(almost) no cross-layered CO_2 movement, which means that (almost) no CO_2 reaches the top surface. In other words, the low-aggradation cases, which have seemed to be unfavorable in our discussion in the previous two sections because of high injection pressure, larger lateral spread, and loss of volumes through the open boundaries, here appear as the most favorable with respect to potential leakage through imperfections the caprock.

Figure 17 shows sensitivities for the leakage risk. Because the total injected volume of CO_2 corresponds to 20% of the available pore volume, a major plume will in a majority of the cases have migrated to the crest of the reservoir already during the injection phase. Hence, the leakage-risk sensitivity shows almost the same profile at the end of injection and the end of simulation. This can also be observed in Figure 16. The sensitivity is slightly less during injection compared to at the end of simulation, because more CO_2 will accumulated below the caprock at the end of simulation. This overtakes the effect of the reduction in mobile volumes because of residual trapping and the increase in the number of plumes at end of simulation, which both result in less risk of leakage.

Once again, aggradation angle and fault criteria are the two most influential parameters. Increasing the aggradation angle improves the vertical communication and contributes to enhance the formation of CO_2 plumes below the caprock. Closed faults limit the movement of the plume and result in less accumulation below the caprock, whereas open faults generally increase the upward migration of plumes.

6 Conclusions

We have presented a study of how various geological parameters influence the injection and early-stage migration of CO_2 in progradational shallow-marine systems. One hundred and sixty equally probable realizations were considered and several flow responses related to storage capacity and risk of point leakage were calculated at the end of injection and after seventy years of gravity-dominated plume migration based on simulations using both linear and nonlinear relative permeabilities. We believe that linear permeabilities are a good starting point when studying the long-term impact of geological heterogeneities when this impact can be considered a first-order effect as herein. Flow predictions using nonlinear relative permeabilities are more sensitive to vertical grid resolution and can lead to severe under-prediction of gravity segregation effects in low-saturation regions if this resolution is not chosen sufficiently fine (see e.g., [36]). A more comprehensive study should therefore investigate the need for vertical (and lateral) grid refinement as in [52]. Vertical grid refinement will typically result in a CO_2 plume that is thinner vertically and has a much larger areal extent. If the segregated plume only fills the upper fraction of the grid cells, the movement of the plume will effectively be governed by linear permeabilities if capillary effects are small. For these reasons, we have herein primarily used linear permeabilities, which give significantly higher wave speeds and lead to earlier accumulation of CO_2 under the caprock and hence provide more pessimistic estimates of the plume migration and the risk associated with point leakage after a prescribed number of years than what is obtained by (possibly under-resolved) simulations with nonlinear relative permeabilities.

Altogether, we have demonstrated and discussed how the heterogeneity induced by different geological parameters give large variations in flow responses. Each geological parameter will influence the flow behavior and can result in local/global pressure build-up or pressure drop, enhance the flow direction, hinder the flow in the medium, or lead to loss of injected volumes over the open boundaries, and may induce different effects during the injection and plume migration. Specifically, we have demonstrated how variation in aggradation angle, fault criteria, and progradation direction significantly change the flow direction within the medium and hence impact the residual trapping and formation of movable CO_2 plumes under the caprock. Barriers are important during injection and must be modeled more carefully if the study focuses on injection operations. The large variations observed herein—e.g., for the reservoir pressure—are of course somewhat exaggerated by the fact that we consider a fixed injection point without regard to whether this point is favorable or not for each specific model realization. Despite this, we believe that our study shows that geological heterogeneity has a major impact on the injection and formation of a CO_2 plume and the subsequent early-stage migration of this plume. Any predictive study should therefore incorporate a realistic and detailed description of the geological heterogeneity as well as estimates of geological uncertainty to provide reliable forecasts of operational risks and the long-term fate of injected CO_2.