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# 4D microtomography of brine-assisted healing processes in deformation-damaged rocksalt: A first look

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## ABSTRACT

Rock salt formations represent key options for storage of natural gas, hydrogen, compressed air energy, and radioactive waste. At depths beyond a few tens or hundreds of meters, undisturbed halite-dominated (>90%) rock salt deposits are practically impermeable and have very low porosity (order 1%). However, as a result of excavation-induced stresses, near-field microcracking and associated dilatancy occur in rock salt, increasing porosity and permeability. The connectivity of a brine- or water-vapour-filled microcrack network in deformation-damaged salt, is expected to decrease over time, partly due to dissolution-precipitation healing. Here, we employ 4D microtomography to study the long-term evolution of microcrack networks in deformation-damaged natural salt. We found substantial microstructural modification or "healing" over periods of days to a few months. Cracks and dilated grain boundaries became crystallographically faceted, necked, discontinuous, and disconnected, producing an increase in tortuosity and a decrease in connectivity of the crack network. The magnitude and rate of associated permeability reduction and its evolution with time remain to be determined in future.


## INTRODUCTION

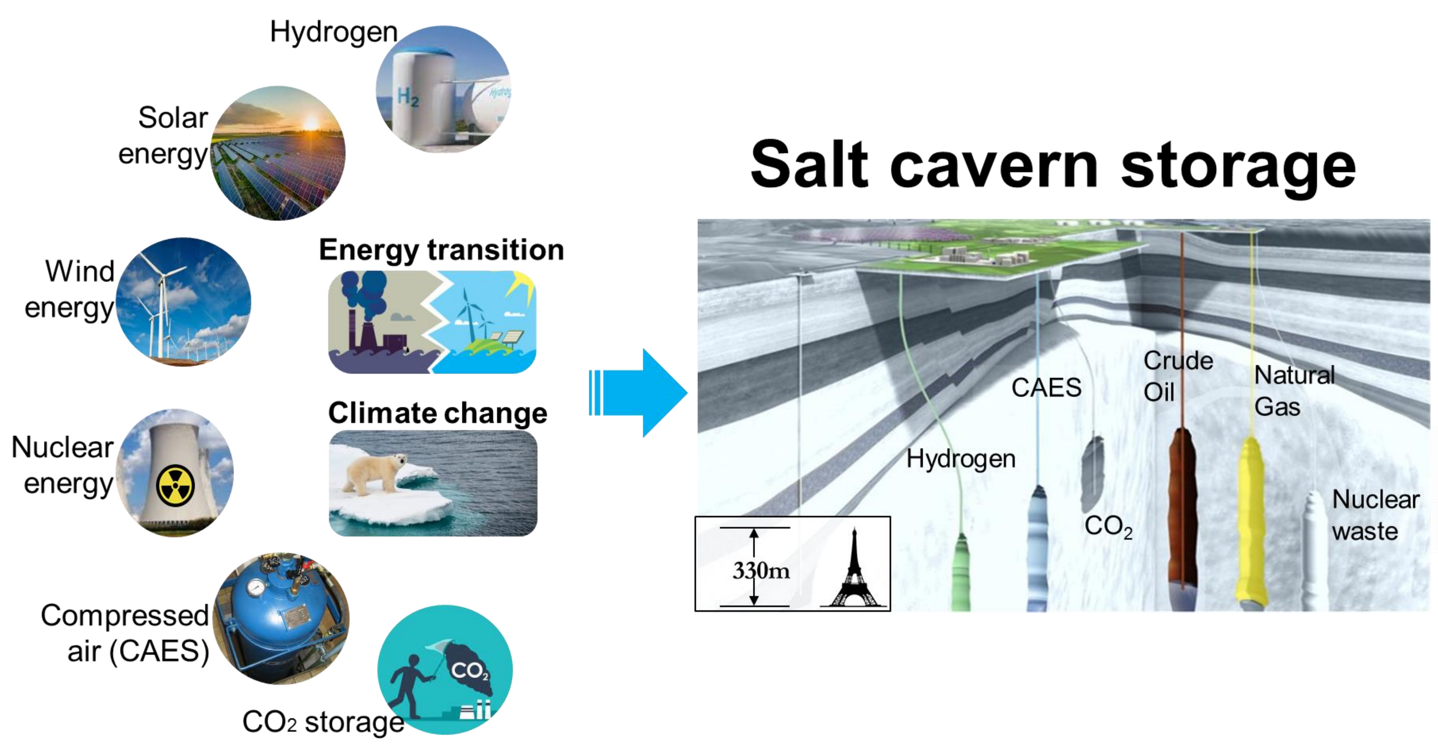


**Figure 1**: Application Prospects and Examples of Salt caverns

- The growing urgency to energy transition and climate change.
- Rock salt can be the key to surface storage.
- **But, Does salt really heal?** A quantitative understanding is needed.
- In this study, we report a series of novel healing experiments performed on cracked natural rock salt, using time-lapse μCT imaging.
- Our goal was to capture evidence for the healing processes under brine-saturated, room P-T conditions.

