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Dynamics of stresses and fractures in reservoir and cap rock under production and injection

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Abstract

Production of hydrocarbons from geological reservoirs, and injection of fluids such as water or CO_2 into geological strata are accompanied with stress changes in the reservoir and in the cap rock. If the stress changes are large enough, they may reactivate faults or pre-existing natural fractures, or induce new fractures in the reservoir and/or the cap rock. Fractures in the cap rock caused by stress changes during CO_2 injection may threaten the cap rock integrity. Fractures within the reservoir may increase its injectivity, improve hydraulic communication and thereby facilitate spreading of the injected fluid. The objective of this work was to classify possible stress dynamics and fracturing scenarios that may take place under geological storage of CO_2. A compendium of stress regimes and expected fracture patterns is compiled that can be used as a quick guide when evaluating the risk of fracturing under CO_2 injection into deep saline aquifers or depleted fields as well as when estimating geomechanical effects of reservoir stimulation.

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Keywords: stress; stress path; production; injection; reservoir; cap rock; geomechanics; reservoir geomechanics; fracture; fault

1. Introduction

Production of hydrocarbons from geological reservoirs, and injection of fluids such as water or CO_2 into geological strata are accompanied with stress changes in the reservoir and in the cap rock. If the stress changes are large enough, they may reactivate faults or pre-existing natural fractures, or induce new fractures in the reservoir

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and/or the cap rock. In addition, induced stresses may jeopardize integrity in the near-well area, and cause casing damage.

Fractures in the cap rock caused by stress changes during CO_2 injection may threaten the cap rock integrity. It is therefore important to be able to predict the likelihood of such fracturing under different tectonic regimes and injection scenarios, as well as the extent, direction, and orientation of fractures, once they occur.

The objective of this work was to classify possible stress dynamics and fracturing scenarios that may take place under geological storage of CO_2. Stress changes accompanying depletion are summarized first. Then, stress changes accompanying injection in three different storage types are treated, namely: CO_2 injection into a deep saline aquifer; CO_2 injection into a depleted reservoir with the stress path equal to the stress path observed during the prior production from the reservoir; CO_2 injection into a depleted reservoir with the stress path coefficient being smaller than the stress path coefficient observed during the prior production from the reservoir. A compendium of stress changes for each of the above scenarios is compiled. This is done for each of the above three storage types assuming either normal or reverse or strike-slip faulting regime.

2. Stress changes and fracturing under depletion

Stress changes during production of oil and gas have been studied in reservoir geomechanics for the past 20 years [1-4]. Stress dynamics during depletion of an oil reservoir is caused by poroelastic coupling between the pore pressure and the mechanical stresses, and is briefly summarized in Table 1, assuming the pore pressure decreases in the entire reservoir, no pore pressure change occurs outside the reservoir (permeability is much smaller in the surrounding rock than in the reservoir), and the stiffness of the reservoir is not much different from the over-, under- and sideburden. The theory behind the summary presented in Table 1 and all subsequent stress analyses in this paper can be found in [1-5]. The reservoir has finite dimensions in all directions (incl. horizontal) in our analyses. Prime in Table 1 designates the effective stresses. Subscripts designate the vertical stress (v), the minimum horizontal stress (h) or the maximum horizontal stress (H). The stress changes indicated in Table 1 affect the Mohr stress circles as schematically shown by blue arrows in Figs. 1, 2 and 3 for the extensional (normal), compressional (reverse) and strike-slip tectonic regime, respectively. Some of the possible resulting fracturing and faulting scenarios caused by depletion are summarized in Table 2. As Table 2 indicates, normal faulting is likely to be promoted in the reservoir during depletion. This indeed has been observed at Valhall and Ekofisk fields [3].

Caution should be exercised when applying the qualitative picture outlined in Tables 1 and 2 for specific field cases since the real-life situations can be by far more complex. In particular, the effect of elastic contrast between the reservoir and the surrounding rock that was neglected when compiling Table 1 can be quite significant, as can be the effect of the reservoir tilt. Moreover, pressure does not change by the same amount in the whole reservoir, as assumed in Table 1. The in situ stress path can therefore be different in different parts of the reservoir and needs to be estimated on the case-by-case basis using e.g. a coupled geomechanical model. This remark is valid also for all subsequent analyses in this paper.

Table 1. Stress changes during depletion. Arrow up designates an increase, the stress becoming more compressive. Arrow down designates a decrease, the stress becoming less compressive.

Location	σ_v	σ'_v	σ_H, σ_h	$\Delta\sigma'_H$, $\Delta\sigma'_h$
Reservoir	↓	↑	↓	↑
Overburden	↓	↓	↑	↑
Sideburden	↑	↑	↓	↓

3. Stress changes and fracturing caused by injection into an undepleted reservoir

If CO_2 is injected into a deep saline aquifer surrounded by low-permeability rocks, and the reservoir has not been previously depleted, the stress dynamics will be opposite to that under depletion, described in Section 2. The stress dynamics during injection into such a reservoir are summarized in Table 3, again under the assumptions of little elastic contrast between the reservoir and the surrounding rocks, and no pore pressure change outside the reservoir.

