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Poroelasticity and self-stimulation around geothermal producers in quadruplet versus triplet configurations

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At the latest since Segall (1989), Teufel et al. (1991), poroelasticity can explain, so to say despite Terzaghi, how fluid depletion destabilizes reservoirs either at their flanks or at their top and bottom, depending on the (extensional or compressional) tectonic regime. By the same token, poroelasticity can alleviate some undesired effects of pore pressure buildup by fluid injection into deep reservoirs, yet it can also counteract desired stimulation effects for the latter. In geothermal reservoirs subject to balanced fluid turnover by simultaneous injection and production from multiple wells, things are less clear-cut (cf. Segall and Fitzgerald 1998). The joint outcome of poroelastic effects and of pore pressure directly on effective stresses will strongly depend on geometry details of multi-well configurations. A scoping simulation example of a hydrothermal reservoir operated by means of a well triplet (one producer, two re-injectors) is presented, to which by placing a fourth well (second producer) within a certain reservoir 'cone', self-stimulating effects will be induced, by virtue of competing pressure diffusion and poroelasticity, within a certain radius around each producer well; the stimulation radius appears to be larger at early operation stages, yet may persist at significant (few MPa) levels even after decades of fluid turnover. Such producer-centered stimulation effects are found to occur **only for the quadruplet**, and **not for the triplet** configuration. At the real-world site underlying this simulation example, adding a fourth well (second producer) is being endeavored in order to maximize the benefit from surprisingly high injectivity at the already existing two injectors, whereas the modest productivity of the existing producer acted as the turnover-limiting factor in the currently operating triplet. Up-sizing to a quadruplet configuration (two producers instead of one) might thus also, by virtue of competing pressure diffusion and poroelastic effects, improve the productivity of the first producer, so to say as an 'added bonus' against the drilling costs of up-sizing. In the currently operating triplet regime, injectivity further appears to increase with operation time i. e. with the cumulative volume of fluid turnover, this being attributed to (thermo-)hydrogeochemical rather than hydraulic-poroelastic effects. Scoping poroelastic simulations are complemented by a comparison of fluid residence time distributions and thermal lifetime expectations between the two (quadruplet versus triplet) configurations.
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ABSTRACT

At the latest since Segall (1989), Teufel et al. (1991), poroelasticity can explain, so to say despite Terzaghi, how fluid depletion destabilizes reservoirs either at their flanks or at their top and bottom, depending on the (extensional or compressional) tectonic regime. By the same token, poroelasticity can alleviate some undesired effects of pore pressure buildup by fluid injection into deep reservoirs, yet it can also counteract desired stimulation effects for the latter. In geothermal reservoirs subject to balanced fluid turnover by simultaneous injection and production from multiple wells, things are less clear-cut (cf. Segall and Fitzgerald 1998). The joint outcome of poroelastic effects and of pore pressure directly on effective stresses will strongly depend on geometry details of multi-well configurations as well as on geological heterogeneity.

A scoping simulation example of a hydrothermal reservoir operated by means of a well triplet (one producer, two re-injectors) is presented, to which by placing a fourth well (second producer) within a certain reservoir cone, self-stimulating effects will be induced, by virtue of competing pressure diffusion and poroelasticity, within a certain radius around each producer well; the stimulation radius appears to be larger at early operation stages, yet may persist at significant (few MPa) levels even after decades of fluid turnover. Such producer-centered stimulation effects are found to occur only for the quadruplet, and not for the triplet configuration.

At the real-world site underlying this simulation example, adding a fourth well (second producer) is being endeavored in order to maximize the benefit from surprisingly high injectivity at the already existing two injectors, whereas the modest productivity of the existing producer acted as the turnover-limiting factor in the currently operating triplet. Up-sizing to a quadruplet configuration (two producers instead of one) might thus also, by virtue of competing pressure diffusion and poroelastic effects, improve the productivity of the first producer, so to say as an added bonus against the drilling costs of up-sizing. In the currently operating triplet regime, injectivity further appears to increase with operation time, i. e., with the cumulative volume of fluid turnover, this being attributed to thermal-hydrogeochemical rather than hydraulic-poroelastic effects.

Within the ongoing study, hydraulic and poroelastic evaluations are to be complemented by a comparison of fluid residence times along with thermal lifetime expectations between triplet and quadruplet settings, revealing further benefits of the latter, which pay up for the additional drilling costs.

1. AIM, METHOD, AND APPROXIMATIONS

The effects of hydraulic-poroelastic coupling in oil and gas reservoirs under continuous depletion (unbalanced fluid turnover) have enjoyed increased attention relatively early (Segall, 1989), driven especially by external public ‘pressure’ to assess and predict (and, as far as possible, avoid or mitigate) hazards of induced seismicity in the vicinity of such reservoirs. Owing to Segall’s pioneering work, a seemingly clear-cut picture could be gained on typical patterns of [hydrocarbon] depletion-induced seismicity [in sedimentary basins]: “*Normal faults develop on the flanks of the field when the depleted reservoir is located in an extensional environment, whereas reverse faults develop above and below the reservoir in compressional environments*” (Segall 1989, Segall and Fitzgerald 1998).

