What we Know About Mobile Shales?

Seismic Expression and Processes

Bureau of Economic Geology

Juan I. Soto

Michael R. Hudec, Tim P. Dooley, and Mahdi Heidari

AGL APPLIED GEODYNAMICS LABORATORY

Professor of Structural Geology and Tectonics (Granada University, Spain) – jsoto@ugr.es

Researcher of the Bureau of Economic Geology (The University of Texas at Austin) – juan.soto@beg.utexas.edu

Acknowledgements

Maryline Le Béon and other colleagues at NCU, together with Academia Sinica, for the invitation and support of my visit.

Permission to use seismic data

Applied Geodynamics Laboratory Consortium
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What is the scientific problem?

How does the fluidification of a consolidated sedimentary rock occur?

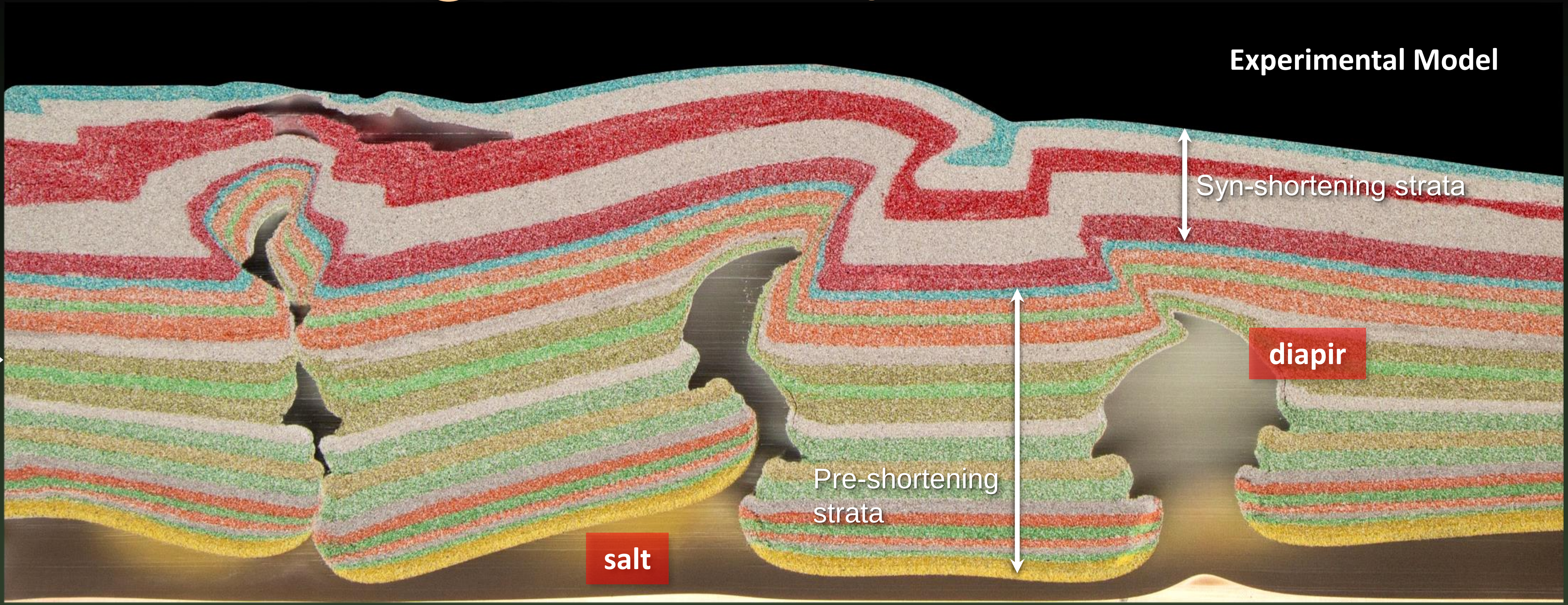
Mud Volcanoes in Onshore Azerbaijan

Martin Hovland

Outline of the talk

1. What is a diapir? Salt vs. Shale diapirs
2. Some principles
3. Mechanical model for mobile shales
4. Tectonic setting of mobile shales
5. Structural styles of mobile shales
6. Experimental models of shales under compression
7. Concluding remarks

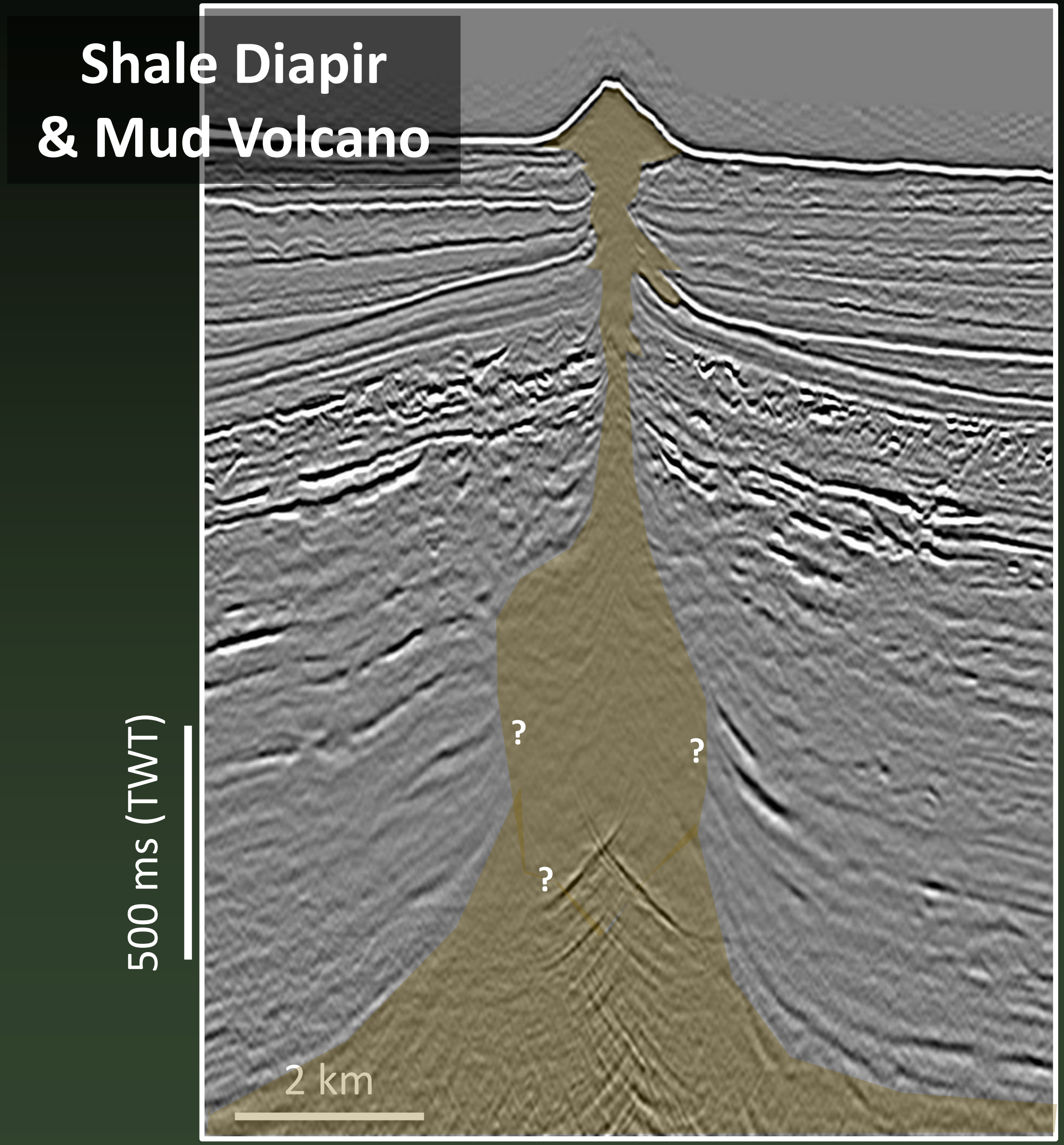
① What is a diapir?

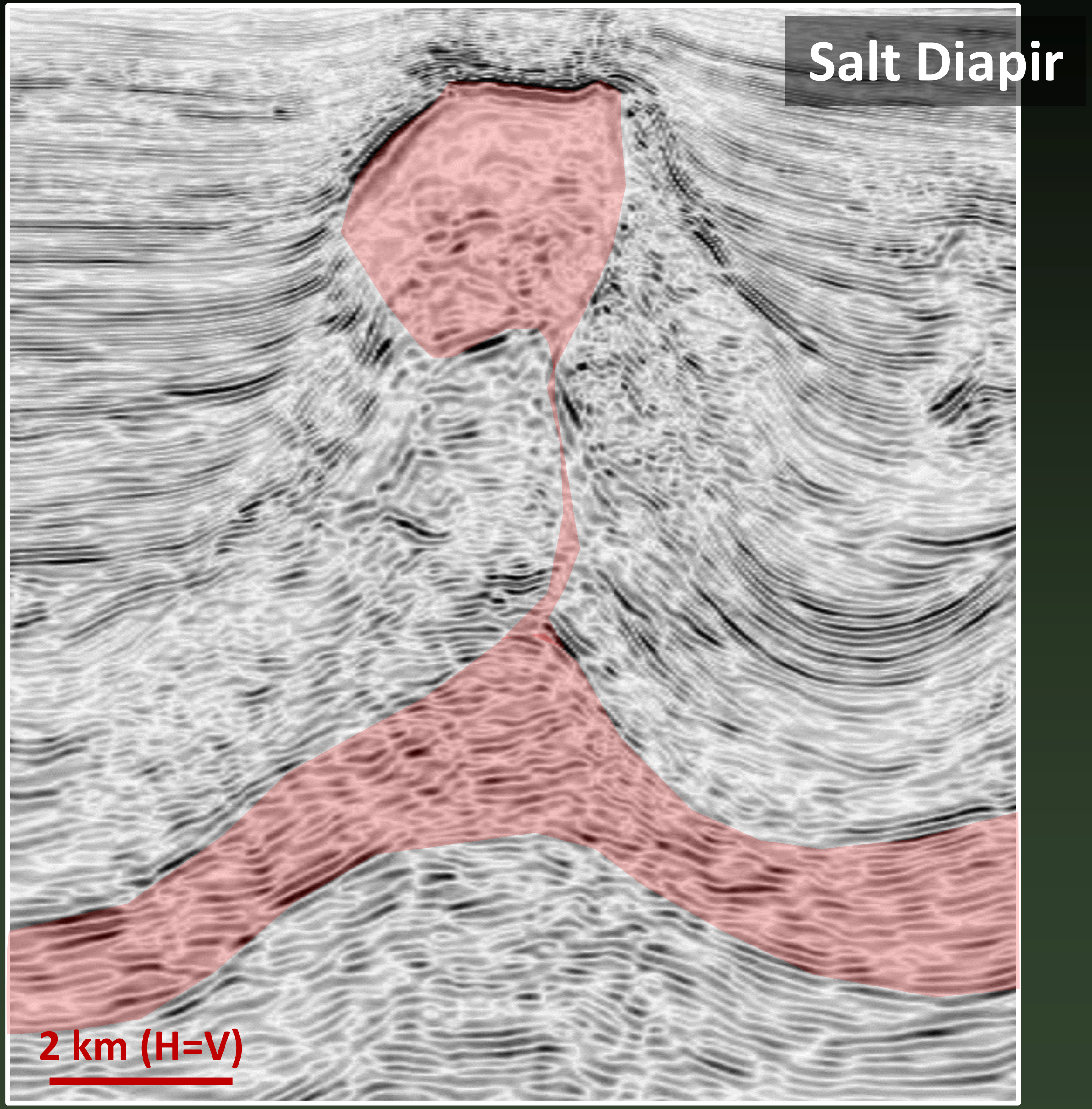


10 cm

"We use the term "diapir" strictly to refer to a body that has pierced, or appears to have pierced, shallower overburden (O'Brien, 1968). Natural diapirs are separated from their cover by a strain discontinuity; nondiapiric structures are in conformable contact with their overburden." (Jackson & Talbot, 1983)

