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Fault linkage and its controls on fault growth and basin evolution: Insights from analogue experiments

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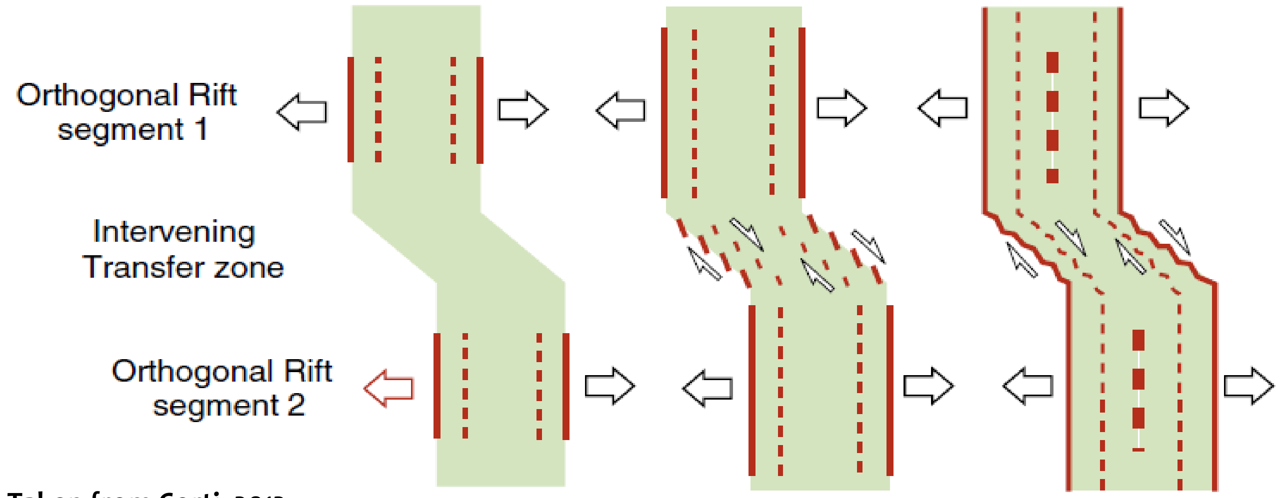
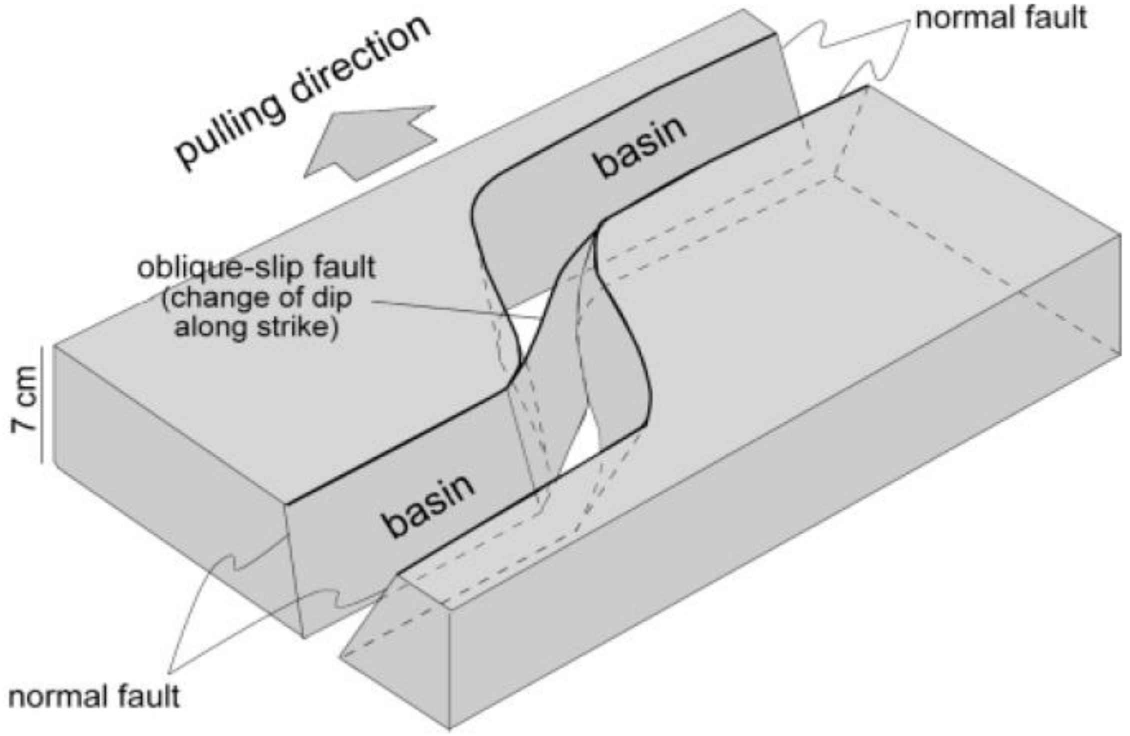
Focus and motivating questions of this study...



Taken from Corti, 2012.



Taken from Acocella et al., 1999.

Considering the linkage of two graben segments: Do the bounding faults join by lateral propagation, or do they maintain a stationary position? In the latter case: Do additional faults accommodate linkage?