In contrast, for geothermal reservoirs operated by multiple, producing and re-injecting wells (with broadly balanced fluid turnover), a much more intricate pattern of various effects (partly counteracting each other) from poroelastic coupling alongside with pore pressure buildup/drawdown is likely to develop, with considerably stronger heterogeneity in the spatial distribution of effective stress variations, not only at reservoir boundaries, but also in-between the wells. Due to the overall balance of fluid turnover (total flow rate ‘in’ equals total flow rate ‘out’ at any time), we are entitled to expect weaker effects at reservoir boundaries (far-field scale), compared to the hydrocarbon reservoir case, yet at the price of experiencing greater effects inside the reservoir (near-field scale). Moreover, the latter will strongly depend on the multi-well assembly’s size and geometry (placement and spacing of production and injection wells relative to each other). Therefore, such ‘universal’ patterns like the previously-cited from the hydrocarbon reservoir realm are unlikely to emerge from geothermal reservoir analyses. In the geothermal operations realm, assessing the joint effects of pore pressure and of hydraulic-poroelastic couplings needs to be conducted specifically for each reservoir design with its particular multi-well assembly.

In the sequel, we explore the joint effects of pore pressure (in the sense of Terzaghi: effective stress reduction by fluid injection, effective stress augmenting by fluid depletion), and of hydraulic-poroelastic couplings (with their, so-to-say, Terzaghi-counteracting effects) occurring during hydrothermal reservoir operation in ~4 km depth at the site "S" in the Molasse-Malm basin, with a main focus on their *differential* effects on maximum and minimum principal stresses (and thus on Mohr circle's position *and radius*), as induced by forced-gradient turnover of reservoir fluid, for two distinct multi-well settings of interest at this site (cf. table 1), namely:

- the currently operating well triplet (one producer, two re-injectors)
- the planned future well quadruplet (one further producer well to be drilled additionally to the existing triplet, in order to augment the benefit from unexpectedly high injectivity encountered at the two injector wells of S).

The evolution of pore pressure and stress tensor components in the reservoir is simulated as a linear superposition of single-well contributions. The latter can be approximated by the closed-form solutions derived by Rudnicki (1986), owing to the large thickness of the reservoir 'aquifer' layer and its geological homogeneity over a radial extension much larger than inter-well distances. This approach is largely similar to that of Altmann (2010), Altmann et al. (2014), but findings will differ, in terms of features that are unique to the triplet and quadruplet settings of site S. Hydrogeological and geomechanical parameter values for the latter are compiled from sparsely available site-related data (Seithel et al. 2015), complemented by knowledge from sedimentary basins worldwide (Kümpel 1991, Economides and Nolte 2000, Hillis 2001, Adu 2019). Values ~ 5 – 15 GPa can be assumed for the Lamé coefficients. For Biot's poroelastic coupling coefficient α, a value of 0.65 is assumed. With these and the more or less known hydraulic properties (transmissivity/storativity) of the S reservoir, the poroelastic extension of hydraulic diffusivity can be estimated at $\sim 6 \times 10^{-3}\ m^2/s$. Once having calculated pore pressure and stress tensor component changes induced by forced-gradient fluid turnover, Mohr circle's alterations can be quantified in terms of a so-called "distance to failure", commonly abbreviated as DMF.

Table 1 : Well triplet and quadruplet settings for site S

well id	Producer1 (existing) [red dot in figs.]	Injector1 (existing) [gray dot in figs.]	Injector2 (existing) [gray dot in figs.]	Producer2 (to be drilled) [red dot in figs.]
x [m]	0	1,300	2,100	3,500
y [m]	0	1,650	–1,350	0
Q [m³/s] for triplet	–0.1	+0.05	+0.05	n. a.
Q [m³/s] for quadruplet	–0.1	+0.1	+0.1	–0.1

Simulated pore pressure and stress tensor changes can be examined in terms of

- overall magnitude of fluid-induced changes to every stress tensor component;
- spatial distribution (heterogeneity 'patterns') of fluid-induced stress tensor changes in wellbore vicinity, in inter-well areas and in remoter reservoir regions (from 'near-field' to 'far-field' scale);
- temporal evolution of fluid-induced alterations to stress tensor components: change propagation speed, non-/monotonicity in time, early 'overshooting' effects and alike;
- a more or less constant correlation between pore pressure and minimum-stress changes, probing the applicability of the so-called "*pore pressure – stress coupling*" concept proposed by Teufel (1996), developed by Hillis (2000, 2001) and frequently invoked by further authors;
- delineating reservoir areas prone to reactivation, with implications for permeability enhancement and possibly fluid-induced seismicity (reservoir 'stimulation' effects at near-/far-field scale, despite the overall balance of fluid turnover), in particular:
- areas of non-zero, 'emergent' shear stress components in the horizontal plane which was formerly a principal stress plane, thereby indicating a fluid-induced *rotation* of the stress tensor.