① *Salt vs. Shale diapirs*

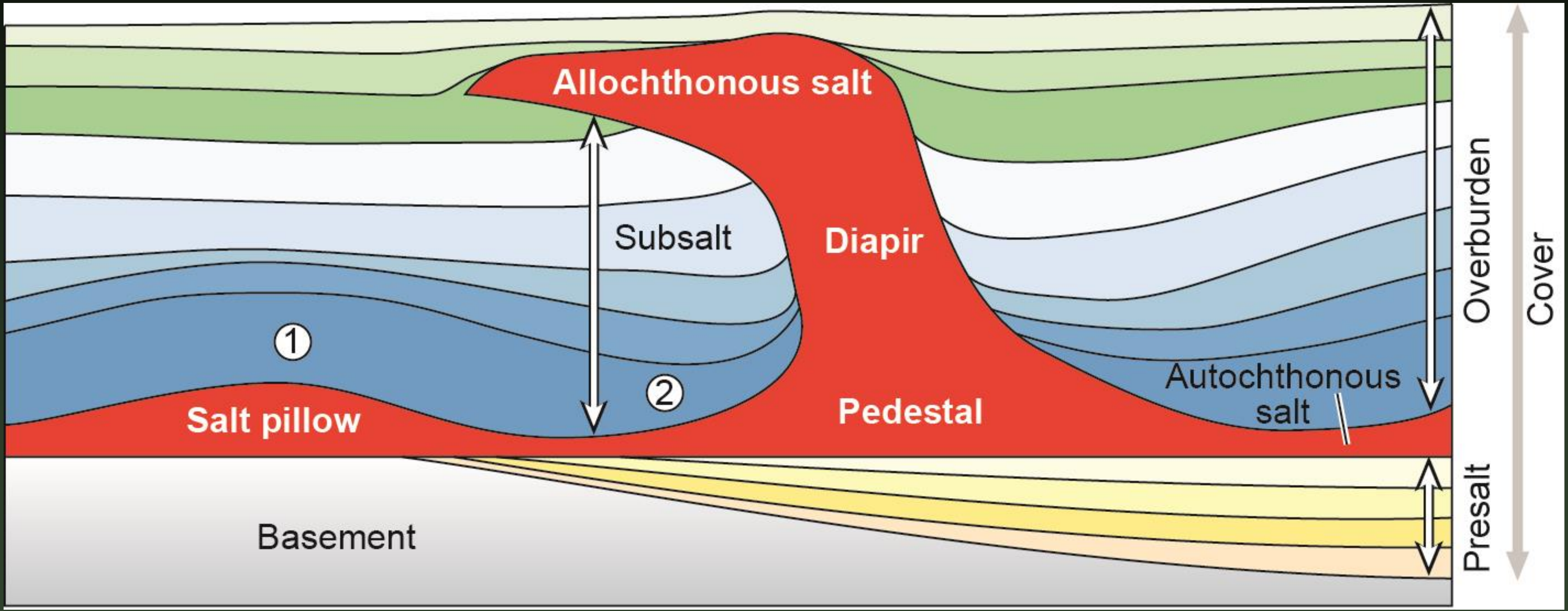




Data courtesy of Ministry of Energy (Trinidad) and CGG

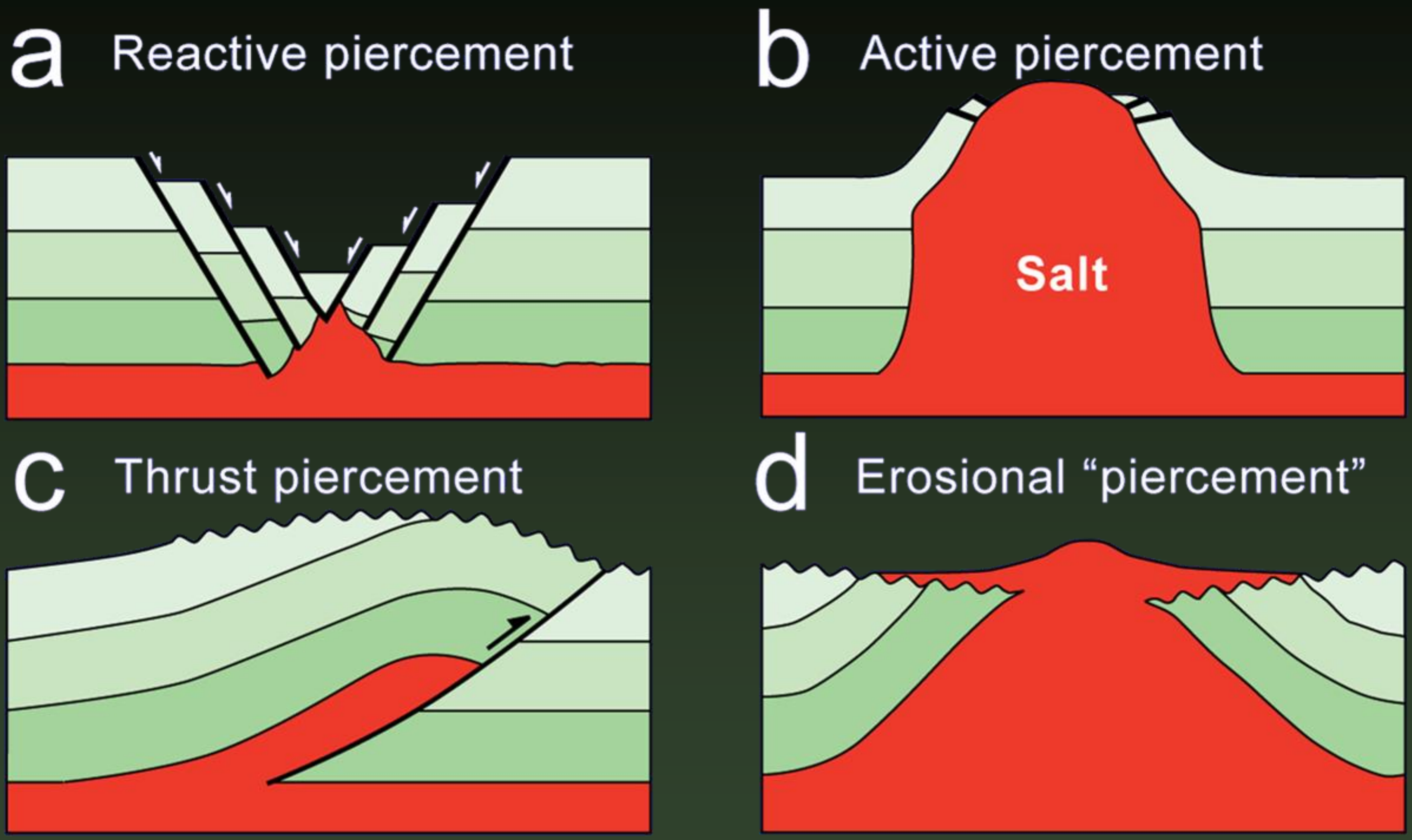
② Type of Sequences

Source layer, presalt, suprasalt (overburden), and subsalt



Jackson & Hudec, 2017

② Piercing mechanisms



"Piercement – Emplacement of a diapir to create a discordant contact, in which the diapiric margin crosscuts surrounding strata."

"Diapir – Structure in which a mobile material pierces its overburden"

(Jackson & Talbot, 1983)

Vendeville et al., 1992a, 1992b
Jackson et al., 1994
(taken from Hudec & Soto, 2021)