## METHODS

Cracked natural salt samples + saturated brine + 4D imaging.

The present experiments were conducted on natural polycrystalline rocksalt at room temperature and atmospheric pressure. Small samples were mechanically deformed, damaged, and dilated under unconfined conditions, flooded with saturated brine at atmospheric pressure, and hermetically sealed. The healing process thus initiated was imaged at different stages (in time-lapse mode employing increasing time intervals) using an X-ray CT microscope.

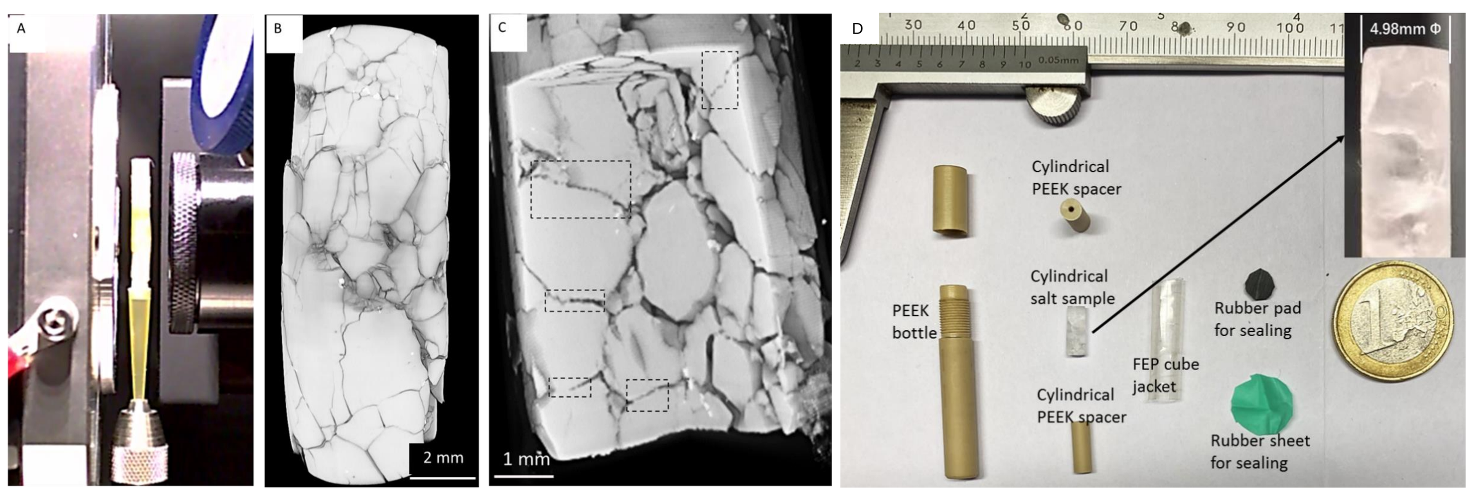


Figure 2: Use of μCT to image a rocksalt sample. (A) An FEP-jacketed rock salt cylinder (5 mm diameter) being scanned in X-ray CT microscopy. (B) Typical 3D CT image of a cracked salt sample (dry, Sample XLSS02). (C) Reconstructed CT image obtained 13 days after driving saturated brine through a deformation-damaged salt cylinder. (D) Sample assembly used for μCT.

| sample name | diameter (mm) | original length (mm) | deformed length (mm) | plastic strain (%) | condition/ healing time (days) | CT voxel size (micron) |
|---|---|---|---|---|---|---|
| XLSS00 | 6.40 | 14.00 | intact | intact | dry | 7 and 1.75 |
| XLSS01 | 4.95 | 11.00 | 10.25 | 6.82 | dry | 5 and 0.8 |
| XLSS02 | 4.95 | 12.90 | 12.25 | 5.04 | Wet/70 | 5.6 |
| XLSS05 | 3.70 | 9.40 | 9.15 | 2.66 | Wet/264 | 4, 2 and 0.4 |
| XLSS06 | 3.50 | 7.90 | 7.70 | 2.53 | Wet/120 | 3.7, 1.85, 0.76 and 0.38 |

Table 1: Samples presented in this study. Wet signifies brine flooded.