With our modeling we address the questions of:

✓ Fault growth model, and

✓ Specific mechanisms of fault linkage

and aim to draw some conclusions about the evolution of depositional basins

Fault grow models

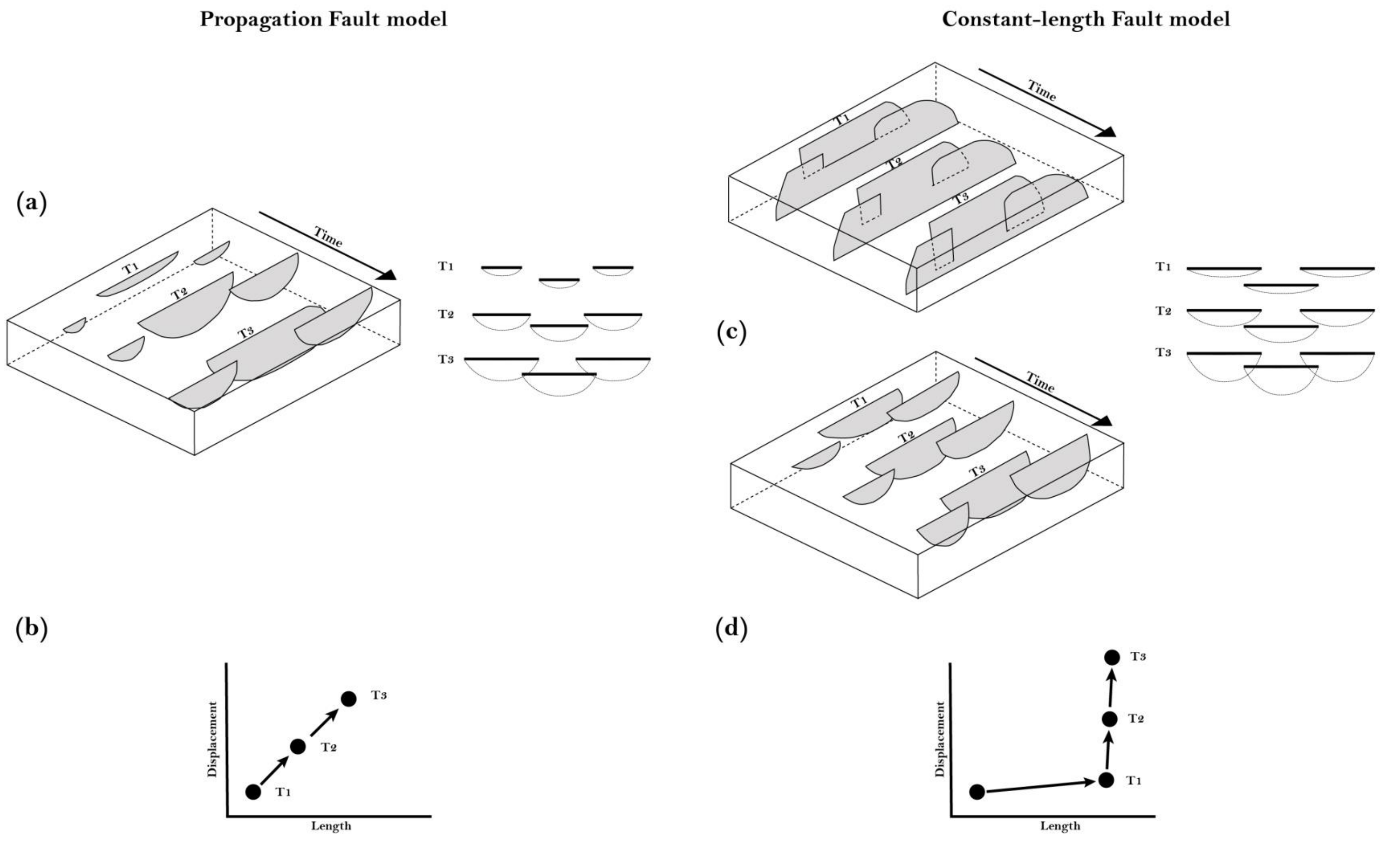


Figure 1. Two fault growth models. (a) Continuously growing faults depicted during three-time steps, in which (b) displacement and length correlate linearly, while in (c) faults maintain a constant length during an increase in displacement. Upper model shows a hard linkage and lower one a soft linkage. (d) The latter model presumes a rapid increase in length and then an increase in displacement, while length is maintained constant. - Modified from Walsh et al., 2003 and Rotevatn et al., 2019.

Two ways of looking at fault growth…

Extrapolating our model results to real Earth, we have to decide whether our observations apply to isolated faults (soft-linkage) or faults that share a common plane (hard linkage). Alternatively, initially isolated faults could combine to form a hard-linked array of fault planes consisting of a set of branching faults.

In this growth process inherited structures (conceived as seeds in our experiments) may influence the final fault pattern.

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A simplified picture of stress fields at fault tips…

Stress fields at fault tips are independent of the fault area, as opposed to the velocity of fracture propagation and stress drops.

Below a critical spacing, overlapping faults curve and join, breaching the ramps enclosed between them.