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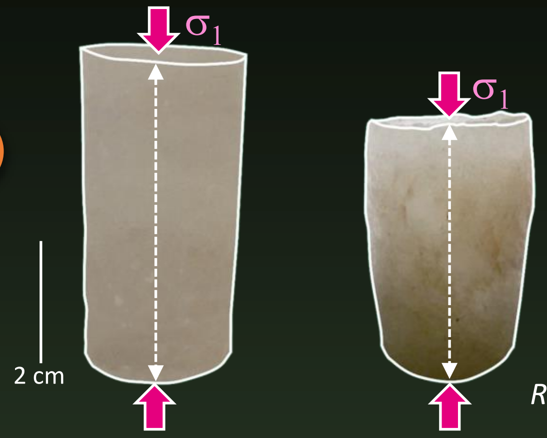
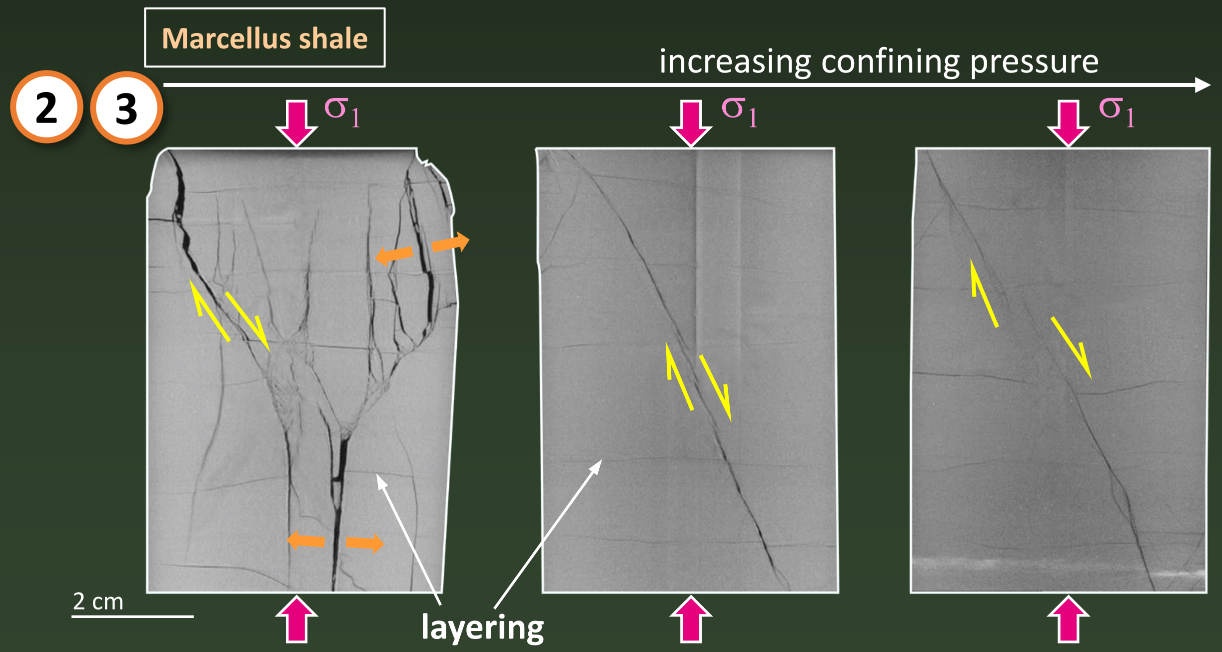
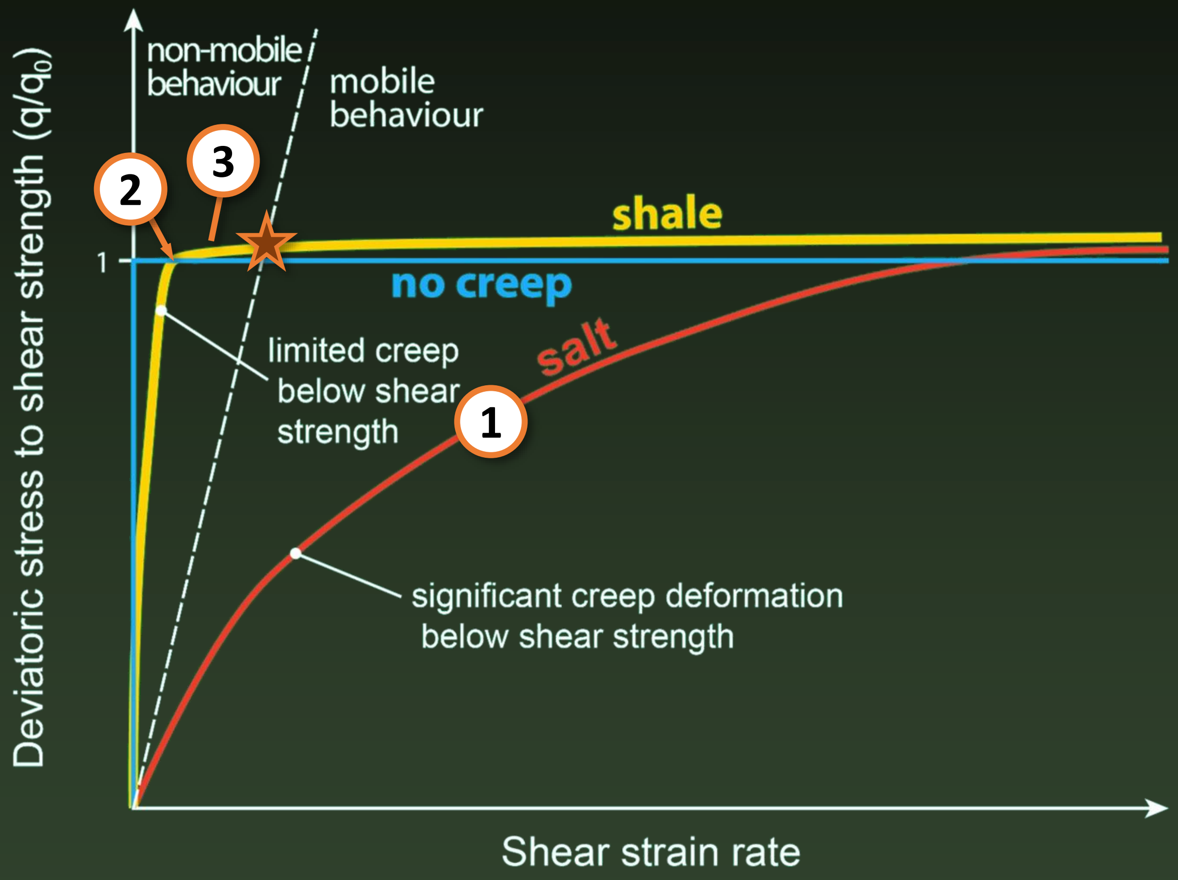
③ Mechanical model for mobile shales

3.1 Mechanical behavior of shales vs. salt



Reza Taheri et al., 2021





shear fracture

tension fracture

Villamor Lora et al., 2016

Soto et al., 2021b

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3.2 Experimental deformation of a natural shale

- Principles of soil mechanics can be extrapolated to cemented shales (e.g., Jones and Addis, 1986; Brown, 1990; Ewy et al., 2020)
- Following Terzaghi's equation, effective stress (σ') is the total stress (σ) less some proportion of pore pressure (u):

$$\sigma' \approx \sigma - u$$

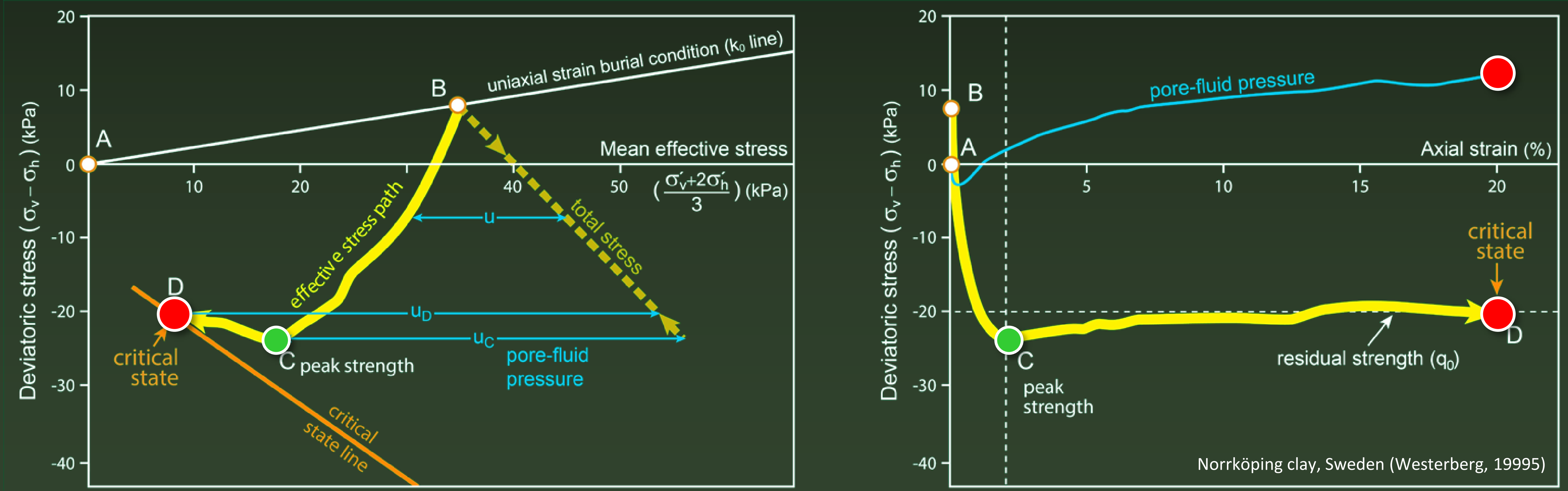
- Stages during <u>undrained</u> triaxial tests on clays/shales:

Ⓐ to Ⓑ Uniaxial burial to final depth

Ⓑ to Ⓒ Horizontal <u>compression</u> ($\sigma_v - \sigma_h < 0$; shear-induced overpressure)

Ⓒ to Ⓓ Strain softening (shear-induced overpressure, formation of continuous fractures)

Ⓓ **Critical State** (high overpressure, fabric collapse, unlimited shear at same stress → sample flows)