## RESULTS

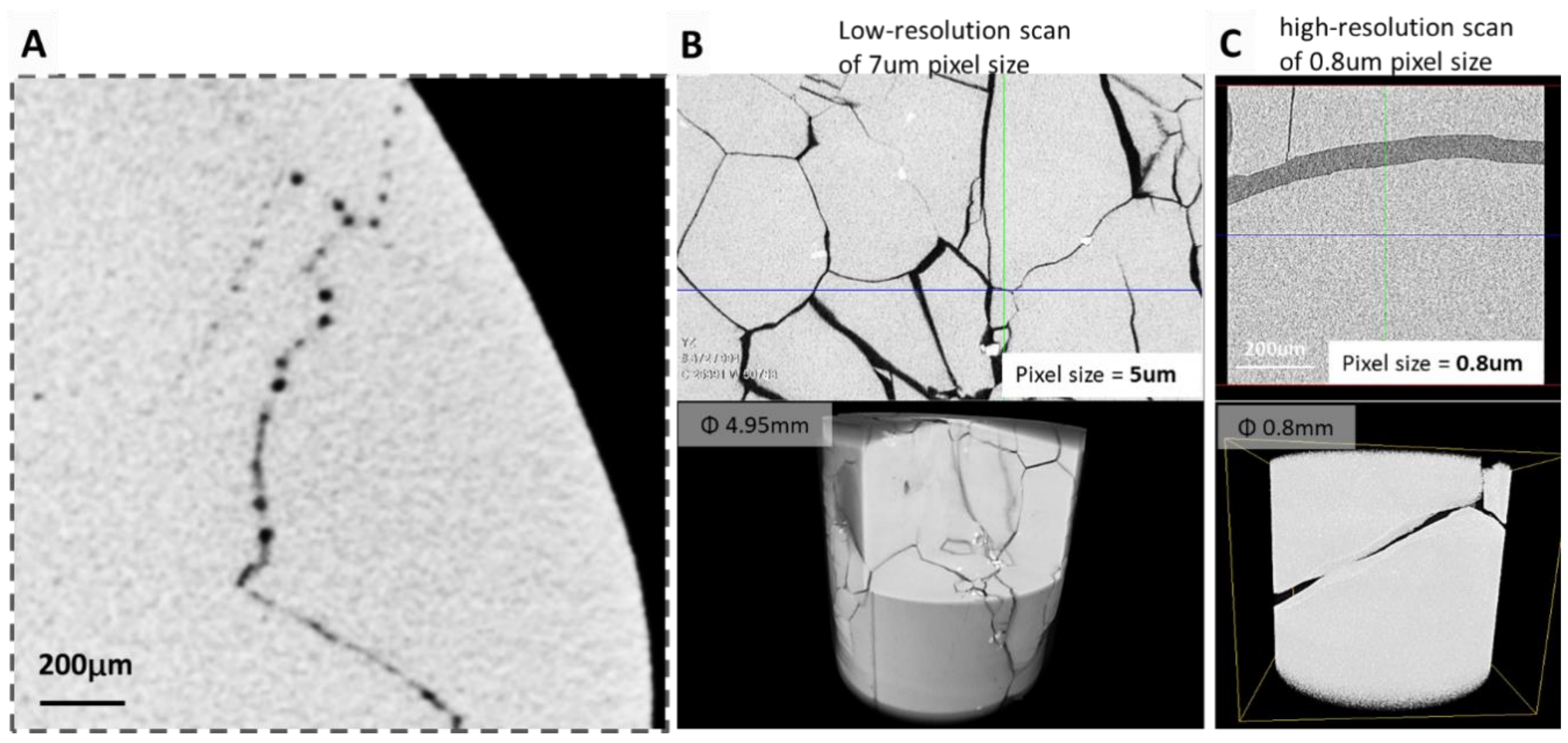


**Figure 3:** Before brine addition and healing. μCT images of undeformed Leine rocksalt samples (A) and axially compressed samples (B) and (C).
(A) Grain boundary with fluid inclusions in the undeformed starting material.
(B) Inter- and transgranular cracks formed after axial deformation of XLSS01, but before brine addition and the onset of healing processes.
(C) A subvolume in (B) at 800nm per pixel.