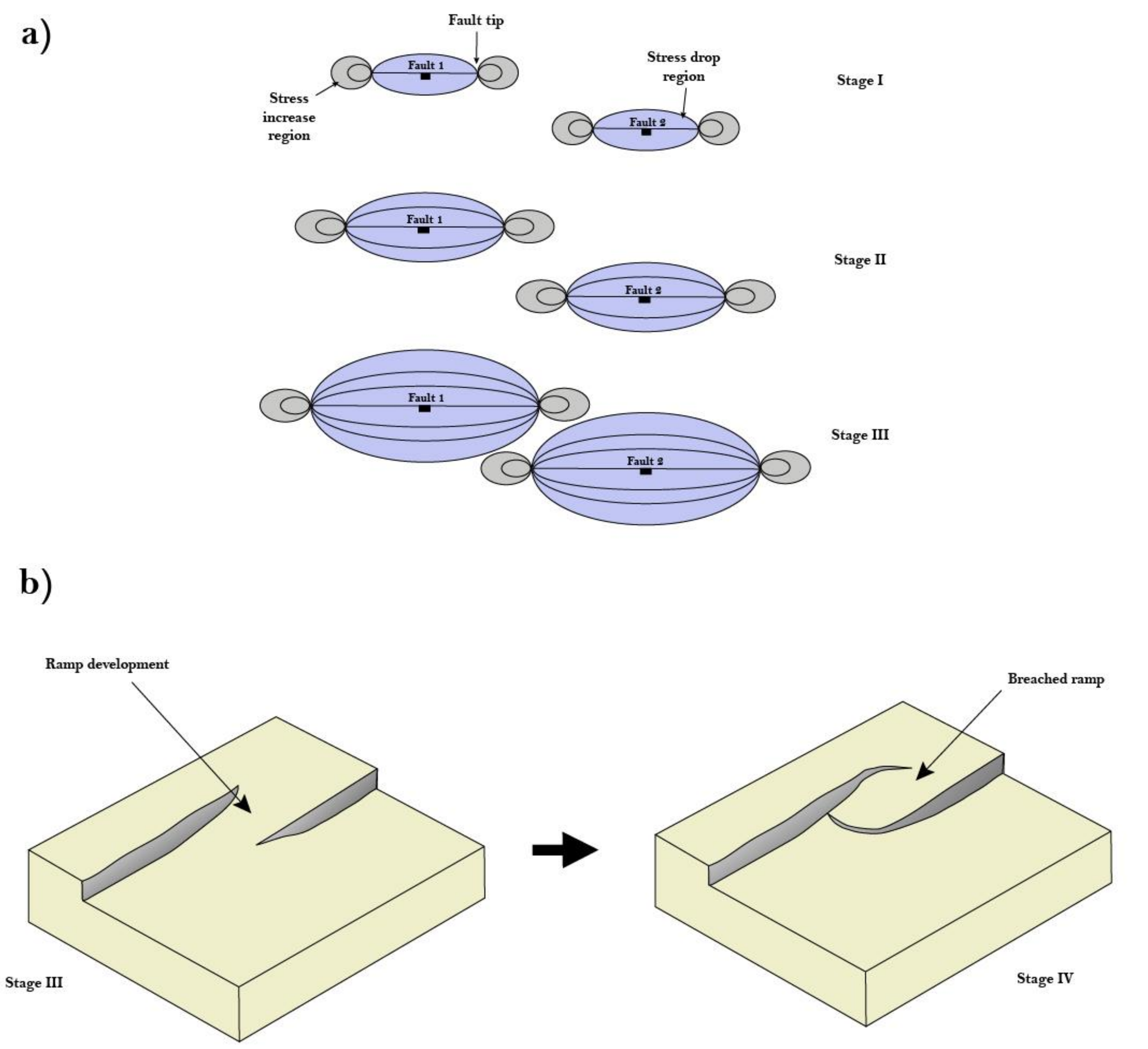

Figure 2. Processes involved in the linkage of faults. (a) Stress regimes associated to the tips of two fault planes. During successive growth stages the stress field remains constant, while the stress drop associated to fault growth increases with fault area. (b) Evolution of a relay ramp between overlapping faults and the breaching of the ramp, as curved fault tips join the opposite fault traces.

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Characteristics of the sandbox model