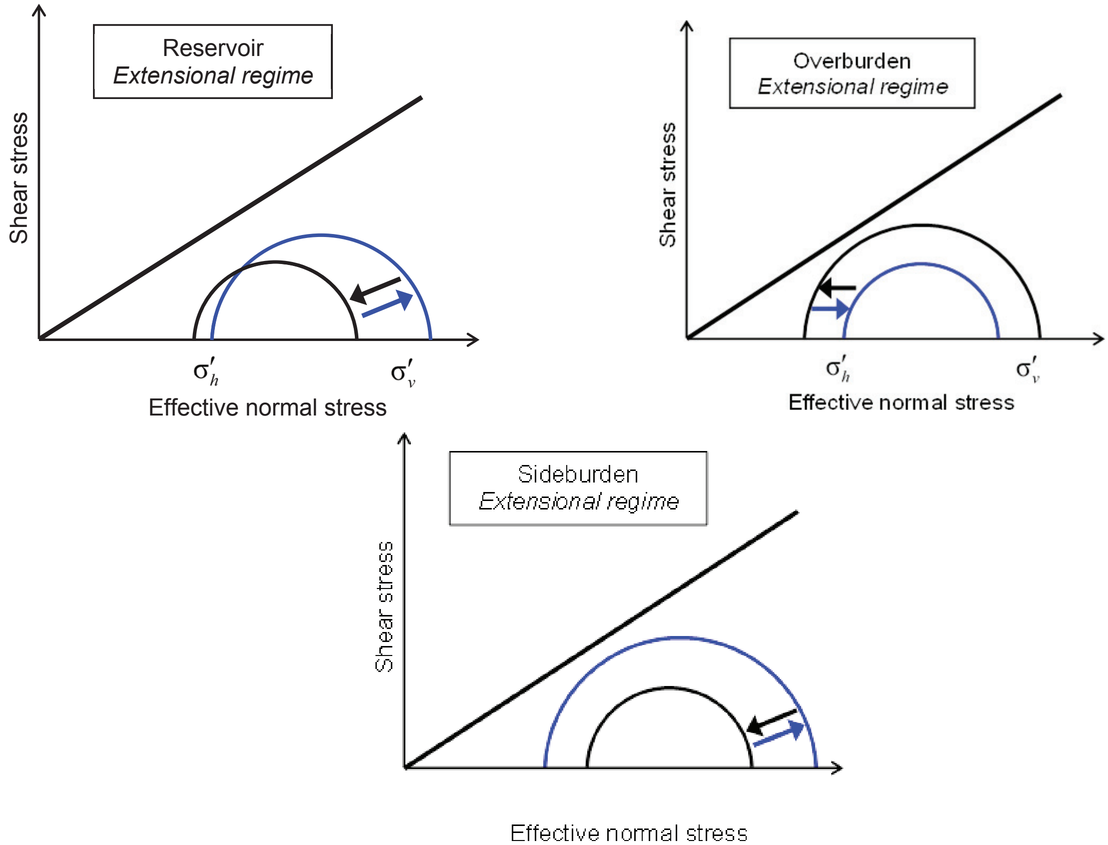

Fig. 1. Effective stress changes in reservoir, overburden and sideburden during depletion (blue arrow) and injection into an undepleted reservoir (black arrow) in extensional tectonic regime (normal faulting). The initial stress state is shown by black Mohr circle for depletion, and by blue Mohr circle for injection. The final stress state is shown by blue Mohr circle for depletion, and by black Mohr circle for injection. Pore pressure is assumed to remain constant outside the reservoir. Mechanical properties of the reservoir and surrounding rocks are assumed to be the same. Subscripts 'v' and 'h' refer to the vertical and minimum horizontal stress, respectively.

Table 2. Possible effects of reservoir depletion on fractures and faults under different tectonic stress regimes. 'Pore pressure' refers to the reservoir pore pressure. Pore pressure in the surrounding rocks is assumed to remain unchanged.

Stress regime	Reservoir	Overburden	Sideburden
Extensional (normal faulting)	Slip re-activation on normal faults. Closing of vertical and horizontal fractures.	Stabilization of normal faults. Possible slip propagation along normal faults from reservoir into overburden.	Slip re-activation on normal faults. Opening of vertical fractures.
Compressional (reverse faulting)	Stabilization of reverse faults. Closing of vertical and horizontal fractures.	Slip re-activation on reverse faults.	Stabilization of reverse faults.
Strike-slip	Closing of vertical and horizontal fractures.	Closing of vertical fractures.	Opening of vertical fractures.