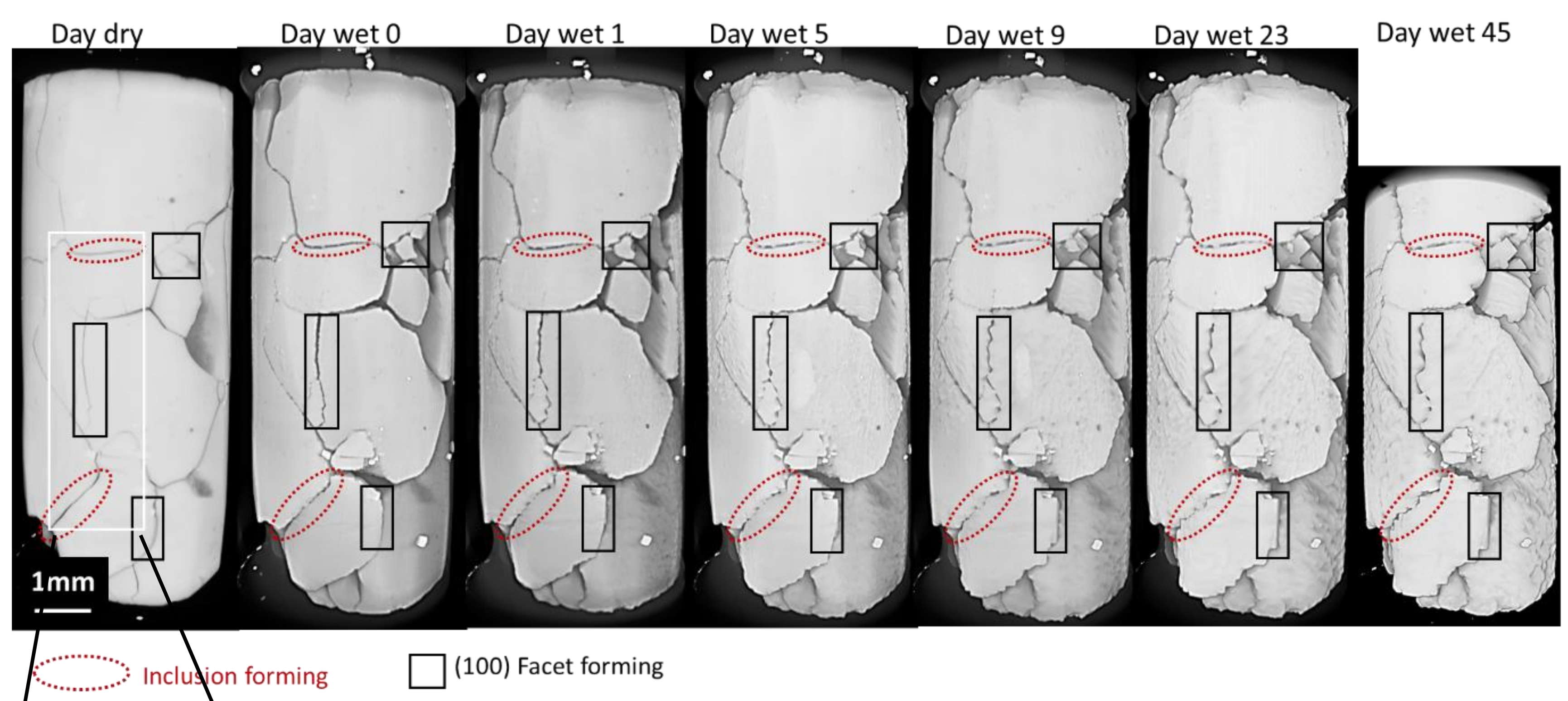


**Figure 4**: μCT images showing the evolution of the crack network in a pre-cracked sample over 45 days of healing. Sample number XLSS06. Salt is in grey, voids (pores and cracks) are in black. Red dashed ellipses mark dilated, brine-filled grain boundaries that are becoming disconnected .