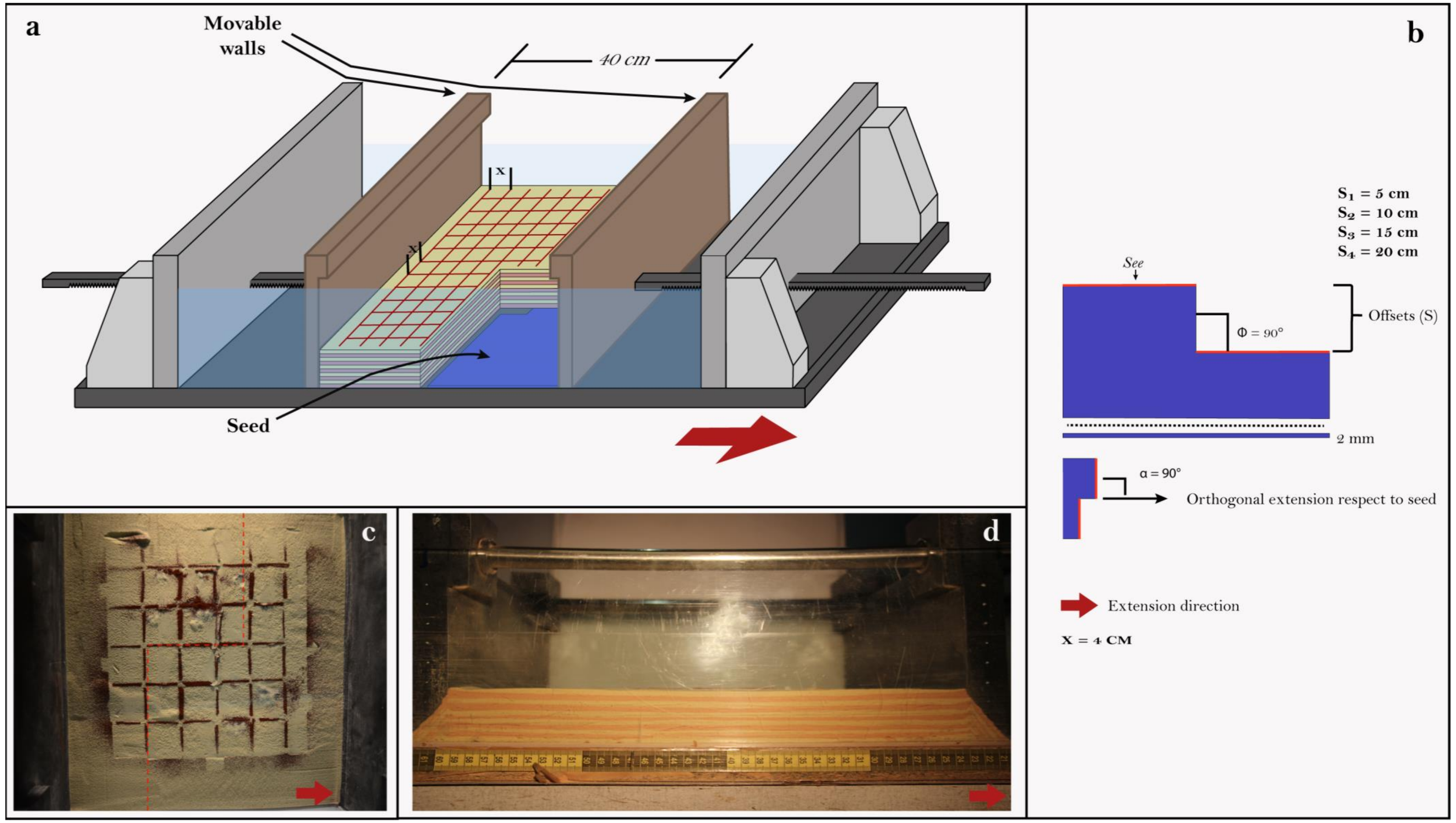

Figure 3. Sandbox model: (a) MOAM machine. Computerized motors move the walls with a user defined velocity. (b) Plan view of the shape of a basal plate attached to the moveble wall. Differences in the offset of its edges (red lines) determined the spacing of the fault array. In order to enhance the interaction between moving wall and sand layers, we attached a sandpaper to the moving wall. We kept the velocity discontinuity between stationary and moving plate at 90° to the movement direction (red arrow). Red arrow shows extension direction. (c) Plan view of experimental setting. The square grid measures 4 x 4 cm, d) View of a profile.

Granular material	
Grain composition	Quartz sand
Grain size	Less than 600 μm
Model characteristics	
Height	5 cm
Length	40 cm
Motion velocity	4 cm/h
Spacing seeds	5 cm , 10 cm, 15 cm and 20 cm
Total extension	4 cm