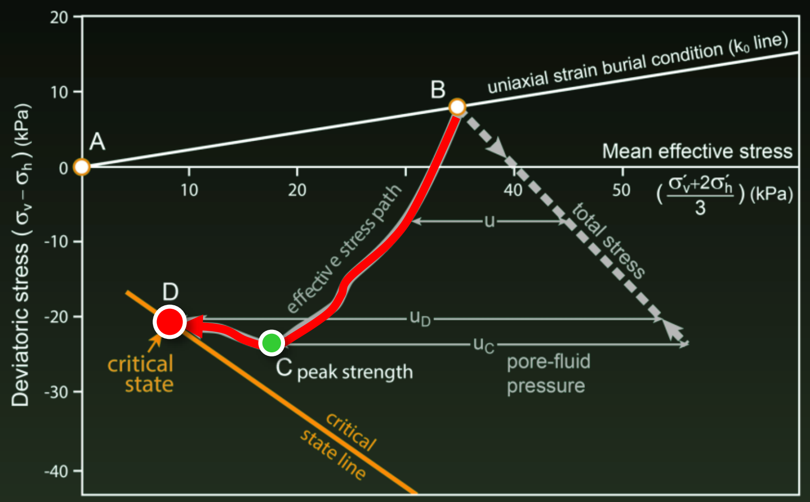
Soto et al., 2021b

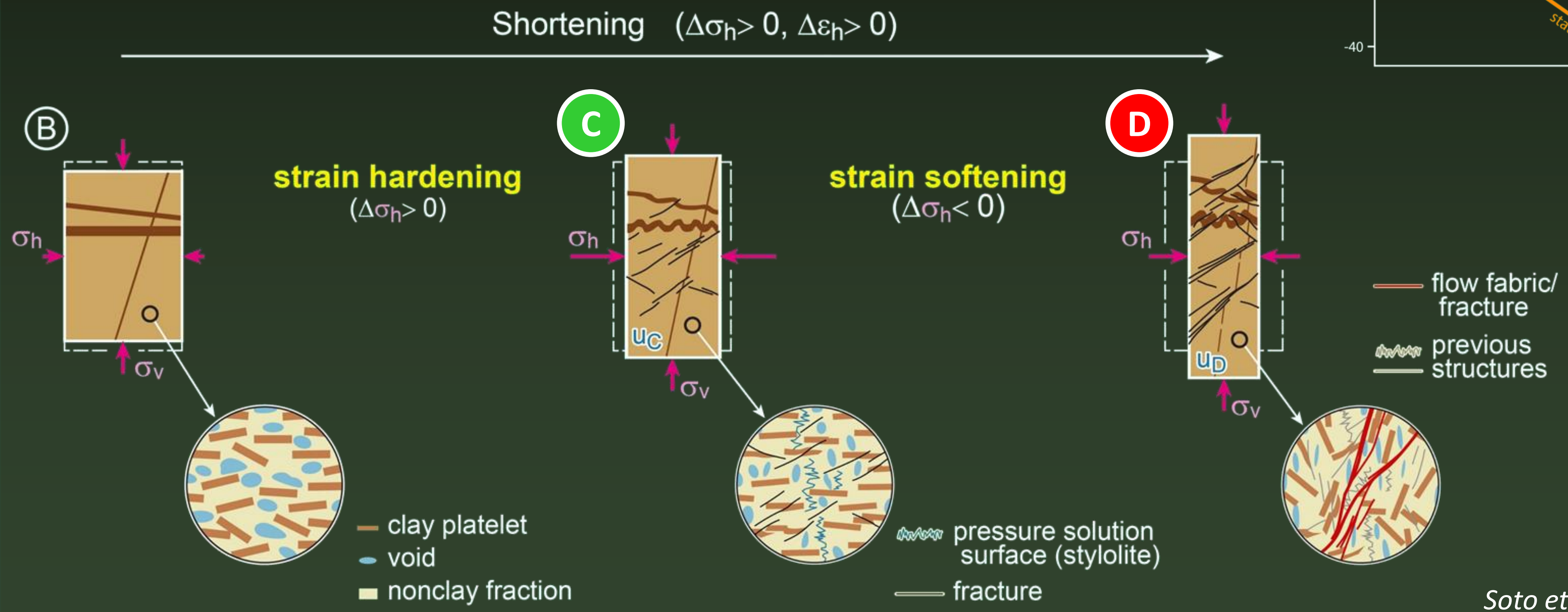
3.3 Evolution of the fabric

B to **C** *Compression, stresses below peak strength*

C *at peak strength* ➡ *formation of continuous fractures*

D *at* ***critical state*** ➡ *complete destruction of the fabric (collapse)*



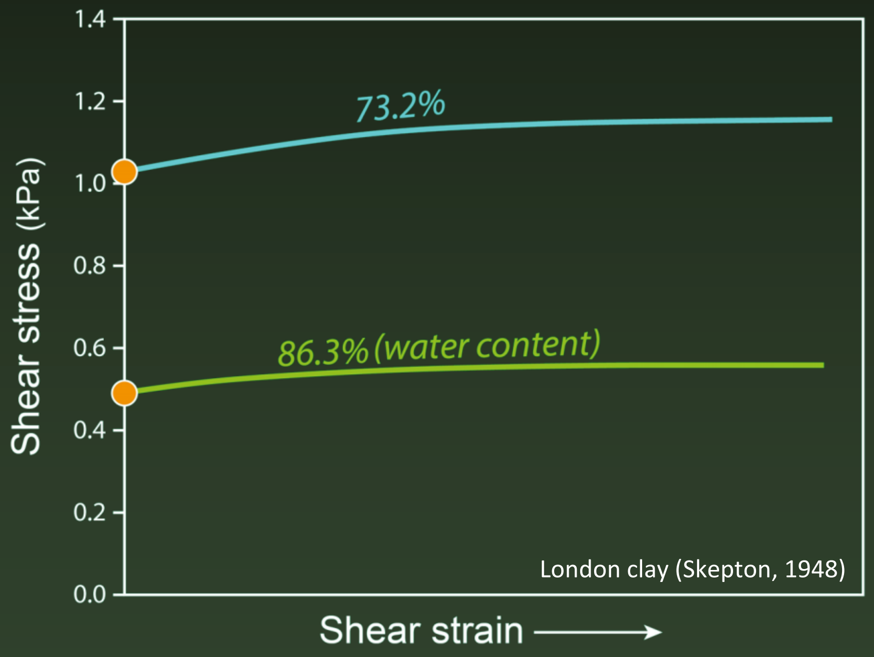


Soto et al., 2021b

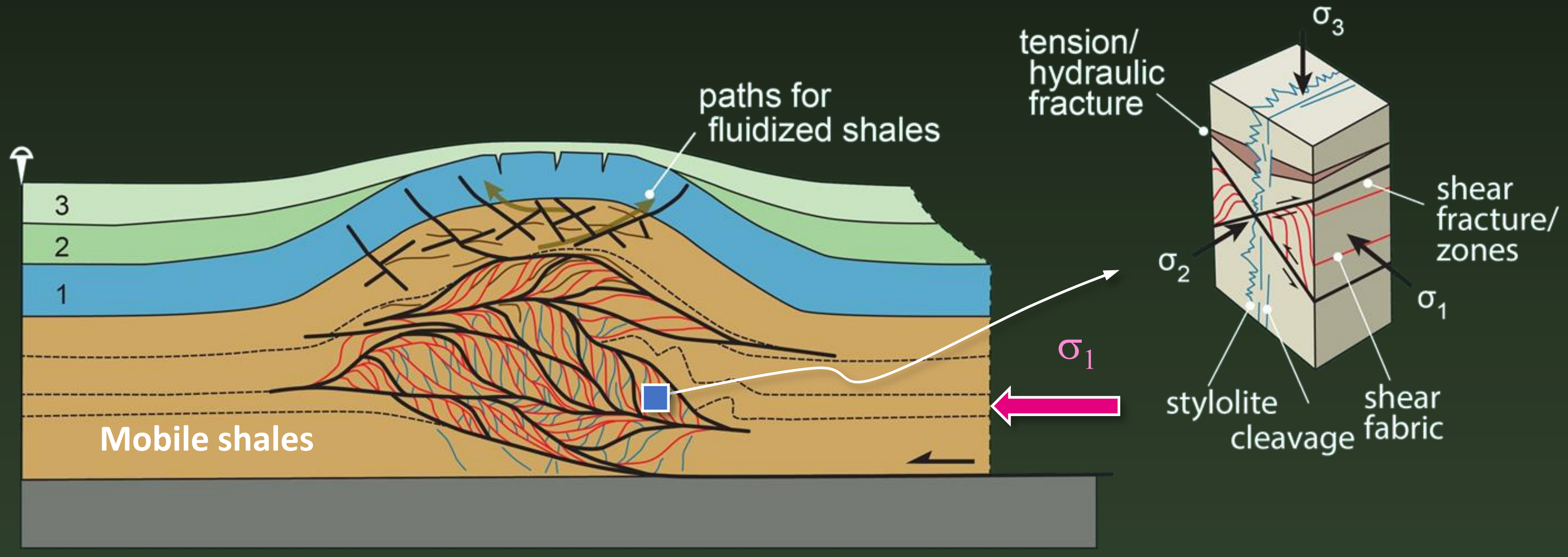
3.4 Mobile shales as bodies deforming at critical state

"Bodies of clay-rich sediment or sedimentary rock undergoing penetrative, (visco-) plastic deformation at the critical state"

At critical state, shale behaves as a Herschel-Bulkley fluid material



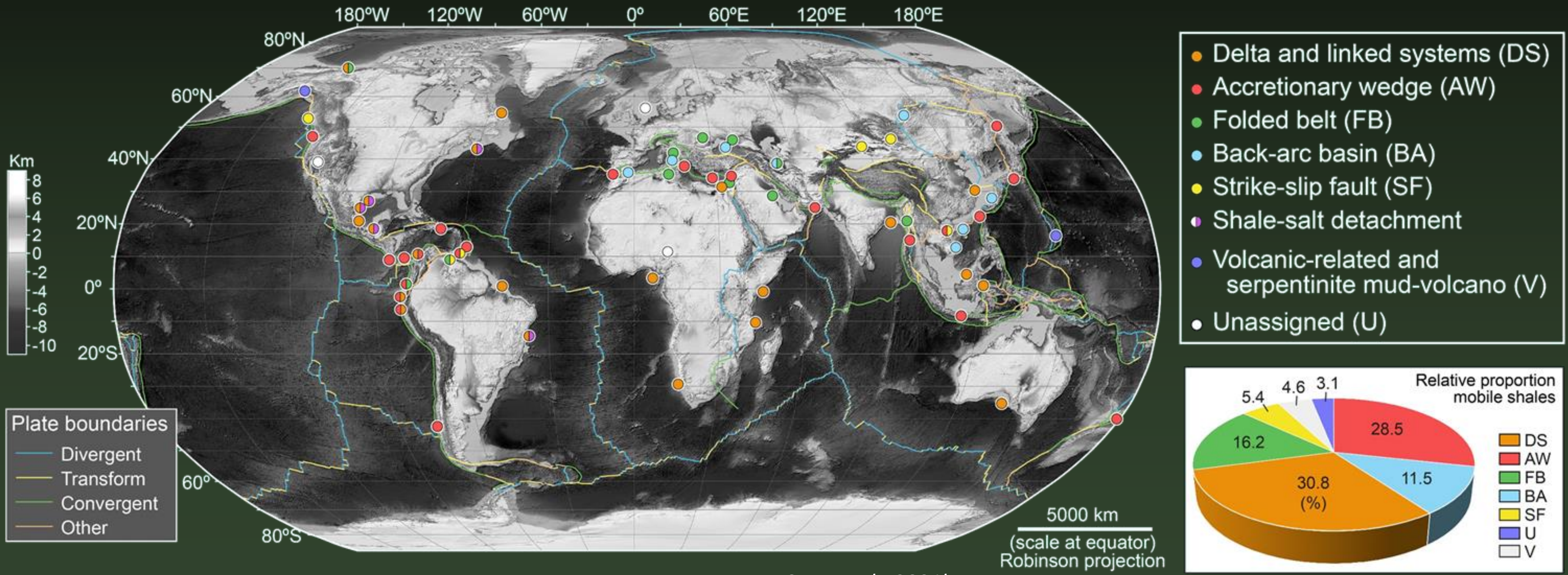
Deformation pattern at critical state



- At critical state, shales deform with a high shear strain without any additional shear stress
- Strength decreases with water content

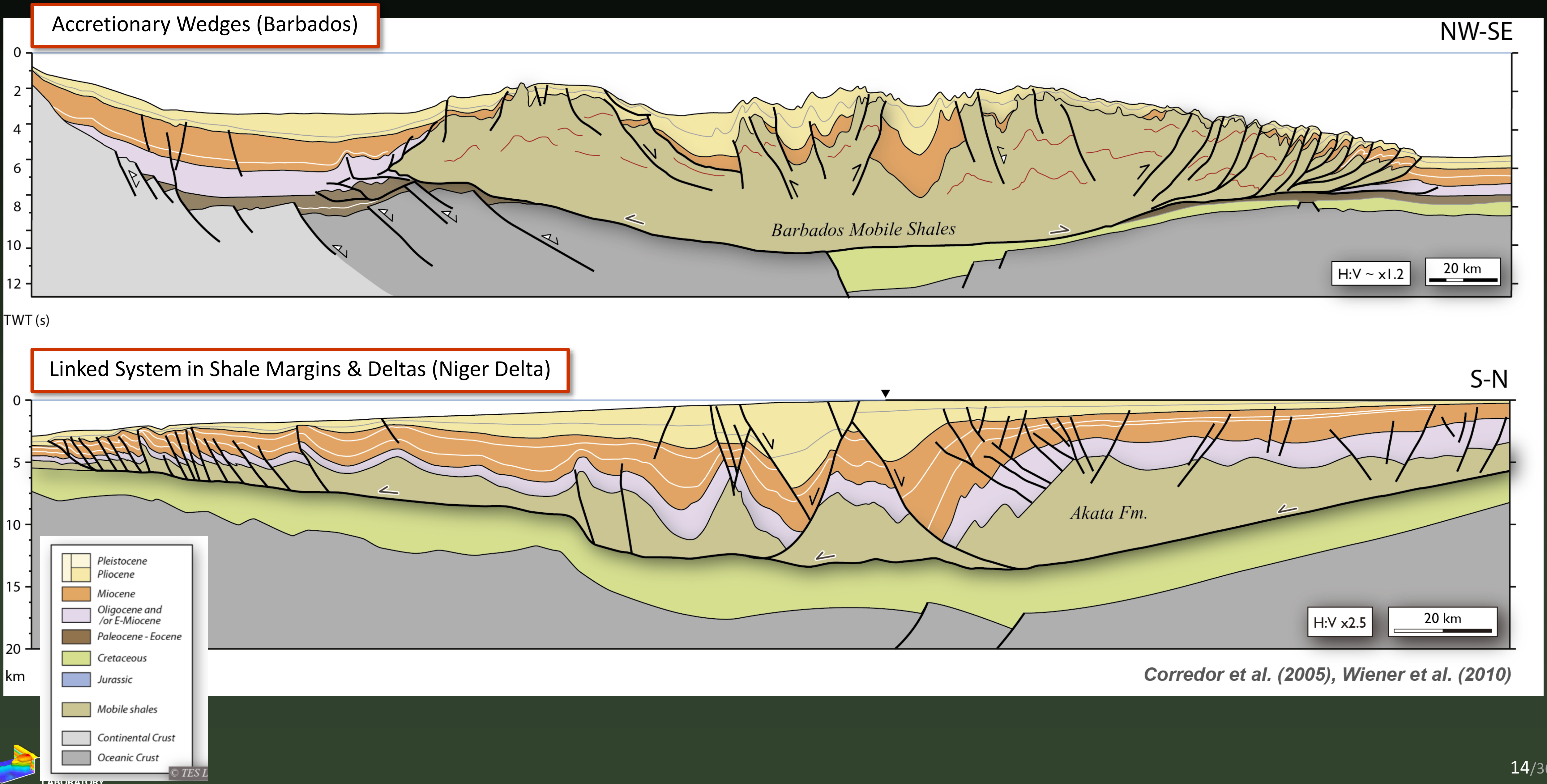
④ Tectonic setting of mobile shales

- Many mobile shales occurs in <u>contractional settings</u> (45%), like accretionary wedges and fold–thrust belts in continental margins
- Linked systems in deltas (updip extension and deepwater contraction) is another important setting (31%)