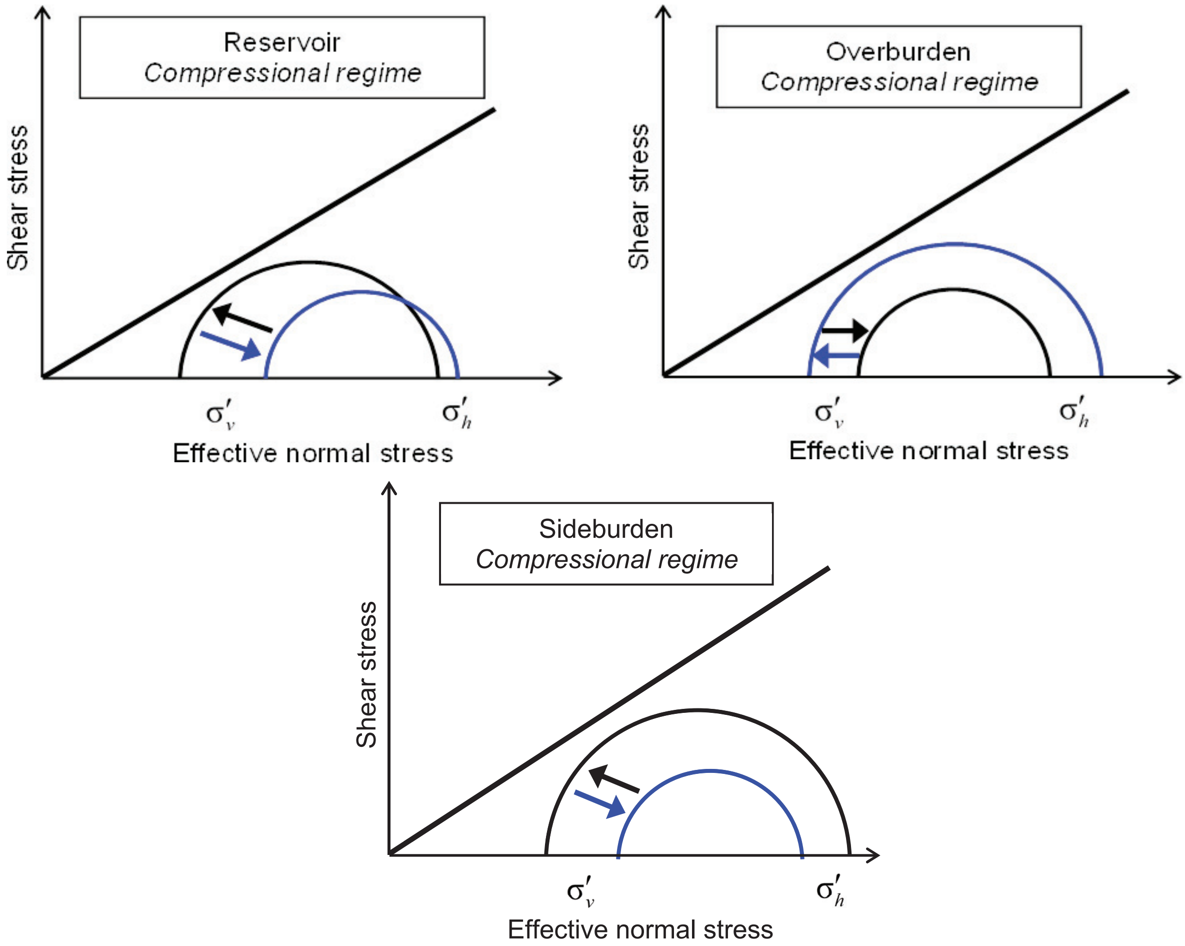

Fig. 2. Effective stress changes in reservoir, overburden and sideburden during depletion (blue arrow) and injection into an undepleted reservoir (black arrow) in compressional tectonic regime (reverse faulting). The initial stress state is shown by black Mohr circle for depletion, and by blue Mohr circle for injection. The final stress state is shown by blue Mohr circle for depletion, and by black Mohr circle for injection. Pore pressure is assumed to remain constant outside the reservoir. Mechanical properties of the reservoir and surrounding rocks are assumed to be the same. Subscripts 'v' and 'h' refer to the vertical and minimum horizontal stress, respectively.

Table 3. Stress changes during injection into an undepleted reservoir. Arrow up designates an increase, the stress becoming more compressive. Arrow down designates a decrease, the stress becoming less compressive.

