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

Yuntao Ji*(y.ji@uu.nl), C. J. Spiers, S.J.T. Hangx, H. de Bresser, M.R. Drury
Department of Earth Sciences, Utrecht University, NL

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.

RESULTS

INTRODUCTION
Salt cavern storage

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 rock salt 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.

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

<table>
<thead>
<tr>
<th>sample</th>
<th>diameter (mm)</th>
<th>original length (mm)</th>
<th>deformed length (mm)</th>
<th>plastic strain (%)</th>
<th>condition/healing duration</th>
<th>CT voxel size (μm)</th>
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<tr>
<td>XLSS01</td>
<td>6.40</td>
<td>14.00</td>
<td>intact</td>
<td>intact, dry</td>
<td>7 and 1.75</td>
<td></td>
</tr>
<tr>
<td>XLSS02</td>
<td>4.95</td>
<td>11.00</td>
<td>10.25</td>
<td>6.82</td>
<td>dry</td>
<td>5 and 0.8</td>
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<td>XLSS03</td>
<td>4.95</td>
<td>12.90</td>
<td>12.25</td>
<td>5.04</td>
<td>Wet70</td>
<td>5.6</td>
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<td>3.70</td>
<td>9.40</td>
<td>9.15</td>
<td>2.66</td>
<td>Wet264</td>
<td>4, 2 and 0.4</td>
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<tr>
<td>XLSS05</td>
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<td>7.90</td>
<td>7.70</td>
<td>2.53</td>
<td>Wet120</td>
<td>3.7, 1.85, 0.76;</td>
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<td>0.38</td>
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</table>

Figure 3: Before brine addition and healing. μCT images of undeformed brine rocksalt samples (A) and axially compressed sample (B) and (C). (A) Grain boundary with fluid inclusion 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. (D) A subregion in (A) 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 to form more isolated inclusions (lower portion). Blue rectangles mark the area of roughness evolving. These data show clear microfaceted disconnection of the crack network over time, invariability resulting in a decrease in permeability.

Figure 6: Reconstructed CT images showing crack network evolution in a deformation-damaged rock salt sample in the undisturbed condition (left), after up to 150 days of healing (right). Sample XLSS06. Salt in grey, voids (pores and cracks) in black. Top panels are horizontal cross-sections oriented normal to the cylindrical sample axis. Bottom panels are vertical cross-sections oriented parallel to the cylindrical sample axis.

CONCLUSIONS

1. We captured 4D healing process in damaged rocksalt.
2. Does salt heal? YES.
4. Why? The process is driven by surface area/energy reduction, i.e. release of stored dislocation strain energy, at low pressure and room temperature.

FUTURE ADVENTURES

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

ACKNOWLEDGEMENTS

This study was part of the TKI NEWGAS (Top Energy Advanced Concepts) project, which was funded by the Dutch Ministry of Economic Affairs and Climate. The research was carried out with financial support from the Netherlands Research Council (NWO) via the EPOS programme and Top Sector Energy and executed by the Multi-scale Imaging and Tomography Facility (MINT) at Utrecht University. This work was also supported with a subsidy from the Dutch Ministry of Economic Affairs and Climate, National Schemes of Large Research and Innovation Programmes (NWO STW 12557–190). The authors acknowledge Janos L. Urai of the Flemish Research Foundation (FWO) for his support and the joint research effort with colleagues at the Royal Institute of Technology (KTH) in Sweden, Leine Centre for Georenewables, the Multi-scale Imaging and Tomography Facility (MINT) at Utrecht University, and the Nodes of the Netherlands Institute for Advanced Metropolitan Solutions (NAMOS) at Utrecht University and the University of Technology of Eindhoven (TU/e).

REFERENCES