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Structural Characterization of the Longyearbyen CO2 Lab Reservoir-caprock Succession

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SUMMARY

This baseline study on fracture populations affecting the Mesozoic sedimentary succession of central Spitsbergen (Svalbard) has been performed to characterize the reservoir-caprock system explored for potential subsurface CO2 storage by the Longyearbyen CO2 Lab project. Integrating structural and stratigraphic analyses of outcrop and borehole data, we identified recurrent litho-structural and structural units (LSUs and SUs, respectively) on the basis of their fracture associations, lithologies and dominant sedimentary facies. A principal fracture set trending approximately E-W (J1) and a subordinate fracture set trending approximately N-S (J2) have been recognized. Subordinate systems of shear fractures (S1) trending roughly NE-SW and NW-SE, and a secondary low-angle, fracture set (S2) striking E-W to NW-SE have been observed. Their origin is interpreted as related to the far-field stress of the Paleogene West Spitsbergen fold-and-thrust Belt. The identified units are thought to influence the local hydrogeologic regime due to the intrinsic variations in the matrix and fracture network properties. The architecture of the reservoir-caprock succession is segmented, with the vertical alternation of intervals characterized by 1) fracture porosity and permeability, 2) microfracturing-related matrix porosity, and 3) preferential subsurface fluid flow pathways.
Introduction

The aim of the Longyearbyen CO\textsubscript{2} Lab project is to develop an onshore, pilot-scale (ca. 60.000 of CO\textsubscript{2} tons/year) site for geologic sequestration of CO\textsubscript{2} in a tight, siliciclastic aquifer located at 700-1000 m depth in Spitsbergen, Svalbard (Braathen et al., 2012). Eight slimline boreholes have been drilled and fully cored at two drill sites, four of which penetrate the targeted reservoir sandstone successions of upper Triassic to lower Jurassic age (De Geerdalen and Knorringfjellet formations). The brine-filled aquifer conforms to a gentle regional monocline and thus reaches the surface ca. 15 km NE of the drill sites, allowing direct outcrop analyses on the exhumed reservoir-caprock section. The target formations are located between two main detachment zones related to the development of the Paleogene, West Spitsbergen Fold-and-thrust Belt (WSFB; Bergh et al., 1997). Subsequent tectonic-sedimentary burial in a foreland basin setting down to ca. 4.5 km during the Eocene caused mechanical compaction and quartz cementation, with consequent lowering of the matrix permeability to less than 2mD (e.g. Michelsen and Khorasani, 1991; Mørk, 2013). Despite this, water injection tests show an average flow capacity of 45 mD·m in the lowermost part of the reservoir (i.e. 870-970 m), thought to be primarily due to the natural fracture network (Ogata et al., 2012). The upper part of the target aquifer, from 672-700 m in Dh4, exhibits better petrophysical parameters with matrix permeability of up to 2 mD (Braathen et al., 2012), and recent water injection tests suggest a radial matrix-dominated response in this part of the succession (Senger et al., 2013). In this contribution we describe the baseline structural datasets of the natural fractures occurring in the reservoir-caprock section of the Longyearbyen CO\textsubscript{2} Lab project, integrating both borehole and outcrop datasets.

Methods

High-resolution (1:10 scale) structural logging was undertaken on a database of nearly 4500 m of drill cores, gathered by the Longyearbyen CO\textsubscript{2} Lab during eight full-coring drilling campaigns on the targeted section of the penetrated reservoir section. High-resolution logging was performed on the drill cores from the Dh4, Dh5R and Dh7A boreholes (ca. 380 m in total) to describe the physical characteristics and frequency distribution of natural discontinuities (as defined by Schultz and Fossen, 2008).

Complementary fieldwork was conducted on the exhumed part of the target reservoir-caprock, where scanlines (i.e. line-intersection method; e.g. Singhal and Gupta, 2010) have been measured to provide fracture spatial distribution and frequency plots along individual intervals. Stratigraphic logging (1:50 scale) was also carried out in order to correlate outcrop and borehole successions, and to organize fracture data in litho-structural units (LSUs) and structural units (SUs). A total of 105 scanlines were collected, totalling about 1400 m with 7672 individual fractures measurements.

Results and discussion

Based on our integration of stratigraphic/sedimentologic and structural observations from boreholes and outcrops, the investigated reservoir-caprock succession has been subdivided into five litho-structural units (LSUs) comprising specific systematic and non-systematic fracture sets mainly controlled by dominant lithologies and sedimentary facies: LSU A) massive to laminated shale-dominated intervals, characterized by high- and low-angle fractures, with a predominance of the latter; LSU B) massive to thin-bedded, heterogeneous, mixed silty-shaly-sandy intervals, characterized by mainly non-systematic strata-bound fractures, both low- and high-angled, and subordinate, high-angled systematic non strata-bound fractures; LSU C) massive to laminated, medium to thick-bedded, medium to coarse-grained sandstones and conglomerates, dominated by high-angle systematic strata-bound and non strata-bound fractures, with some subordinate low-angle ones, sometimes showing evidence of strike-slip and dip-slip shearing, respectively; LSU D) igneous intrusions (i.e. dolerite dykes and sills) characterized by syn- and post-emplacement, non strata-bound and strata-bound fractures, and veins sub-parallel and sub-perpendicular to the intrusion boundaries; LSU E) carbonate beds (i.e. limestones, bioclastites), dominated by high-angle non strata-bound and strata-bound fractures and calcite veins.
Figure 1 A. Cake diagrams showing the relative amount (volume %) of the identified LSUs in boreholes and outcrops. B. Rose diagrams representing fracture strike data for each LSU investigated in the reservoir and caprock section. C. Schematic cartoon summarizing the inferred tectonic evolution phases responsible for the development of the observed structural discontinuities in the upper Triassic-Jurassic succession of Central Spitsbergen.