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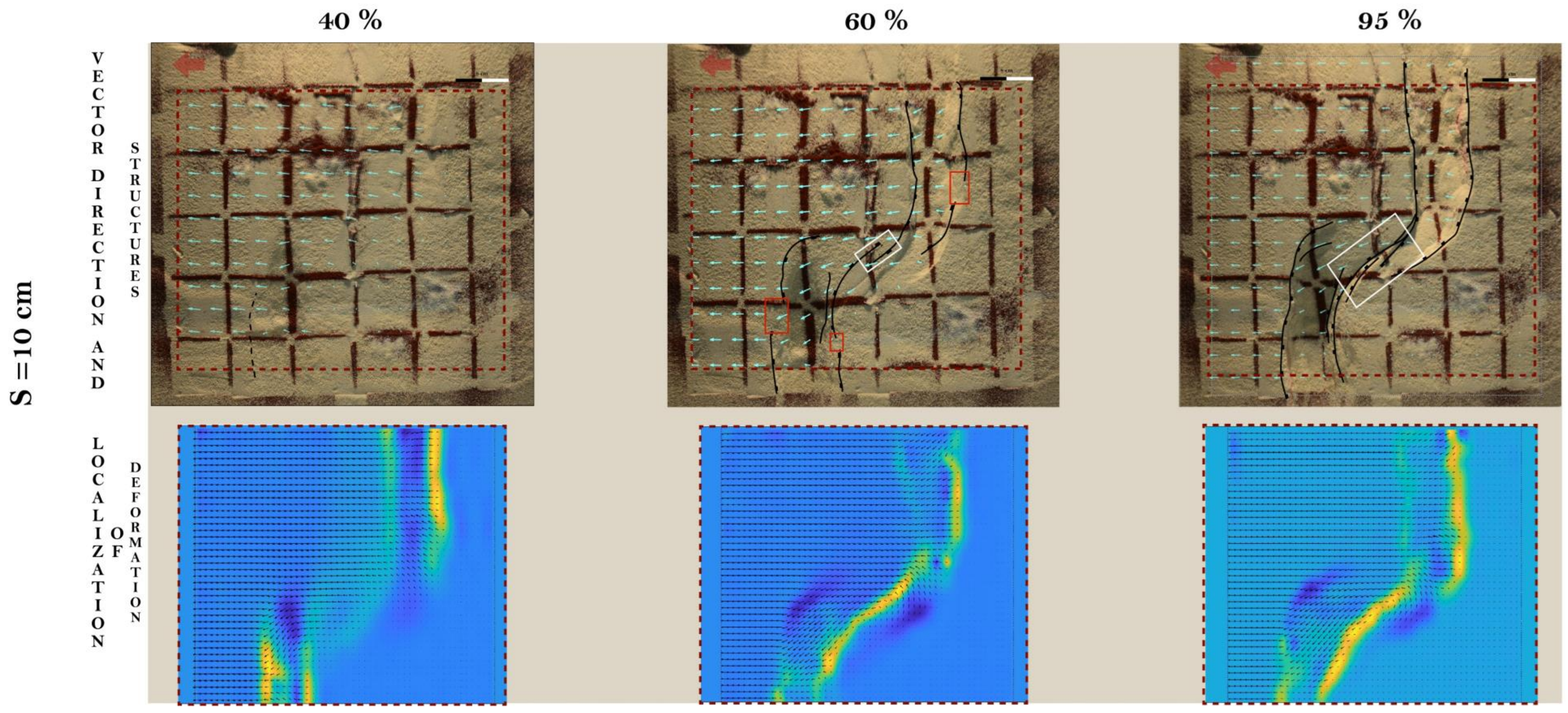
Offset of faults at 10 cm

Pictures show the deformed surface grid at intervals of 40% 60% and 95% of the total displacement. Conjugate faults define a segmented graben structure which mimics the offset imposed by the shape of the basal plate. The composite graben structure consists of an internal (lower part) and external (upper part of picture) segment. White vectors represent an incremental displacement field, as calculated by the PIVlab tool. Within the central transfer zone and the external graben segment these vectors highlight a rotational component, as they tend to turn into an axis-parallel (or N-S) trend of the external graben segment. At a high extension (60%) a stepped array of normal faults links the internal fault of the upper graben structure with the external fault of the lower graben structure. These faults are not continuous but separated by a horst. Approaching the total extension (95%), this array evolves into a single shortcut. Red boxes depict fault segments separated by ramps. The white box depicts the transfer zone.

In the lower part the localization of deformation shows how in the first part is principally at rising bounded-faults, but then change to concentrate at transition zone.



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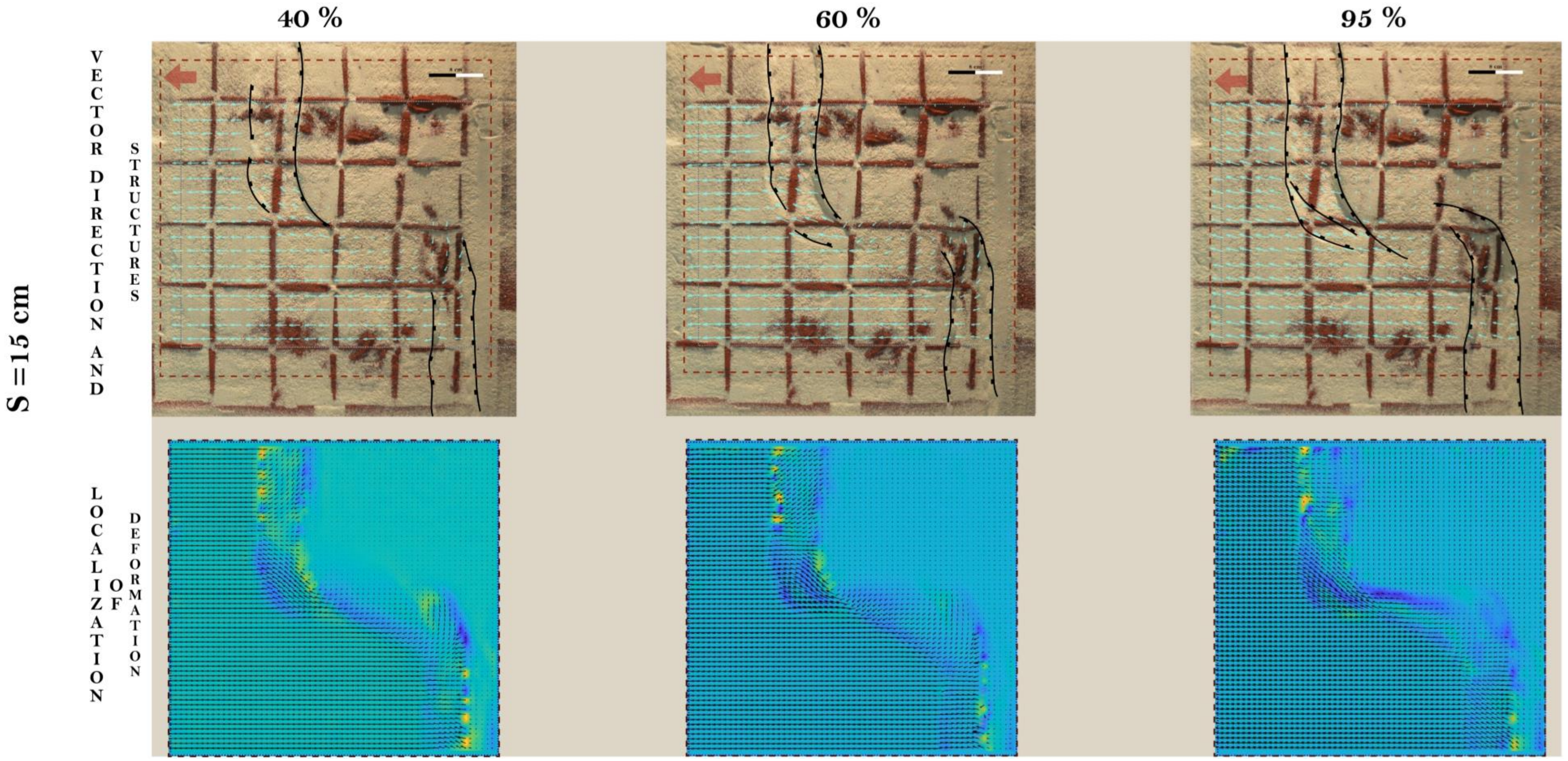
Offset of faults at 15 cm