Location	σ_v	σ'_v	σ_H, σ_h	$\Delta\sigma'_H$, $\Delta\sigma'_h$
Reservoir	↑	↓	↑	↓
Overburden	↑	↑	↓	↓
Sideburden	↓	↓	↑	↑

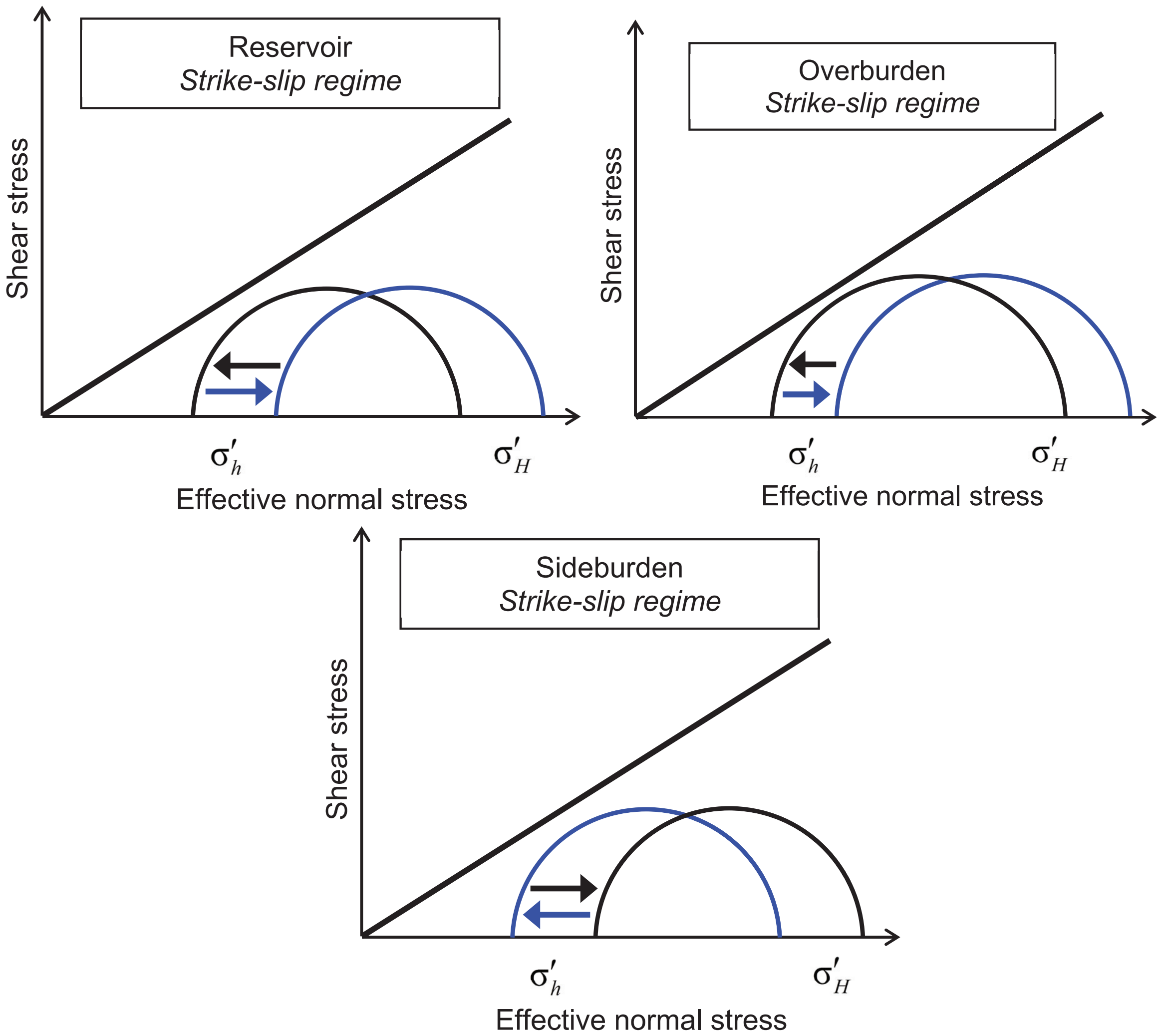

Fig. 3. Effective stress changes in reservoir, overburden and sideburden during depletion (blue arrow) and injection into an undepleted reservoir (black arrow) in strike-slip tectonic regime. The initial stress state is shown by black Mohr circle for depletion, and by blue Mohr circle for injection. The final stress state is shown by blue Mohr circle for depletion, and by black Mohr circle for injection. Pore pressure is assumed to remain constant outside the reservoir. Mechanical properties of the reservoir and surrounding rocks are assumed to be the same. Subscripts 'v' and 'h' refer to the vertical and minimum horizontal stress, respectively.

The stress changes indicated in Table 3 affect the Mohr stress circles as schematically shown by black arrows in Figs. 1, 2 and 3 for the extensional (normal), compressional (reverse) and strike-slip tectonic regime, respectively. Some of the possible fracturing and faulting scenarios caused by injection into an undepleted reservoir are summarized in Table 4, based on the stress changes given in Table 3.