The defined LSUs can be recognized both in the boreholes and outcrops (Fig. 1A), and reflect contrasting rheological/mechanical behavior. They are therefore inferred to represent proxies of geomechanical units (Shackleton et al. 2005). Lateral and vertical changes in fracture set orientations and fracture frequencies are observed within the LSUs, especially at their boundaries.

This framework is complicated by the presence of structural units (SUs), such as fracture corridors, related to mesoscopic (i.e. sub-seismic) normal faults and the chilled/sheared margins of the dolerite intrusions. Each individual LSU and SU is characterized by distinct structural associations, which is inferred to influence subsurface fluid flow by preferentially driving it laterally and/or vertically. According to their inferred genetic mechanisms and their mutual crosscutting relationships, these structures record the local tectonic history, being interpreted as products of overlapping and progressive deformation events. The bulk of the brittle deformation, and thus fracturing, is thought to take place during the Paleogene time-synchronous with the development of the transpressional WSFB. The main joint set J1 is aligned to the main inferred ENE-WSW regional horizontal compression along with the bisector defined by the coeval, high-angle, strike-slip, conjugate shear fracture set S1 (Fig. 1B). Thus, J1 and S1 together are interpreted to record the eastern foreland far-field stress related to the evolution of the western transpressional belt. Contemporaneous layer-parallel shearing developed the low-angle, dip-slip reverse and normal faults arranged in conjugate systems (S2), particularly pervasive and closely spaced within the shaly intervals (i.e. LSU A). The cumulative horizontal displacement of these shear zones is interpreted in the order of meters. However, in sum the S2 shear fracture system yields significant layer-parallel shortening (ca. 5-20%), especially in shaly lithologies.
It is worth to note that, at larger scale, a striking contrast in fracture orientation between the reservoir and the cap rock interval can be recognized. This suggests a marked mechanical decoupling between the two at the level of the upper detachment (about 200-250 m above the reservoir; Fig. 1B). The roughly E-W striking meso-scale normal faults are consequently interpreted as local extensional zones related to the differential tectonic loading and perturbations of the compressional regime along-strike of the WSFB. Such E-W normal faults are well documented from coal mines in the basal units of the Paleogene succession, making up the fill of the foreland basin system. In the mines, there is a close link between thrusts and the extensional faults, suggesting a contemporaneous development (M. Jochmann, pers. comm.). We suggest that the extensional faults formed parallel to the maximum horizontal stress during thrusting. The joint set J2, sub-perpendicular to the J1, could thus be interpreted as related to this mechanical accommodation, as also suggested by the high dispersion of data. Notably, they are oriented parallel to the folds of the WSFB. Reworking of earlier systematic deformations such as syn-sedimentary faulting, gravitational collapses and differential subsidence/compaction may have played a role in the distribution of these fractures.

Conclusions

The moderate injectivity of the tight, naturally fractured reservoir of the Longyearbyen CO2 Lab project testifies that CO2 may potentially be injected and stored, with a major contribution from the regional network of meso-scale fracture sets mapped and analyzed in both drill cores and outcrops. The main conclusions are hereafter summarized:

1) The investigated section has been subdivided into five recurrent litho-structural units (LSUs), each one inferred to locally control lateral and vertical fluid migration, influencing the internal connectivity of the reservoir and the preferred fluid flow directions.

2) Other structural units characterized by directional enhanced fracturing and thus possible fluid conduits are represented by fracture corridors developed within the contact aureole of dolerite intrusions and the damage zones of meso-scale normal faults.

3) We identified a main fracture set J1, comprising systematic joint populations oriented approximately E-W and a subordinate fracture set J2 characterized by systematic joint populations oriented approximately N-S. Along with these, a high-angle, conjugate set of shear fractures S1 trending roughly NE-SW and NW-SE were identified mainly in the coarser-grained and more cemented lithologies, whereas a low-angle, shear fracture set S2 striking E-W to NW-SE is observed within finer grained lithologies and some igneous intrusions (S2b).

4) The identified fracture populations represent the intrinsic mechanical response to a polyphased and progressive tectonic evolution comprising: i) syn-sedimentary deformation, ii) horizontal compression/transpression, iii) tectonic loading, and iv) uplift/unroofing-related decompression.

Due to the present day stress regime and the orientation of the most promising fracture systems (i.e. J1) in terms of possible fluid conductivity, we propose a NNW-SSE oriented horizontal drilling of the injector well at the reservoir level to optimize the fracture permeability and to maximize the related fluid flow. In the proposed framework we expect an E-W spreading of the injected buoyant plume with a focussed drift toward the E-NE, through horizontal and vertical diffusion within the finer- and coarser-grained intervals, respectively. The derived semi-quantitative results are recommended for the reservoir modeling efforts. Accordingly, the processed data were directly used as input parameters in the development of a static geological model of the target aquifer (Senger et al., 2013).

Acknowledgments

This work is part of the “Geological input to Carbon Storage (GeC)” project funded by the CLIMIT program of the Research Council of Norway, with Kim Senger’s fieldwork supported by Arctic Field Grants from the Svalbard Science Forum. Andreas Rittersbacher, Dave Richey, Laura Farrell, Marie Marušková, Gareth S. Lord, Ingrid Anell, Benedikte Jarsto, Berit Husteli, Aleksandra Smyrak-Sikora,
Sebastian Sikora and Srikumar Roy are thanked for the fruitful discussions and for their assistance in the field. The GeC project team works in close co-operation with the Longyearbyen CO2 Lab managed by the UNIS CO2 Lab AS (http://co2-ccs.unis.no) and the SUCCESS center. Shapefiles from NPI-Geonet have been used to construct the geological maps.

References