Soto et al., 2021b

④ Tectonic setting of mobile shales



Corredor et al. (2005), Wiener et al. (2010)

⑤ Structural styles of mobile shales

5.1 Mud volcanoes

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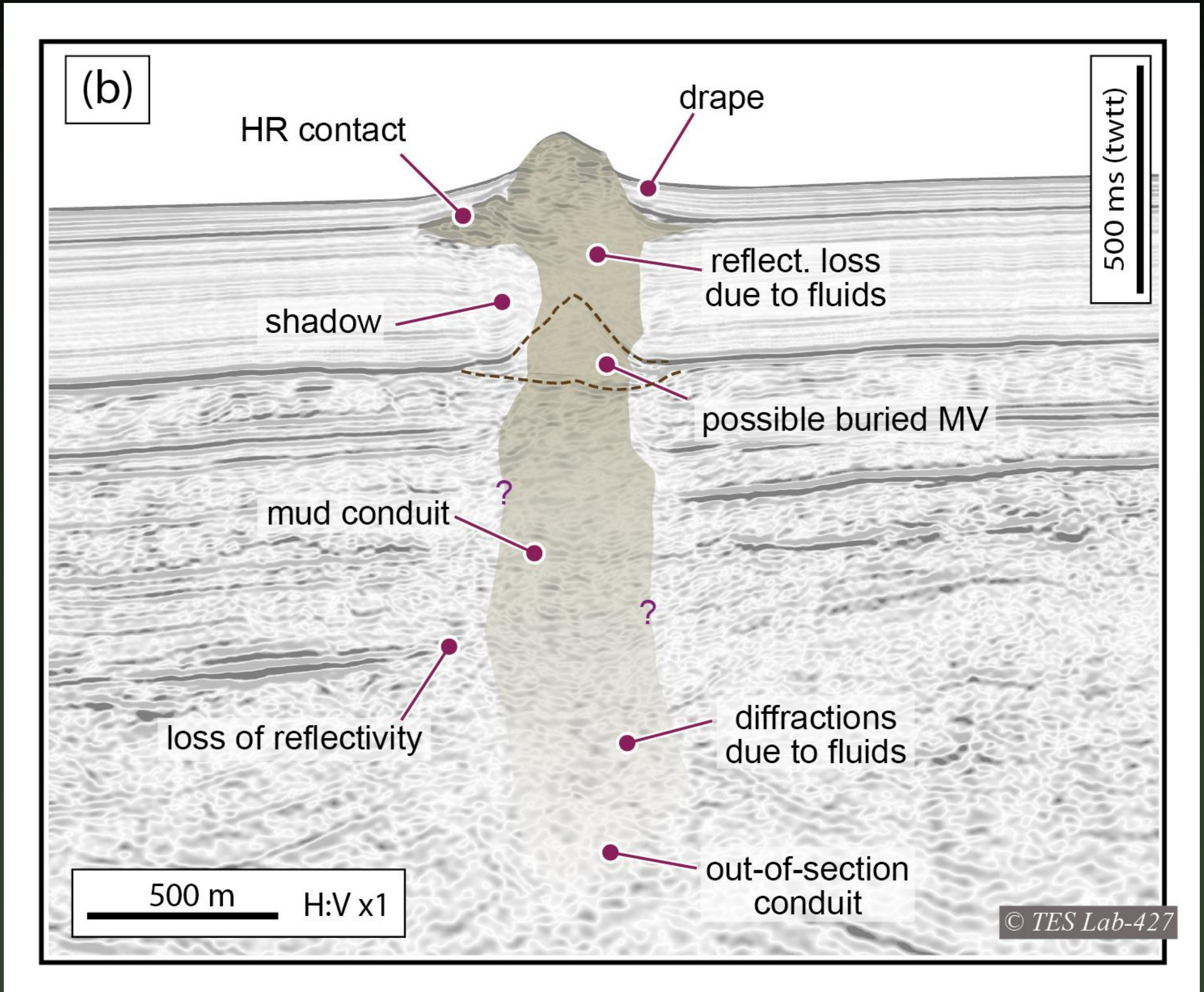
⑤ Structural styles of mobile shales

5.1 Mud volcanoes



Offshore Barbados

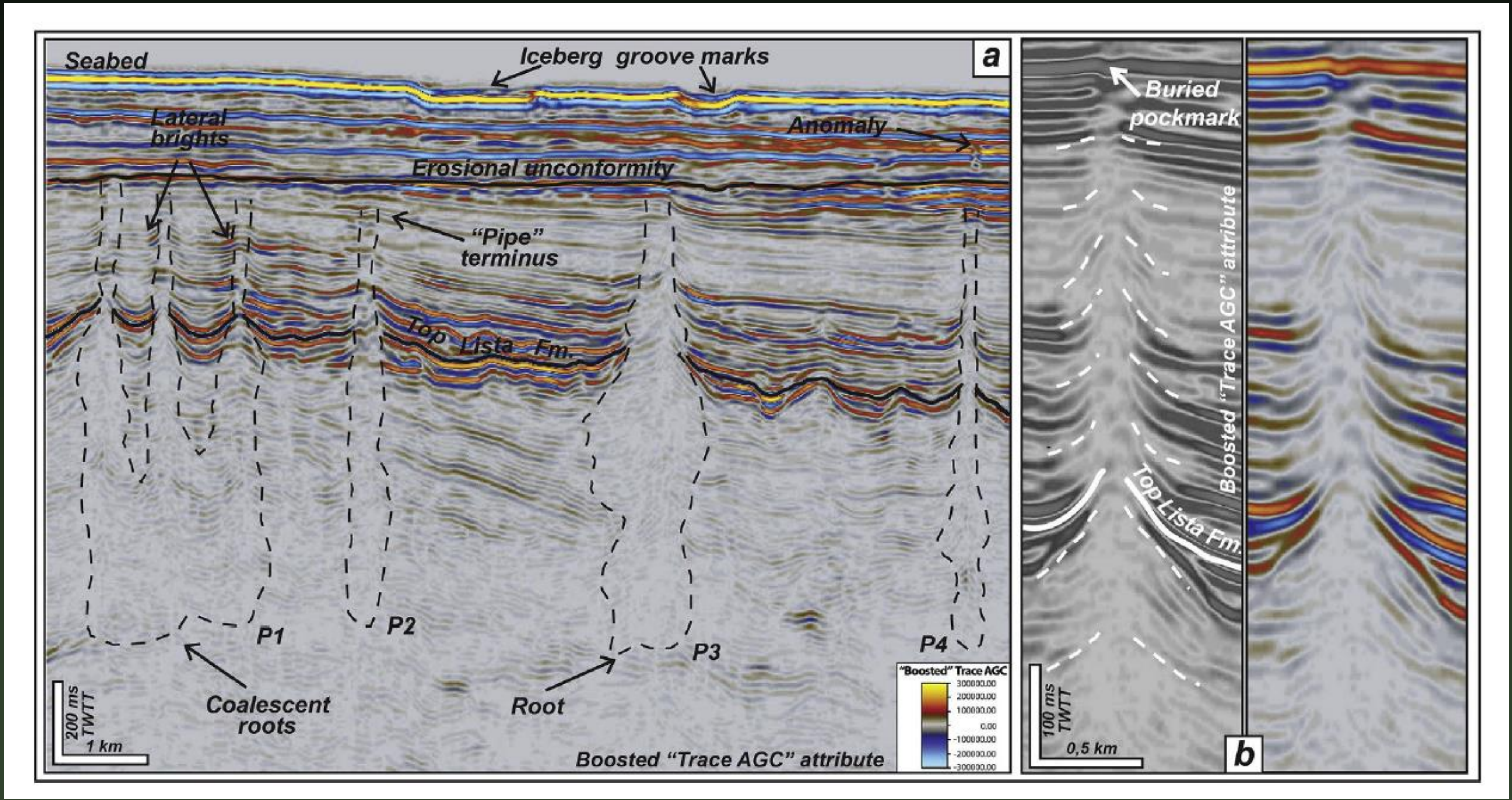
(data courtesy of REPSOL)

Soto et al., 2021a

⑤ Structural styles of mobile shales

5.2 Mud (gas) pipes

North Sea (Offshore UK)