Table 4. Possible effects of injection into an undepleted reservoir (e.g. deep saline aquifer) on fractures and faults under different tectonic stress regimes. 'Pore pressure' refers to the reservoir pore pressure. Pore pressure in the surrounding rocks is assumed to remain unchanged.

Stress regime	Reservoir	Overburden	Sideburden
Extensional (normal faulting)	Stabilization of normal faults. Opening of vertical fractures.	Slip reactivation on normal faults. Opening of vertical fractures.	Stabilization of normal faults. Closing of vertical fractures.
Compressional (reverse faulting)	Slip reactivation on reverse faults. Opening of horizontal fractures.	Stabilization of reverse faults.	Slip reactivation on reverse faults.
Strike-slip	Opening of vertical fractures.	Opening of vertical fractures.	Closing of vertical fractures.

4. Stress changes and fracturing caused by injection into a depleted reservoir

The overall vector of stress alteration during injection into a depleted reservoir will be similar to that shown in Table 3 for injection into an undepleted reservoir. The magnitudes of the stress changes will, however, be affected by the reservoir stress path which may differ in depleted and undepleted formations.

The reservoirs stress path can be defined as the ratio of the increase in the total horizontal stress to the increase in the pore pressure that caused it, $\beta_h = \Delta\sigma_h / \Delta P_p$ or $\beta_H = \Delta\sigma_H / \Delta P_p$ where ΔP_p is the pore pressure change in the reservoir. While the stress path during depletion can often be about 0.5-0.8 [6], it can be much smaller, down to almost zero, during subsequent injection into the depleted field [7]. More research on stress path during depletion/injection is needed in order to find out how common the abnormally low stress paths reported in the literature are under different tectonic regimes and geological settings.

From geomechanical viewpoint, depletion corresponds to reservoir loading (increase of effective stresses). Subsequent injection into a depleted reservoir corresponds to unloading. Zero (or low) stress path is believed to be due to plastic deformation created in the reservoir during depletion. Detrimental role of a possibly zero stress path during injection of CO_2 into a depleted field was recognized in [8].

Assume that during both depletion and subsequent injection the pore pressure only changes inside the reservoir, and the stiffness of the reservoir is not much different from that of the over-, under- and sideburden. Under these assumptions, stress changes under depletion and injection are illustrated in Figs. 4, 5 and 6 for extensional (normal faulting), compressional (reverse faulting) and strike-slip regimes, respectively. (The reservoir panels of Fig. 4 and Fig. 6 correspond to those provided in [8] for a specific field case.) Stress changes during depletion are shown by blue arrows. Two cases are illustrated in each Figure: The case of zero reservoir stress path during injection is shown by a yellow arrow. The case of unchanged, original stress path during injection is shown by a black arrow. The latter case corresponds to a reversible reservoir deformation during depletion-injection. The pore pressure is assumed to be restored to its pre-depletion level after the injection. Thus, the black circle in Figs. 4-6 designates both the pre-depletion stress state and the post-injection stress state in the case of an unchanged stress path. The stress paths in the over- and sideburden are assumed to remain unchanged during depletion and injection, i.e. no irreversible deformation occurs in these rocks under depletion. Moreover, the stress paths in the over- and sideburden are assumed to be unaffected by a possibly zero reservoir stress path. In reality, the latter might not always be the case.

Figures 4 and 6 suggest that non-zero stress path and non-unity Biot effective stress coefficient reduce the risk of fault reactivation in the reservoir in normal and strike-slip regimes, in agreement with [8, 9].

Irreversibility represented by a zero (or very low) stress path may have some further effects on the reservoir and cap rock integrity. In particular, if faults have been reactivated in the reservoir during depletion, they might not be able to return to their pre-depletion state during injection because it is not possible to reconstruct the pre-depletion state of stress by simply re-pressurizing the reservoir to the same pressure, if the stress path is reduced. In addition, hydraulic conductivity of fractures subject to shear deformation is irreversible [10] and thus may persist even in the case of a sufficiently high stress path, β_h, during injection.

Some of the possible fracturing and faulting scenarios caused by injection into a depleted reservoir are summarized in Table 5. In addition to the effects listed in Table 5, reactivation of shear fractures and faults may enhance permeability in the direction of the intermediate in-situ stress due to the "tubular" effect at shear fracture intersections [11]. This may, consequently, facilitate horizontal spreading of CO_2.