Pictures show the deformed surface grid at intervals of 40% 60% and 95% of the total displacement. The bounding faults of the graben segments evolve from an underlapping to an overlapping array. Fault linkage, however, does not occur. Like the previous experiment, the central transfer zone displays a highly rotational vector field, with vectors rotating into an axis-parallel orientation of both internal and external graben segments.

In the lower part, the localization of deformation shows how in the first part is principally at rising bounded-faults, but then change to concentrate to the middle part of model. Although, in this case is not possible to see a main centre location of deformation, typically of soft-linkage.



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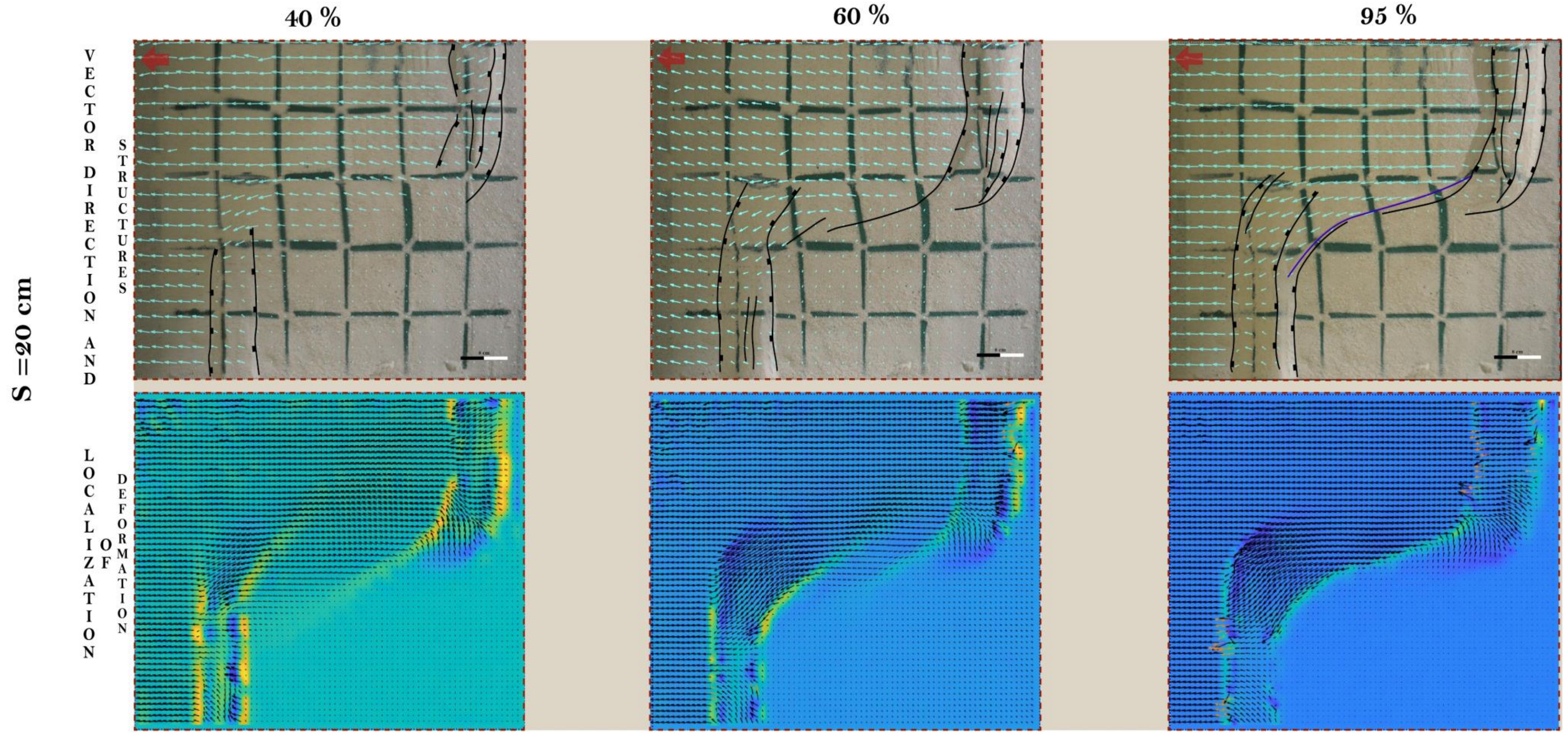
Offset of faults at 20 cm