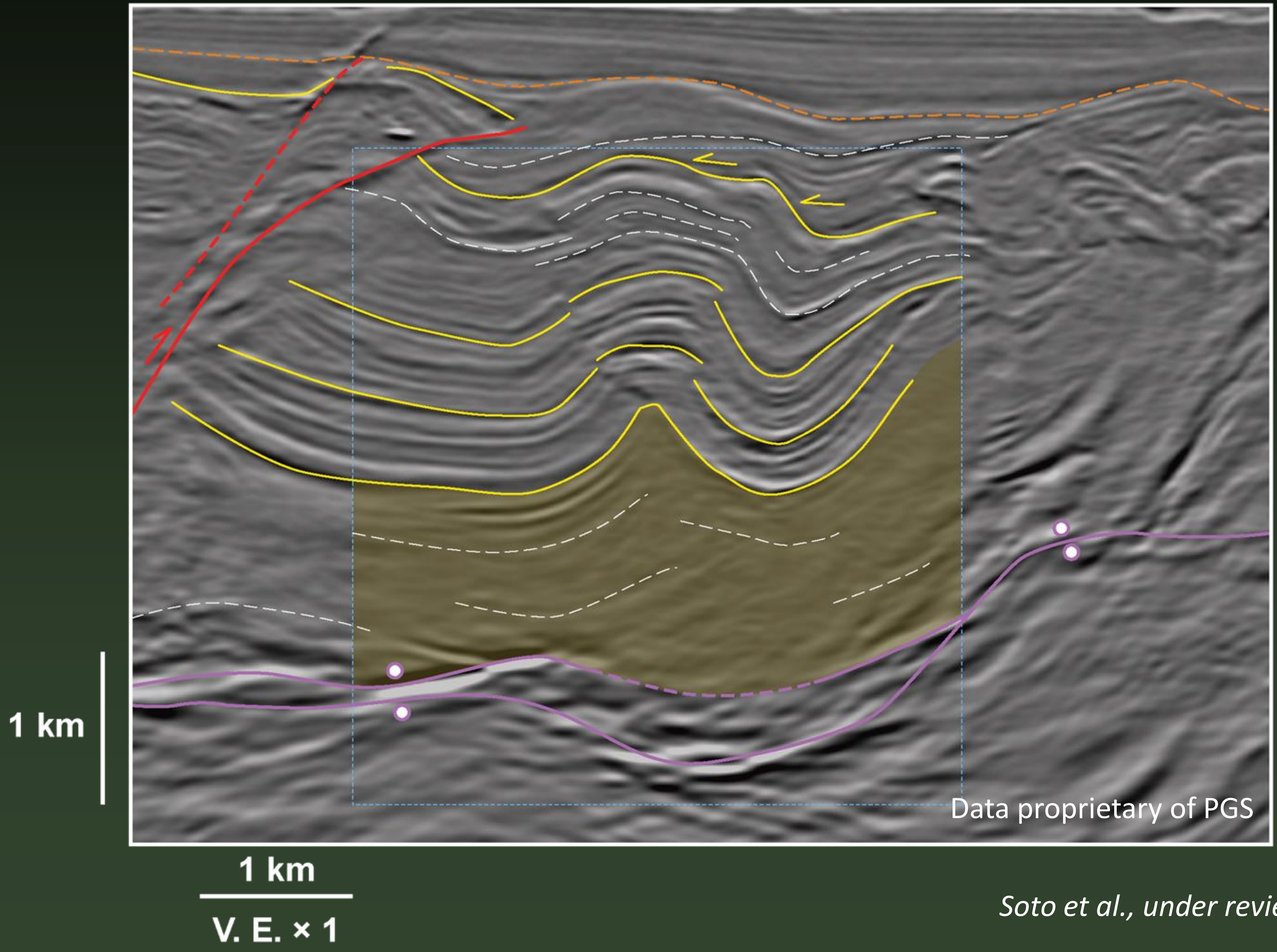


Maestrelli et al., 2017

⑤ Structural styles of mobile shales

5.3 Detachment folds (with homogeneous strata)

East Breaks Fold Belt (Gulf of Mexico)

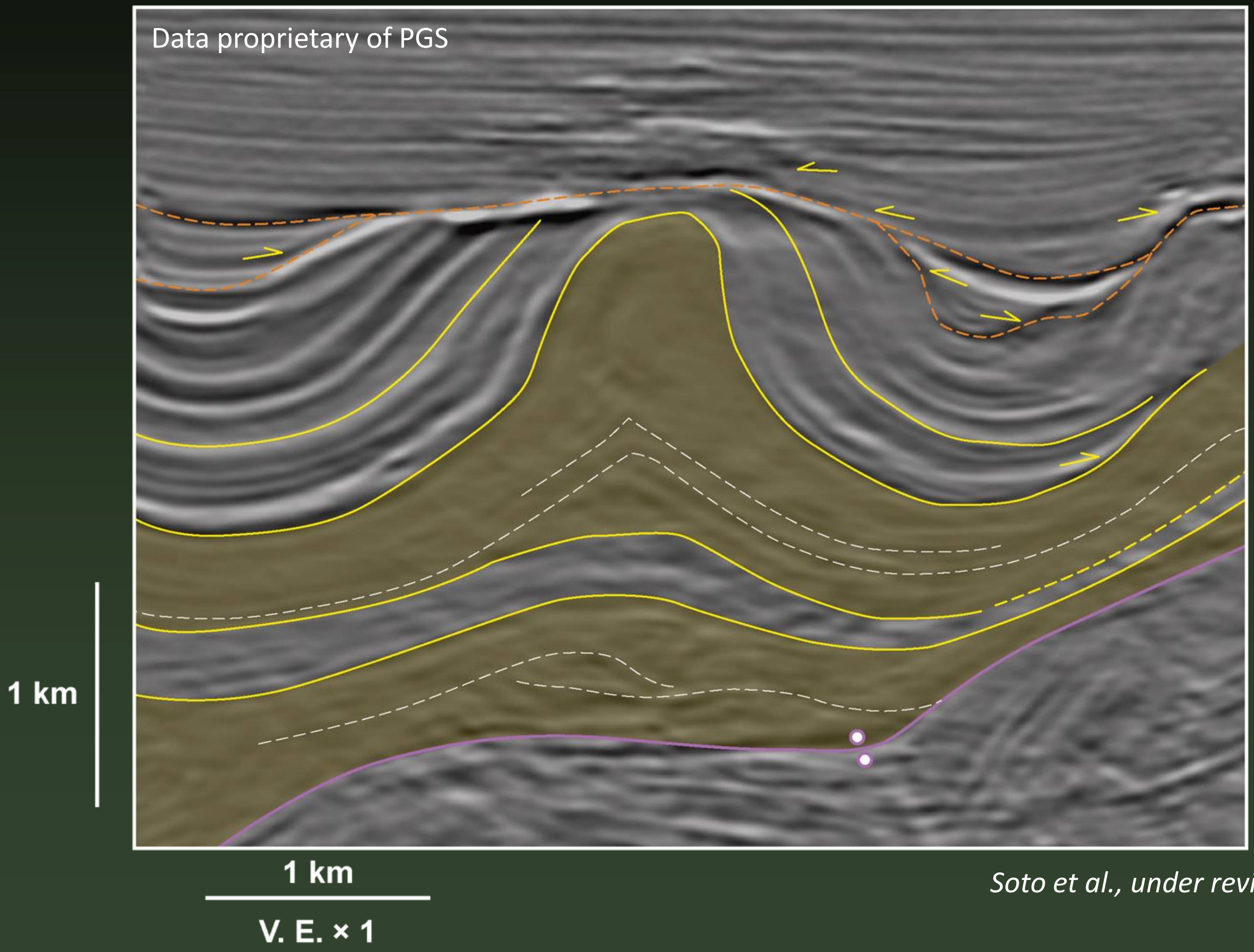


Soto et al., under review

⑤ Structural styles of mobile shales

5.3 Detachment folds *(with heterogeneous layered strata)*

East Breaks Fold Belt
(Gulf of Mexico)



Soto et al., under review

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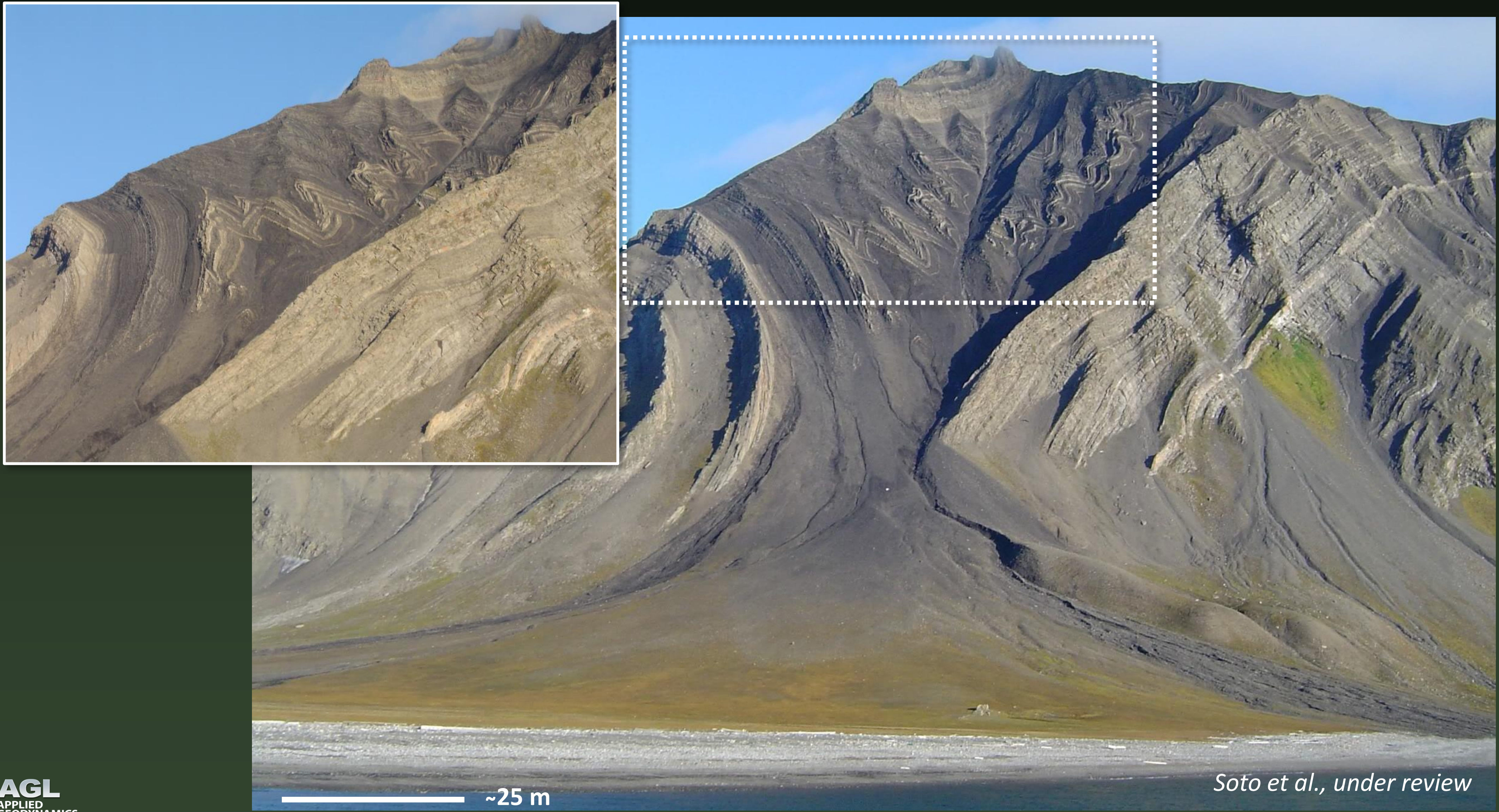
⑤ Structural styles of mobile shales

Field examples of detachment anticlines



Ingeborgfjellet cliff in Spitsbergen (Svalbard, Norway)

Image courtesy of Prof. Ólafur Ingólfsson

⑤ Structural styles of mobile shales

Detached lift–off anticline *(sensu Mitra, 2003)*

Big Show, near Crowsnest Pass (Alberta, Canada)