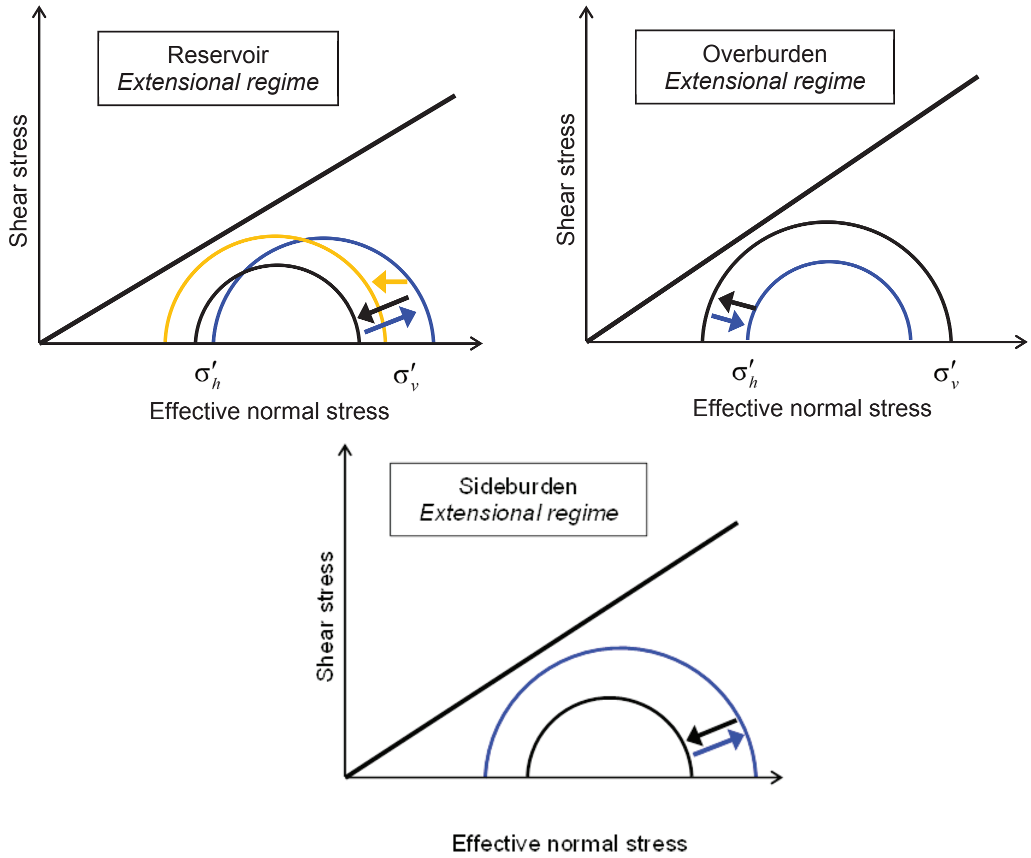

Fig. 4. Effective stress changes in reservoir, overburden and sideburden during depletion (blue arrow) and subsequent injection into depleted reservoir (black and yellow arrows) in extensional tectonic regime (normal faulting). The pre-depletion stress state is shown by black Mohr circle. The stress state upon depletion is shown by blue Mohr circle. The stress state after injection, assuming unchanged stress path, is shown by black Mohr circle. The stress state after injection assuming zero stress path is shown by yellow Mohr circle. Pore pressure is assumed to remain constant outside the reservoir. Mechanical properties of the reservoir and surrounding rocks are assumed to be the same. Subscripts 'v' and 'h' refer to the vertical and minimum horizontal stress, respectively.