Model using a rigid based that simulated inherited anisotropies with 20 cm the distance between each seed. In the upper part we can see the structures developed in 40%, 60% and 95% of the total movement. In addition, vector directions calculated with PIVlab tool show the rotation of the most central model, inside the basins, through out a faults with different movement direction but in the middle part too.

The transition zone is characterised by the developed of a large fault that in the late model moment, began to move with a transcurrent component this zone.

In the lower part the localization of deformation shows how in the first part is principally at rising bounded-faults, but then change to concentrate at transition zone with the different respect to other models that at the final an possible transcurrent fault is dominant over basin bounded-faults.



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Fault growth in time steps

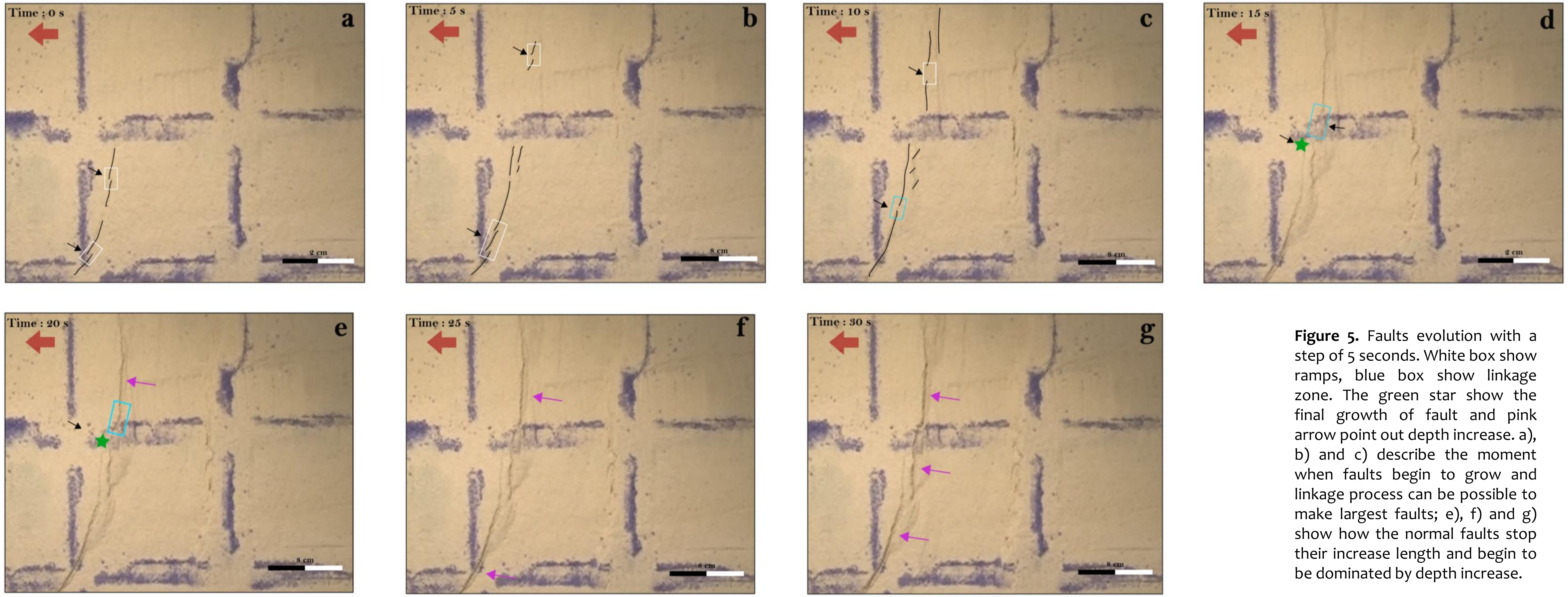

Figure 5. Faults evolution with a step of 5 seconds. White box show ramps, blue box show linkage zone. The green star show the final growth of fault and pink arrow point out depth increase. a), b) and c) describe the moment when faults begin to grow and linkage process can be possible to make largest faults; e), f) and g) show how the normal faults stop their increase length and begin to be dominated by depth increase.