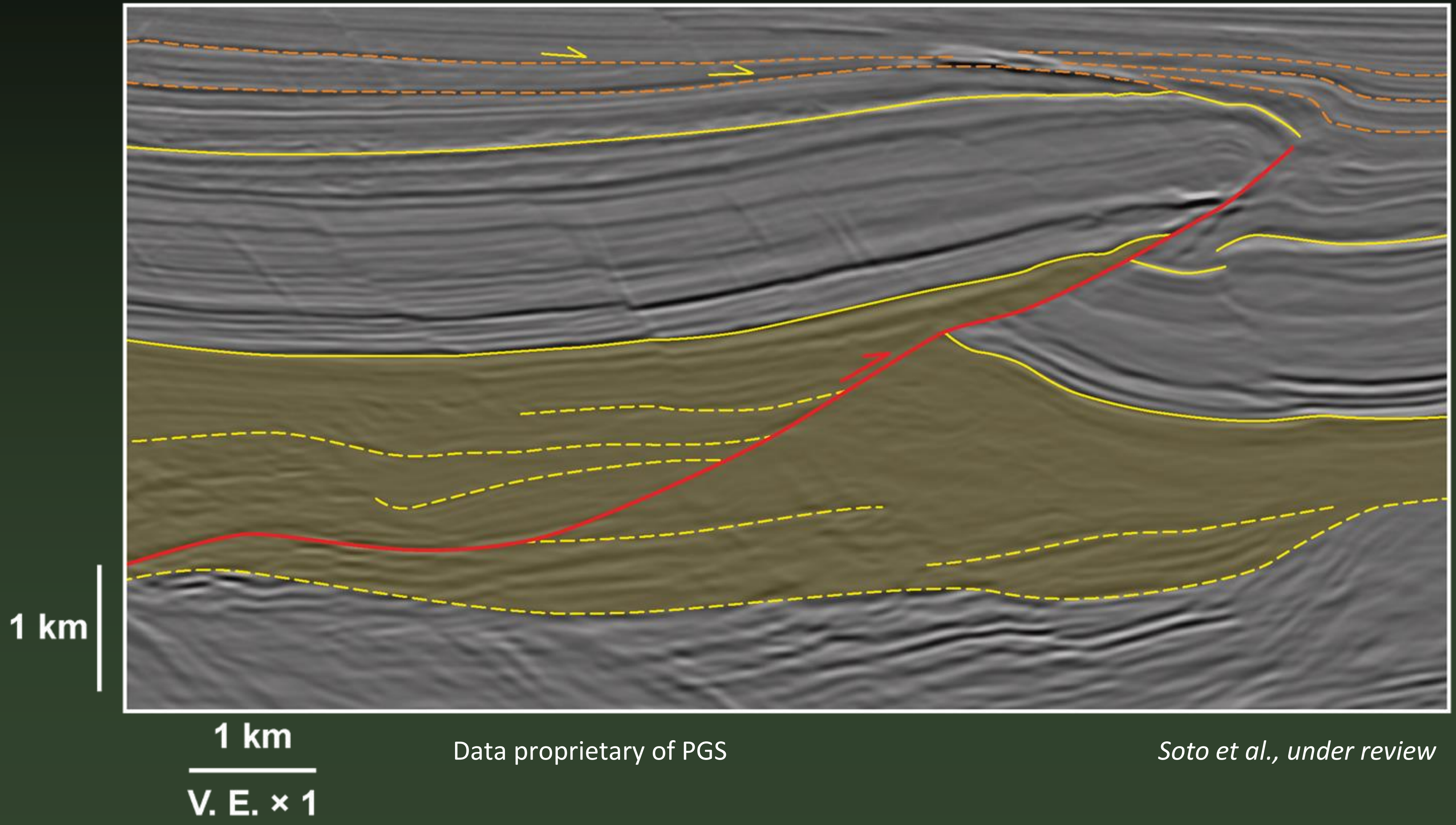
Image courtesy of Willem Langenberg

Soto et al., under review

⑤ Structural styles of mobile shales

5.4 Thrust–related folds

East Breaks Fold Belt (Gulf of Mexico)



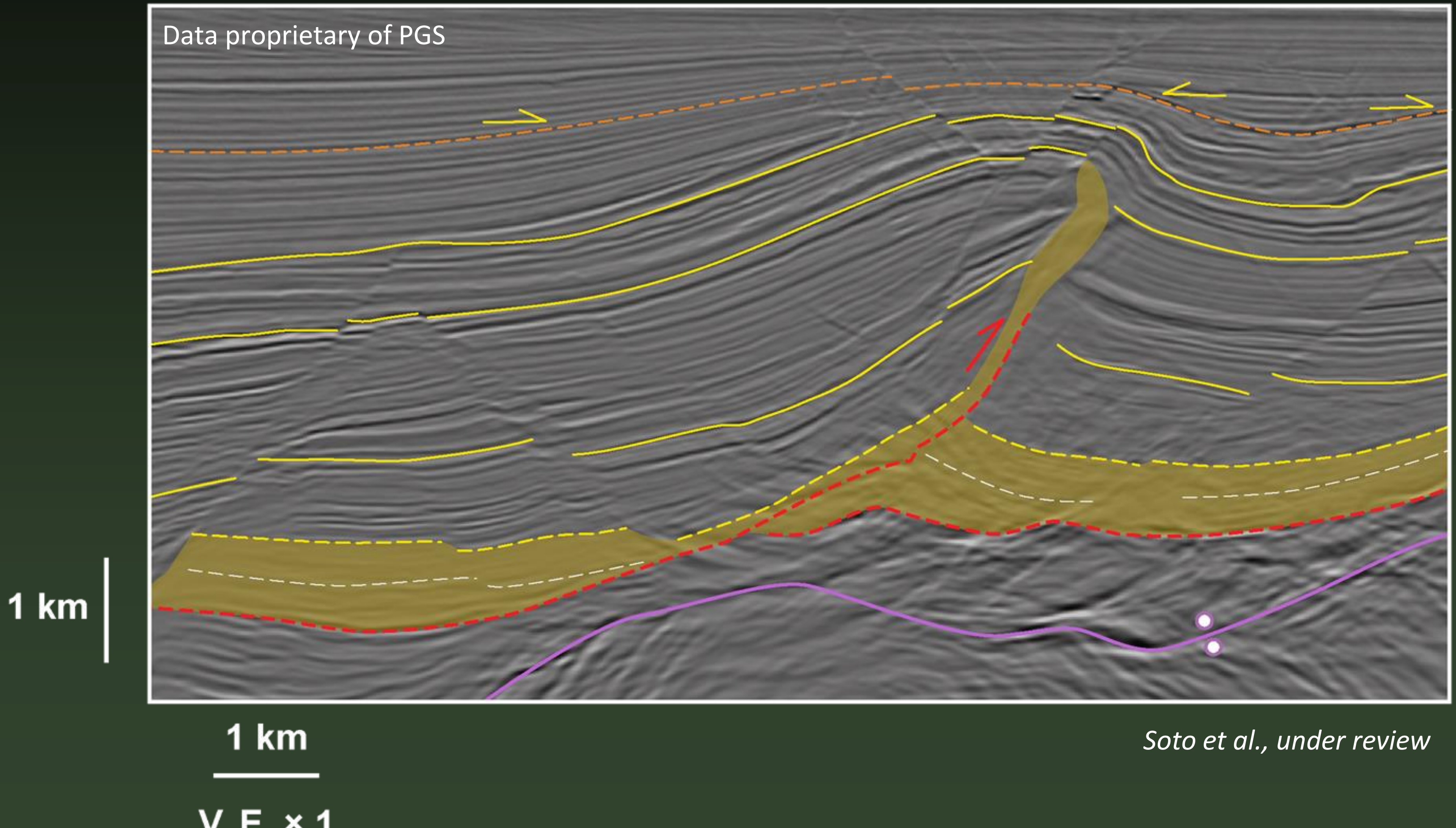
Data proprietary of PGS

Soto et al., under review

⑤ Structural styles of mobile shales

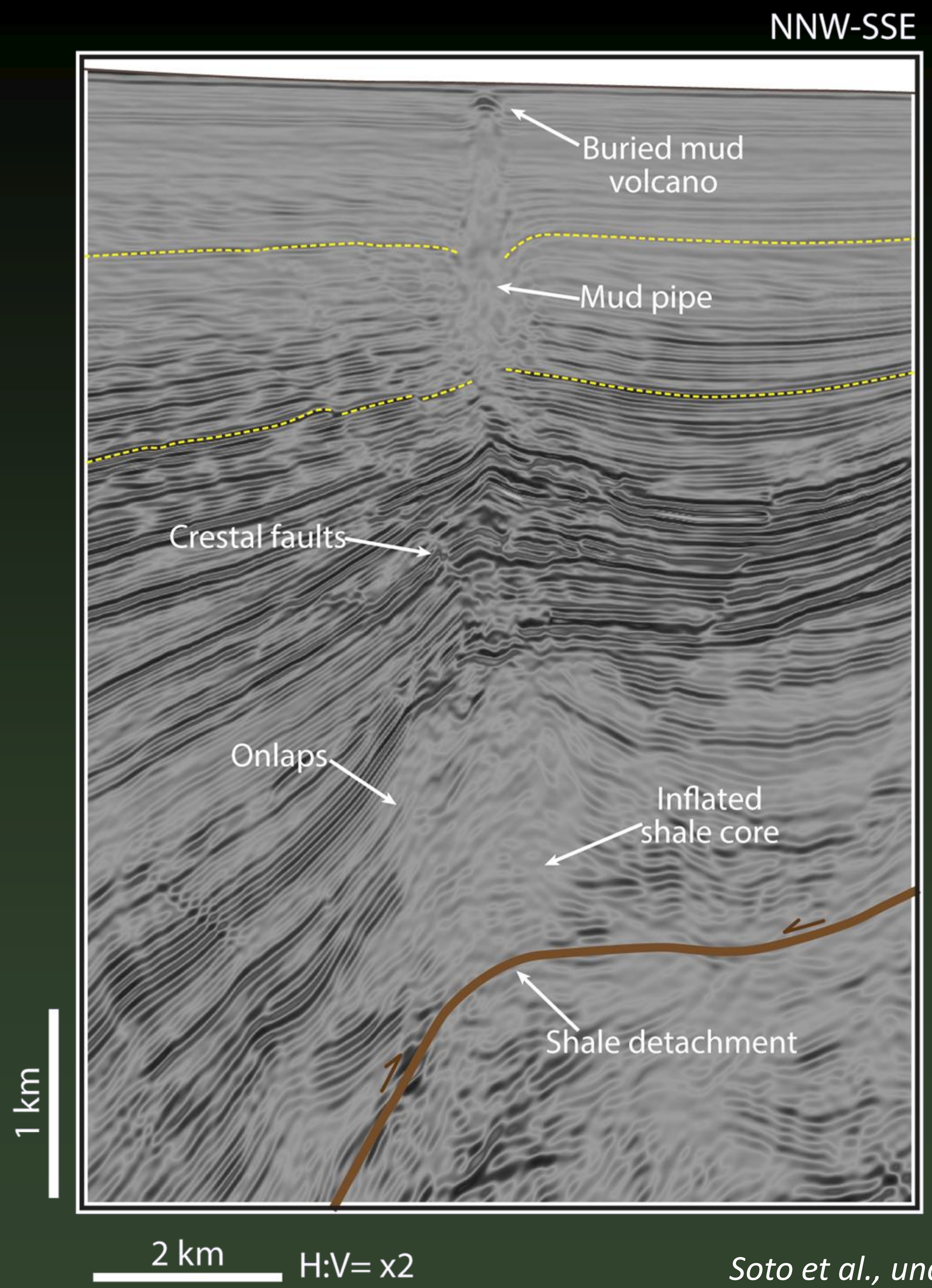
5.4 Thrust–related folds

East Breaks Fold Belt (Gulf of Mexico)