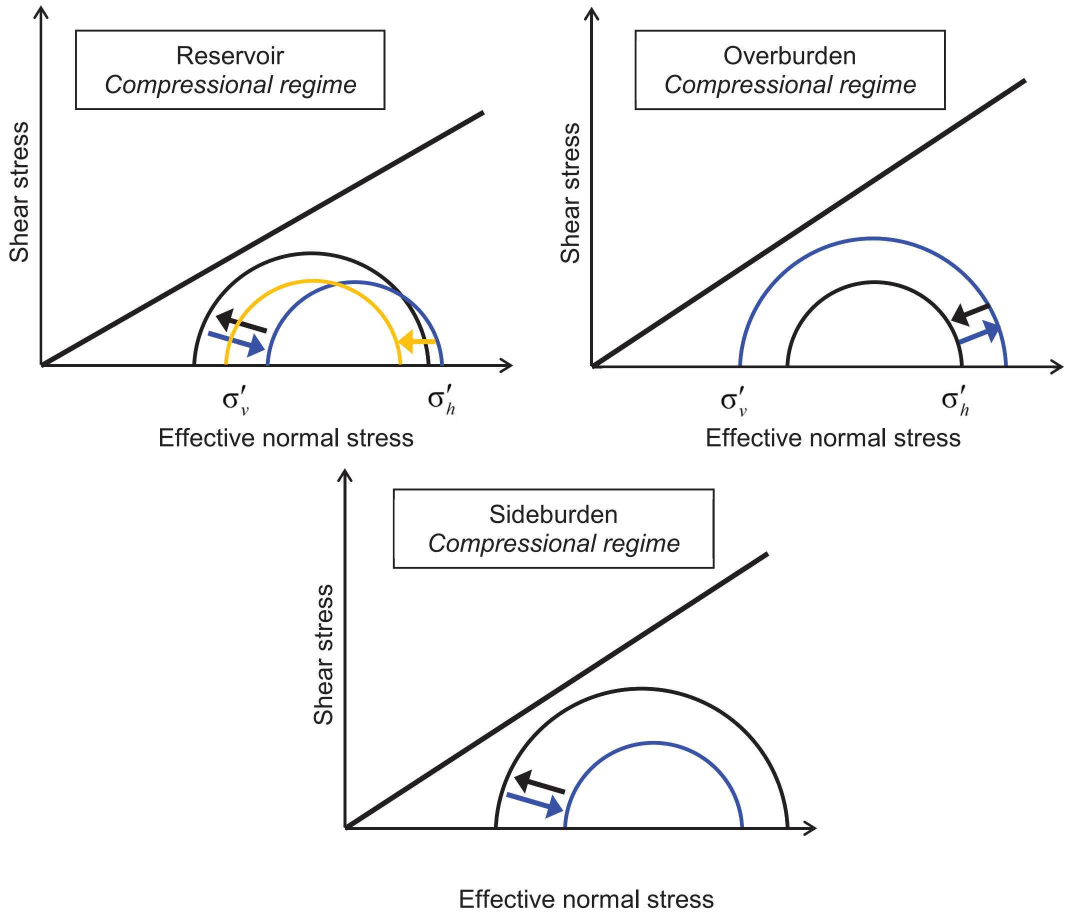

Fig. 5. Effective stress changes in reservoir, overburden and sideburden during depletion (blue arrow) and subsequent injection into depleted reservoir (black and yellow arrows) in compressional tectonic regime (reverse faulting). The pre-depletion stress state is shown by black Mohr circle. The stress state upon depletion is shown by blue Mohr circle. The stress state after injection, assuming unchanged stress path, is shown by black Mohr circle. The stress state after injection assuming zero stress path is shown by yellow Mohr circle. Pore pressure is assumed to remain constant outside the reservoir. Mechanical properties of the reservoir and surrounding rocks are assumed to be the same. Subscripts 'v' and 'h' refer to the vertical and minimum horizontal stress, respectively.

5. Discussion

Activation of the failure mechanisms outlined in Tables 4 and 5 ultimately depends on the mechanical properties of rocks and faults, and on the specific values of the pore pressure and stress magnitudes before, during and after injection. The scenarios shown in Tables 4 and 5 only indicate what can possibly happen, provided that the fluid pressure becomes sufficiently large and the rock strength is sufficiently small. Also, in real life, the picture can be complicated by the pore pressure diffusion from the reservoir into the surrounding low-permeability rock that was neglected in our analyses. Moreover, even when fracturing occurs, it will not necessarily lead to leakage. For instance, fractures may fail to establish a connected network. Some fractures might close after the injection is finished provided that shear displacement was sufficiently small on those fractures. A detailed analysis is required for each specific case in order to assess the risk associated with stress changes and possible fracturing during CO_2 injection.

It should be noted that shear and tensile fractures generated or reactivated in the reservoir might improve the injectivity by reducing the flow resistance [6]. However, propagation of such fractures into the cap rock may represent a risk for cap rock integrity [9, 12]. And so may fault reactivation inside the reservoir if the slip displacement propagates into the cap rock. In any event, the effect of changing reservoir pressure on the stress state in the cap rock is typically smaller than on the stress state in the reservoir itself [9]. Therefore fracture and fault reactivation will most likely be able to develop in the cap rock only after the onset of fracturing or fault reactivation in the reservoir. Another important contributing factor that should be carefully examined when considering storage in depleted reservoirs is the damage that possibly has been created in the cap rock during depletion [9, 12]. This may include fault reactivation, wellbore casing failure or formation of new fractures [12].