Photos from different stages in a fault evolution. One fault begins its growth as a result of stress variations and spreads by means of interaction among different planes (propagation fault model). Although, it is possible that the length increase will be forced to cease, in that moment it is when possibly a depth increase dominated over length increase.

Basins and Faults

We started today with these two questions : : Do the bounding faults join by lateral propagation, or do they maintain a stationary position? In the latter case: Do additional faults accommodate linkage?

As we saw, the propagation fault model takes a relevant position during fault evolution but is not the only process involve. At first, a fault begins its propagation, but then a cease of length grow is following by a depth increase. We think that the fault located at transfer zone works in the same way with the difference that linkage process cannot be present, whereas a horst might be developed.

We propose three possible stages when a basin can be developed. Stage I is dominated by propagation fault model, Stage II presents a ramp development and begin of fault linkage by means of breached ramps. In this second stage, the basin extends towards an interaction zone where is taken place a transition zone and the basin-bounded faults curve in a hook form. At the end, the Stage III does not involve more length increase and the faults begins to taken place in a constant-length fault model where only depth increase.

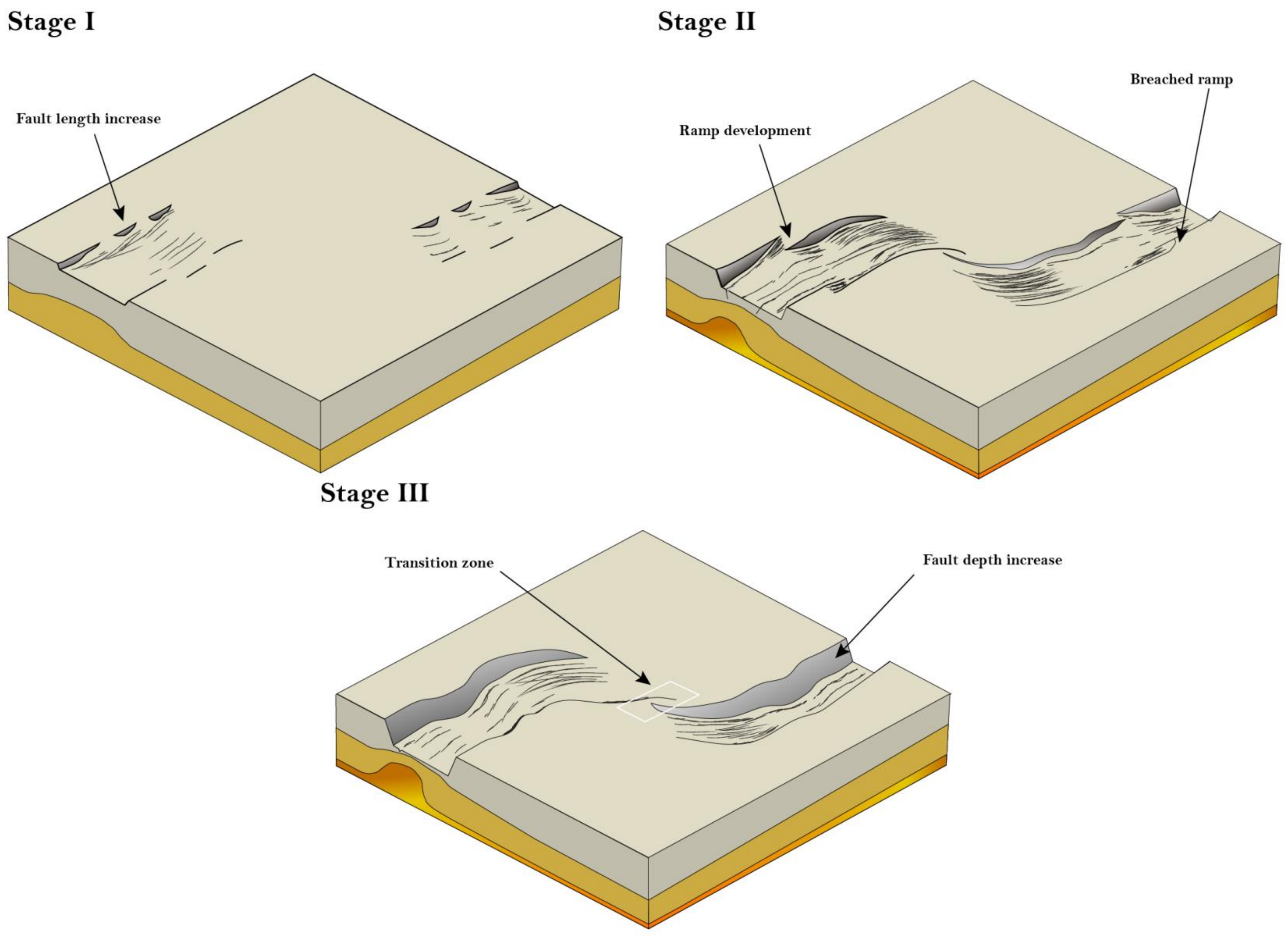

Figure 6. Basin structural evolution. It has defined 3 different stages in which each of ones it is characterized by shows a specific phase related to fault grow and fault linkage.

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