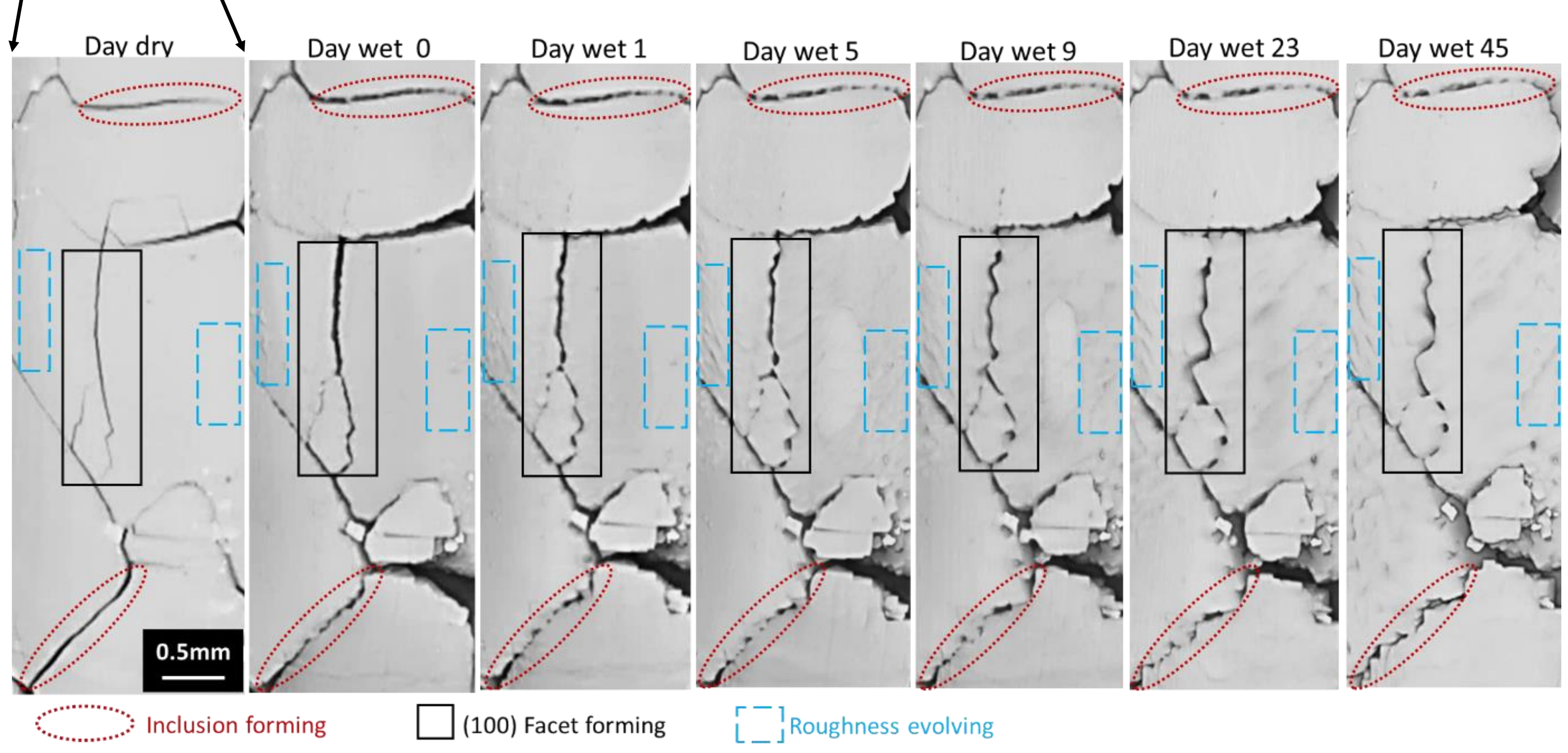


**Figure 5**: Enlargement of the subregion marked with the white rectangle in Figure 4. Black rectangles show sites of marked crack migration with local necking of the internal fluid film to form more isolated inclusions (lower portion). Blue rectangles mark the area of roughness evolving. These data show clear modification and disconnection of the crack network over time, inevitably resulting in a decrease in permeability.