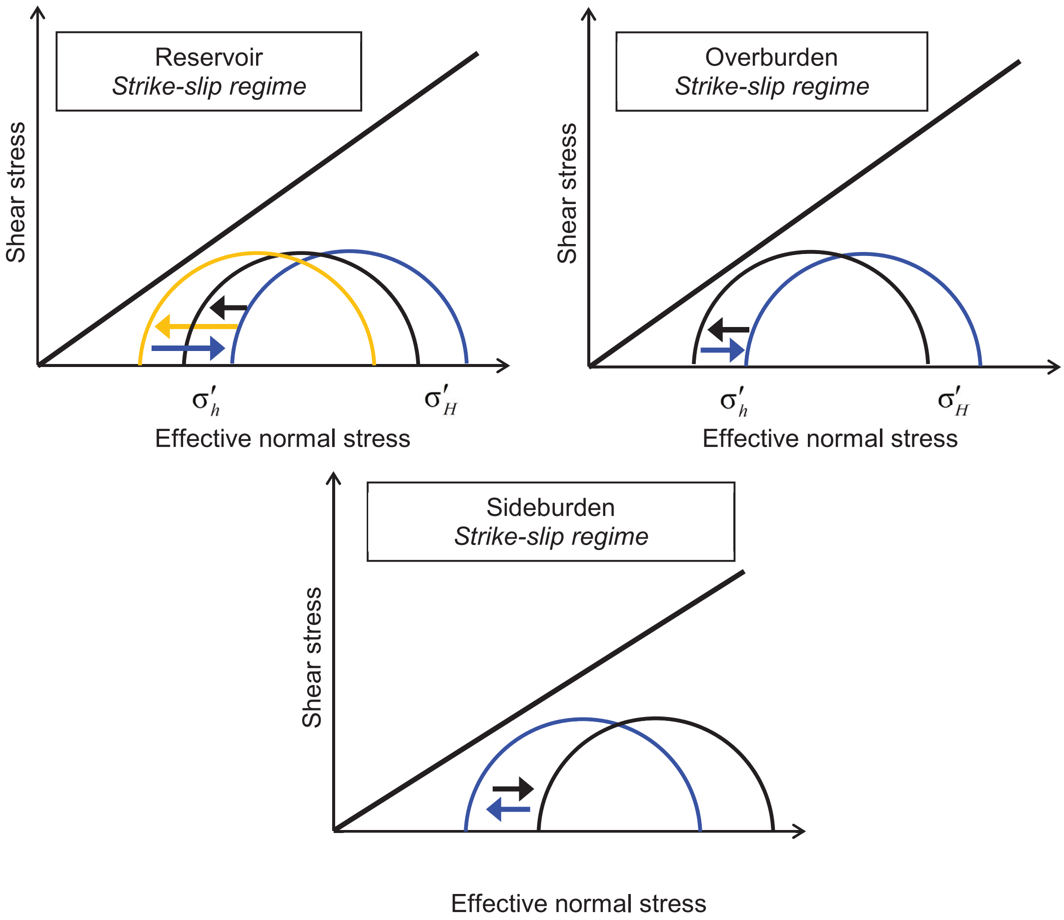

Fig. 6. Effective stress changes in reservoir, overburden and sideburden during depletion (blue arrow) and subsequent injection into depleted reservoir (black and yellow arrows) in strike-slip tectonic regime. The pre-depletion stress state is shown by black Mohr circle. The stress state upon depletion is shown by blue Mohr circle. The stress state after injection, assuming unchanged stress path, is shown by black Mohr circle. The stress state after injection assuming zero stress path is shown by yellow Mohr circle. Pore pressure is assumed to remain constant outside the reservoir. Mechanical properties of the reservoir and surrounding rocks are assumed to be the same. Subscripts 'v' and 'h' refer to the vertical and minimum horizontal stress, respectively.

Table 5. Possible effects of injection into a depleted reservoir on fractures and faults under different tectonic stress regimes. 'Pore pressure' refers to the reservoir pore pressure. Pore pressure in the surrounding rocks is assumed to remain unchanged.

Stress regime	Reservoir	Overburden	Sideburden
Extensional (normal faulting)	Possible slip on normal faults if the reservoir stress path is sufficiently low during injection. Possible opening of vertical fractures.	No effects as long as the pre-depletion reservoir pressure is not exceeded.	No effects as long as the pre-depletion reservoir pressure is not exceeded.
Compressional (reverse faulting)	No effects as long as the pre-depletion reservoir pressure is not exceeded.	No effects as long as the pre-depletion reservoir pressure is not exceeded.	No effects as long as the pre-depletion reservoir pressure is not exceeded.
Strike-slip	Possible slip on normal faults if the reservoir stress path is sufficiently low during injection. Possible opening of vertical fractures.	No effects as long as the pre-depletion reservoir pressure is not exceeded.	No effects as long as the pre-depletion reservoir pressure is not exceeded.

6. Conclusion

A compendium of stress regimes and expected fracture patterns has been compiled for three scenarios in three tectonic regimes under some simplifying assumptions (little contrast in elastic properties between the reservoir and the surrounding formation; pore pressure change only in the reservoir). Based on the stress analyses, plausible scenarios for fracturing and fault reactivation during CO_2 storage have been analyzed. With regard to both fracturing and fault reactivation, storage in depleted reservoirs has been found to be more preferable than storage in an undepleted reservoir (such as a deep saline aquifer). The stress path has a profound effect on stress dynamics and fracturing/faulting when injecting into a depleted reservoir.

The compendium can be used as a quick guide when evaluating the risk of fracturing under CO_2 injection into deep saline aquifers or depleted reservoirs as well as when estimating geomechanical effects of reservoir stimulation.

Acknowledgement

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