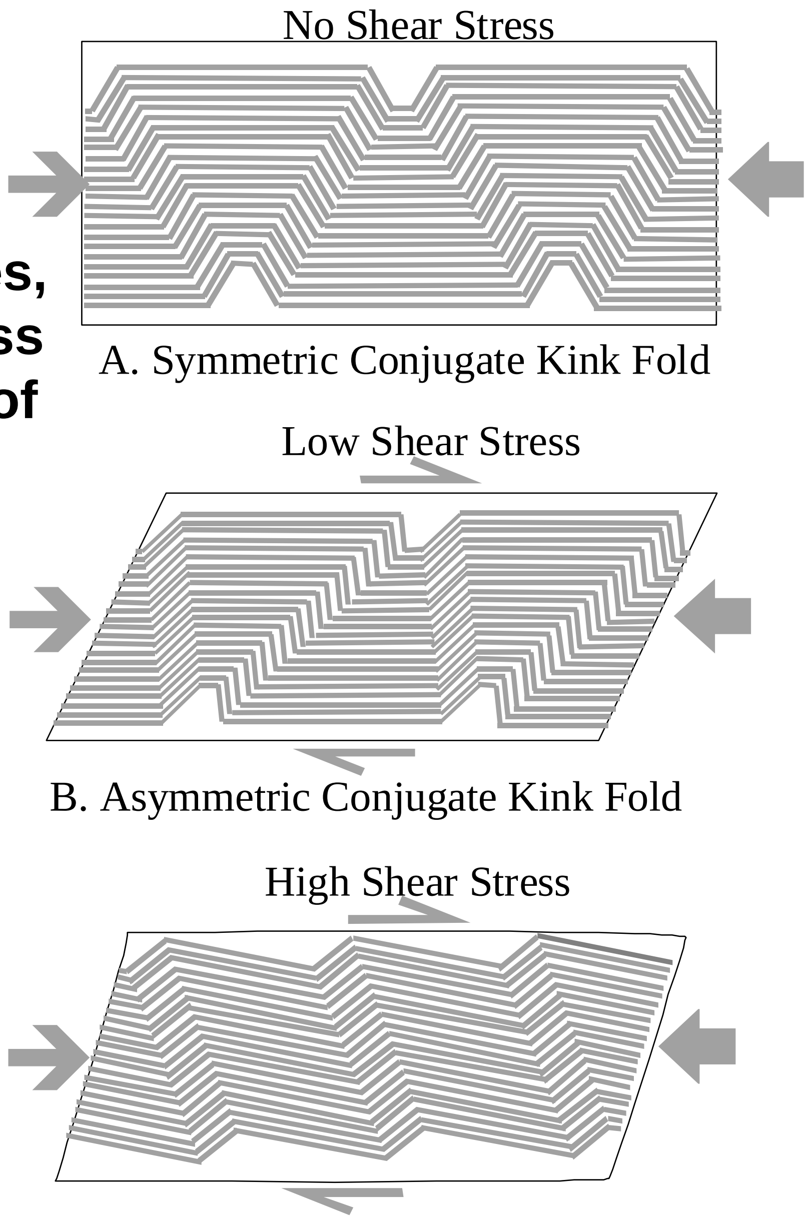
◆**If the answer is yes, then, given certain theoretical properties, can you quantify the states of stress that will produce conjugate kink bands in a multilayer material?**

Ans: Yes.

- We find a multilayer with certain cohesive strength stand-alone on its interfaces can produce conjugate folds under compression parallel to the interface but with frictional strength alone only cannot.
- We find that **the lower bound** of stand-alone cohesion divided by Young's modulus ranges from 10^{-3} to 10^{-2} and friction cannot produce conjugate folds if the ratio of the vertical initial remote stress to horizontal initial remote stress is small than 0.2 under the shortening of 36% with an incremental far-field strain of 0.02 for multilayer models of 16 interfaces.

Future work

◆Given certain theoretical properties, can you quantify the states of stress that will produce these three kinds of kink folds in a multilayer material?



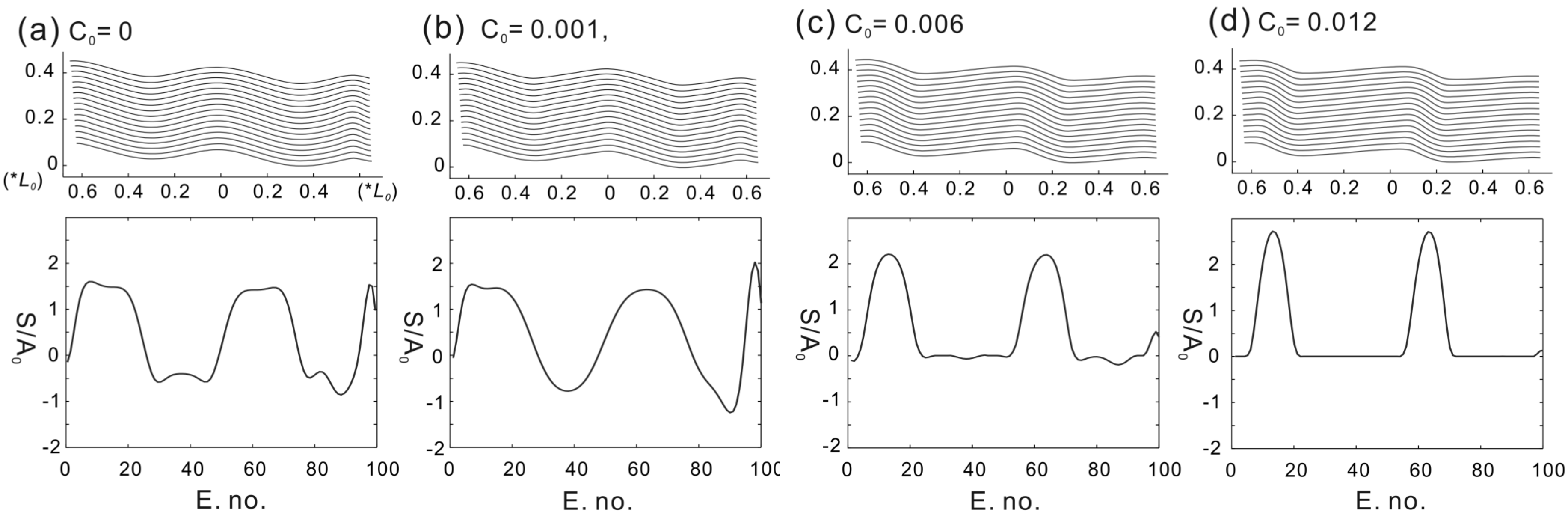
A. Symmetric Conjugate Kink Fold

B. Asymmetric Conjugate Kink Fold

C. Monoclinal Kink Fold

Thank you for your attention!

Monocline kink fold



Monocline kink fold