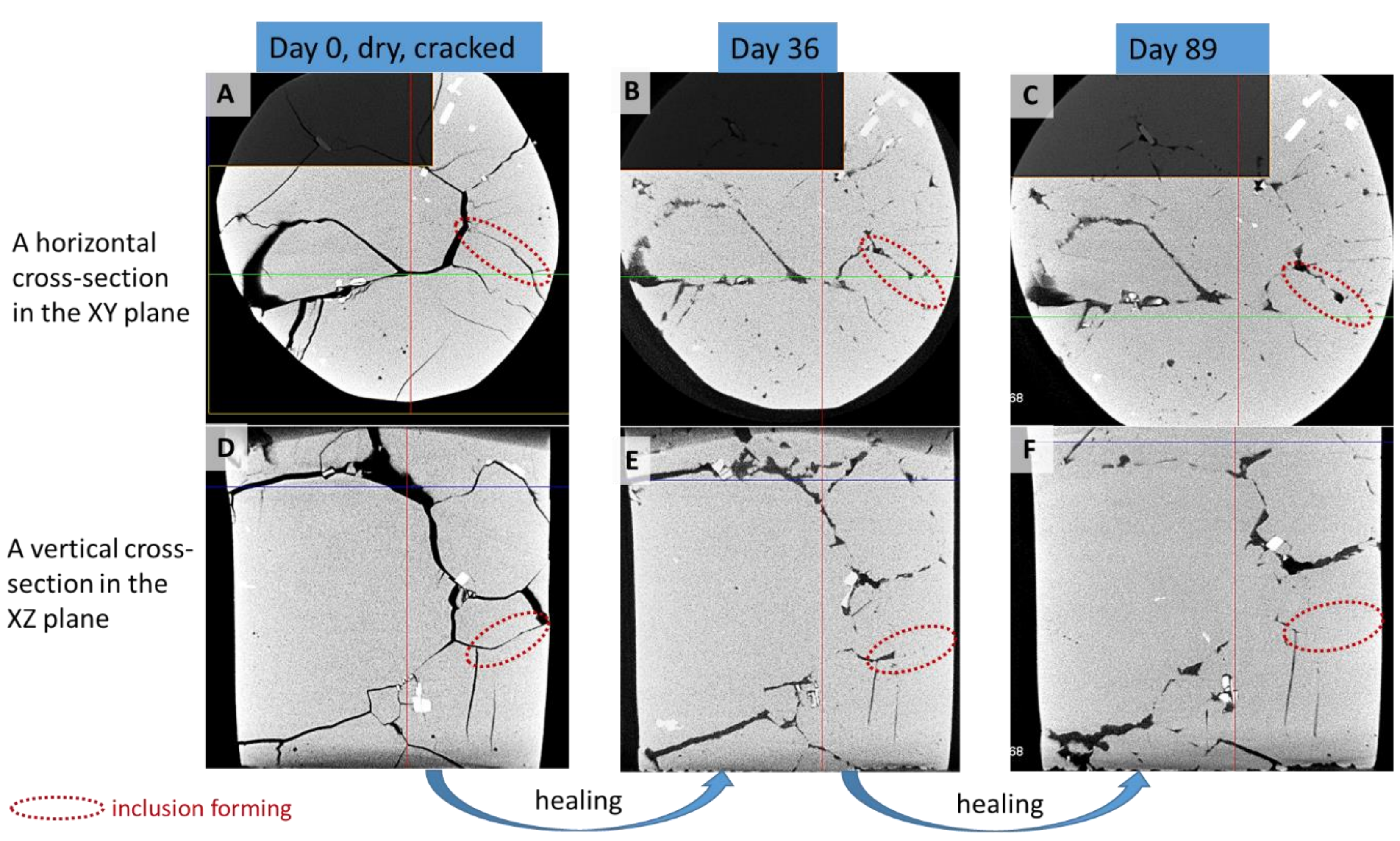


**Figure 6:** Reconstructed CT images showing crack network evolution in a deformation-damaged rock salt sample in the initial dry condition (left), after 36 days of healing following brine addition (center), and after 89 days of healing (right). Sample number XLSS05. Salt in grey, voids (pores and cracks) in black. (A), (B) (C) are horizontal cross-sections orientated normal to the cylindrical sample axis. (D), (E), (F) are vertical cross-sections orientated parallel to the cylindrical sample axis. Red dashed ellipses mark regions containing cracks that are becoming disconnected due to the formation of inclusion arrays. Local grain/interface boundary migration is also visible.

## CONCLUSIONS

1. We captured 4D healing process in damaged rocksalt.
2. Does salt heal? YES.
3. How? Tortuosity increase -> permeability decrease
4. Why? The process is driven by i) surface area/energy reduction, ii) release of stored dislocation strain energy, at low pressure and room temperature.

## FUTURE ADVENTURES

- A more microphysical model.
- Experiments with longer healing times.
- Experiments at higher temperatures and effective stress states.
- Determine the permeability evolution during healing.

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