Soto et al., under review

Mud volcanoes and shale diapirs

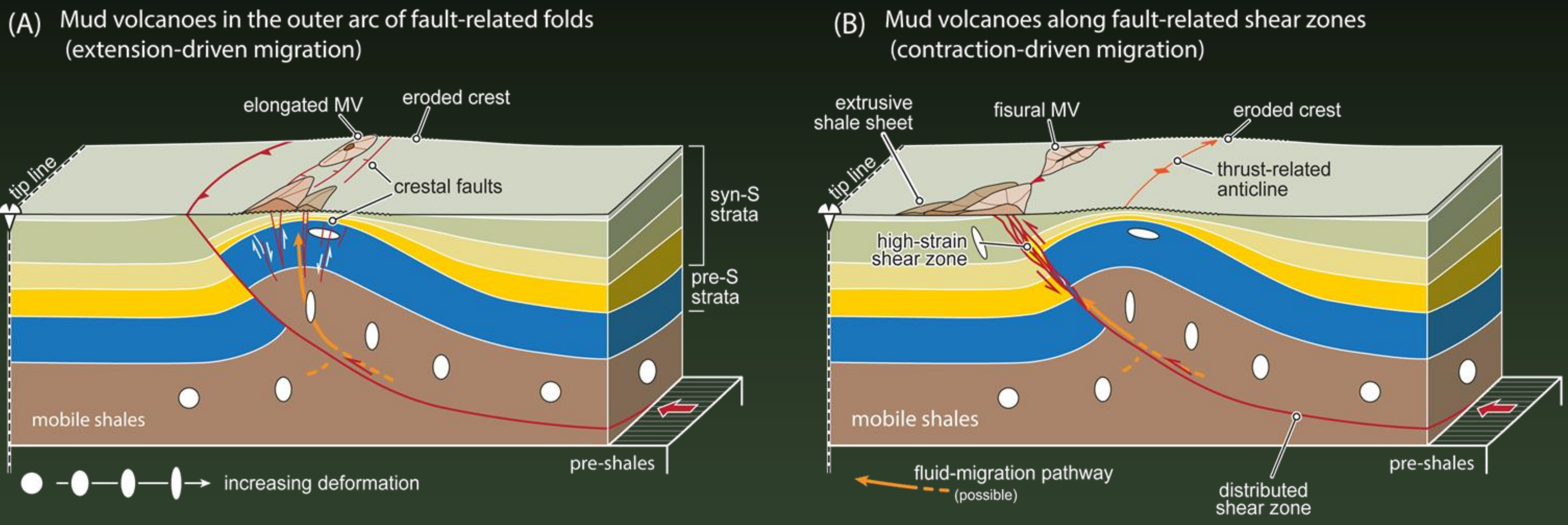


East Breaks Fold Belt (Gulf of Mexico)

Data proprietary of PGS

Soto et al., under review

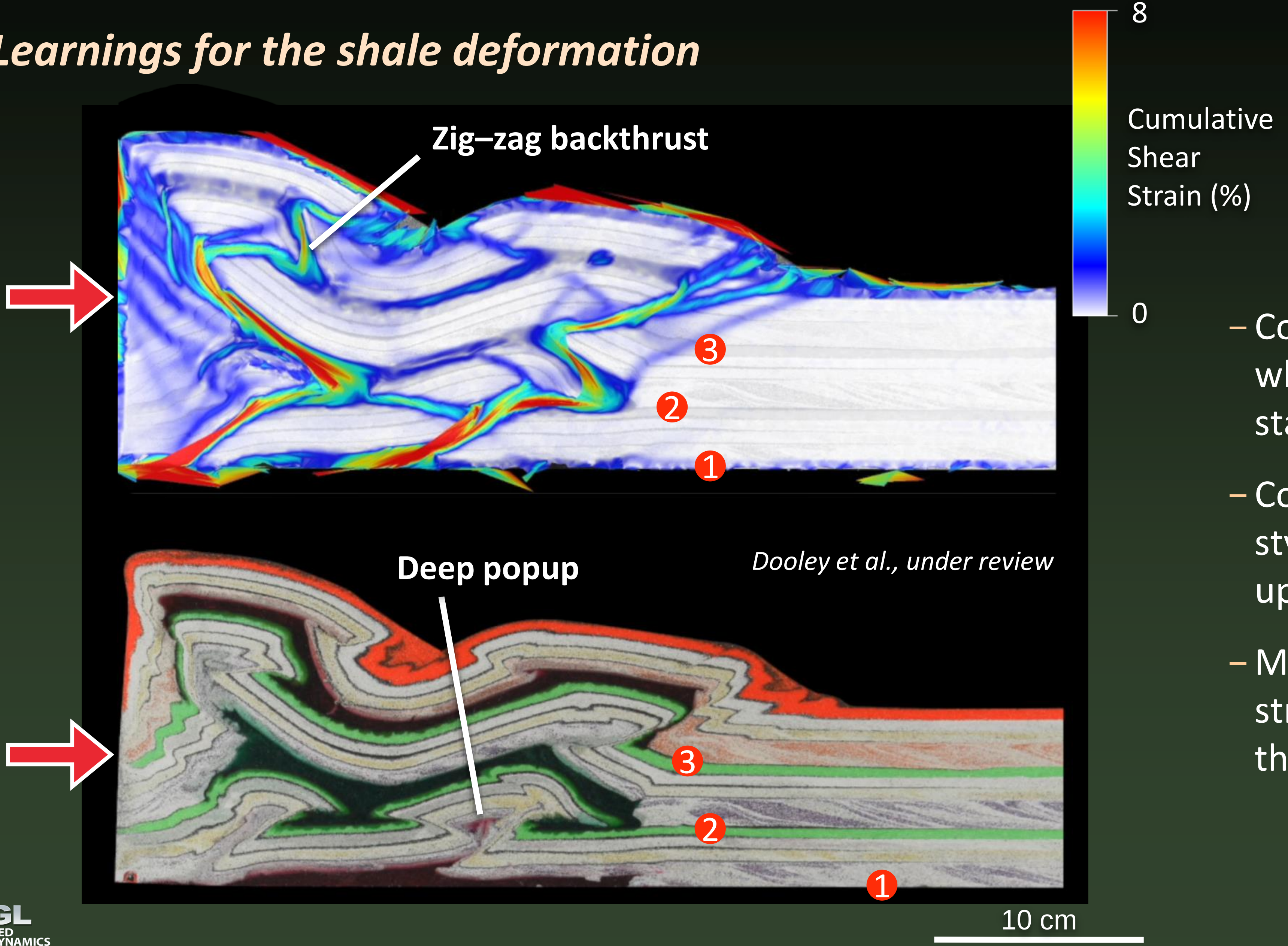
Where are located the mud volcanoes?



Soto & Hudec, 2023

⑥ Experimental models of shales under compression

Learnings for the shale deformation



- Complex zig–zag thrusting when three weak layers are stacked
- Complete detached structural styles between lower and upper levels
- Multiple changes in the structural vergence favored by the weak layers

⑦ Messages to Keep

1) Mobile shales are formed by **visco-plastic deformation at critical state.**
2) **Deformation is penetrative** at critical state and may contain a combination of brittle and ductile structures, and possibly evidence of volume changes.
3) **Deformation also induces overpressures** (shear-induced overpressure).
4) **Mobile shale structures** vary from complex fold cores and thrust-related folds to shale sheets and mud volcanoes.
5) Mobile shales preferentially occurs in **contractional settings**, constituting very efficient decoupling levels for deformation, forming detached structures in the fold–thrust belts.
6) In fold–thrust belts, weak shales deform internally through discrete, anastomosing, and non-stationary **shear zones**.

Publications on Mobile Shales:

2024 • Hassan, Le Béon, Lin, Ching, Soto, Chen & Nguyen. Structural analysis in the actively deforming western foothills in southwestern Taiwan: Fault-related folds or mobile shale processes? *Interpretation*, under review.

2024 • Soto, Dooley, Hudec, Peel & Apps. Shortening a mixed salt and mobile shale system: A case study from East Breaks, NW Gulf of Mexico. *Interpretation*, under review.

2024 • Namaz, Guliyev & Soto. Structure and formation of mud volcanoes in the South Caspian Basin according to seismic data. *Interpretation*, under review.

2024 • Dooley, Soto, Reber, Hudec, Peel & Apps. Modeling mobile shales under contraction: Critical analyses of new analog simulations of shale tectonics and comparison with salt systems. *Interpretation*, in press.

2023 • Soto & Hudec. *Geology*, 51(8), 779–784.

2023 • Hudec, Peel, Soto & Apps. *Marine and Petroleum Geology*, 155, 106391.

2023 • Erdi, Jackson & Soto. *Basin Research*, 35(3), 1071–1101.

2021b • Soto, Heidari & Hudec. *Scientific Reports*, 11, 23785.

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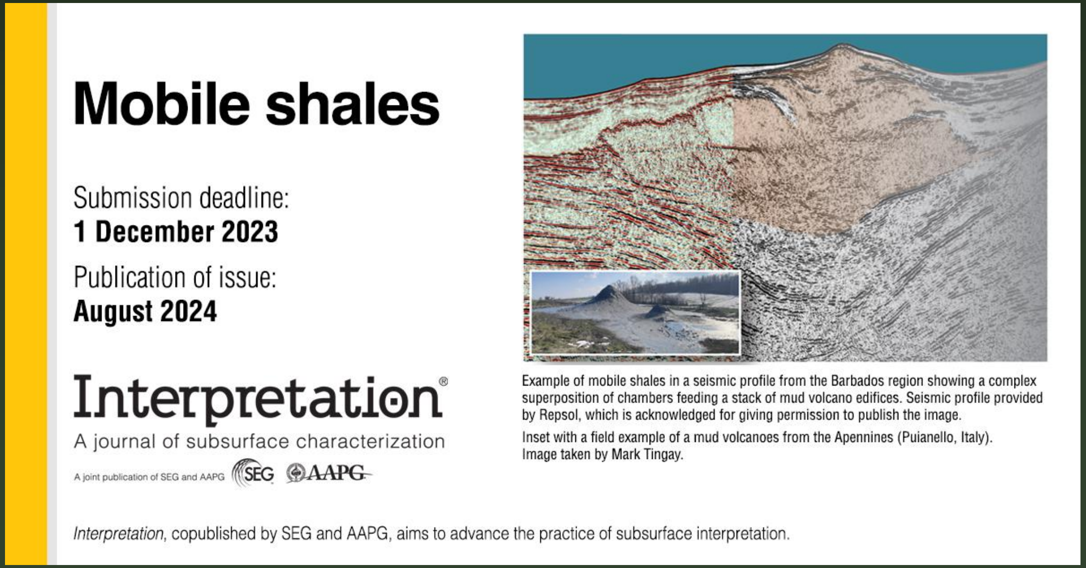
2021 • Hudec & Soto. *Basin Research*, 33(5), 2862–2882.



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Vendeville, B.C., Jackson, M.P.A., 1992b. The fall of diapirs during thin-skinned extension. Marine and Petroleum Geology, 9(4), 354–371.

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