DMF can be derived from pore pressure and stress principal-component changes, irrespective of the applicability of closed-form solutions for the latter, but requiring knowledge of the friction angle (a value of 30° being chosen for DMF plots shown in figs. 1 – 2), on which the above considerations, in turn, do not depend:

$$\delta\,\mathrm{DMF} = \delta\,\sigma_{min}\,(1+\sin\varphi)/2 - \delta\,\sigma_{max}\,(1-\sin\varphi)/2 - \delta\,P_{pore}\sin\varphi$$

2. MAIN FINDINGS

Irrespective of multi-well configuration type (triplet or quadruplet), it can be recognized that

- radial stresses propagate twice as fast in radial direction, than in tangential direction,
- vertical stress components propagate isotropically in the horizontal plane (no preference for a particular direction in this plane to which they are always tangential) at half the speed of radial stresses,

which is in good agreement with analytical expectations, and fits into the broad pattern predicted by Rudnicki (1986), reconfirmed by Altmann (2010) and Altmann et al. (2014). This is also reflected by the approximate ratios (½ or ~2, respectively) of stress change magnitudes, seen in table 2 to be observed in both configurations (triplet and quadruplet).

Table 2 : Approximate ranges of pore pressure and stress tensor component changes

change to component	**well triplet**	**well quadruplet**
late horizontal $\delta\ \sigma_{xx}$	– 200 MPa , + 50 MPa	– 65 MPa , + 45 MPa
late horizontal $\delta\ \sigma_{yy}$	– 100 MPa , + 65 MPa	– 33 MPa , + 60 MPa
late vertical $\delta\ \sigma_{zz}$	– 100 MPa , + 35 MPa	– 33 MPa , + 30 MPa
early new horizontal shear $\delta\ \sigma_{xy}$	– 18 MPa , + 11 MPa	– 10 MPa , + 13 MPa
(early) pore pressure $\delta\ P_{pore}$	– 460 MPa , + 160 MPa	– 230 MPa , + 160 MPa

The quadruplet configuration alters the prevailing focal-mechanism style, compared to the triplet configuration. The alteration is most pronounced for the vertical stress component, followed by the stress component orthogonal to the direction in which a new producer well was added (the latter happens to be σ_h for the Alpine foreland's spot of interest, but the general finding is independent on this particular choice). The stress component parallel to the latter is less affected.

It appears that in certain reservoir areas, occurring not only in wellbore vicinity but also far away from the wells, shear stress variations change sign during reservoir operation. At some of these locations, negative peaks of tensile stresses occur, which may further contribute to fissure / fracture opening and thus to permeability enhancement (reservoir 'stimulation').

Changes are rather fast at early times, in both multi-well configurations; as of approximately *six years* from the onset of reservoir operation (i. e., start of fluid forced-gradient turnover), a quasi-steady state is reached, with but little more changes during subsequent *decades* of operation. Fluid-induced shear stresses are found to develop and propagate even faster, in both multi-well configurations, reaching quasi-steady state within less than *half a year* from the onset of reservoir operation.

The quadruplet configuration reduces the imbalance that was inherent to the triplet configuration (seen between the 'injection-dominated' left-hand side, and the 'depletion-dominated' right-hand side of the reservoir in figs. 1, 2). Not only asymmetry in space, but also the magnitude of stress component changes is significantly reduced by the quadruplet, compared to the triplet configuration (cf. values in table 2). Depletion-related drawdown of pore pressure is also halved, thanks to splitting the prescribed production rate between two wells, whereas the injection-related buildup of pore pressure does not change, given the same two re-injector wells that are common to both configurations.

Although the quadruplet configuration significantly reduces asymmetry between the two reservoir sides along the direction of the added producer, a persistent imbalance is found: pressure build-up 'fronts' growing around the re-injectors, as well as drawdown 'fronts' around the producers (particularly conspicuous at the fourth well), are not well-centered, but shifted towards the added producer.

One can also consider the ratio between changes of each normal-stress component and the pore pressure change: $\Delta\sigma_{xx,yy,zz} / \Delta P_p$. Depending on the local tectonic regime, one of these components can be the minimum principal stress, for which the ratio is then supposed to be relevant, $\Delta\sigma_{min} / \Delta P_p$, and usually deemed as the "*pore pressure – stress coupling ratio*". The authors who originally introduced it, and found it worth special focus and elaboration (Teufel 1996, Hillis 2000) have deemed it to be a characteristic of the reservoir under consideration, in the context of either production (depletion) or injection (over-pressurizing); Hillis (2001) also distinguished between reservoir field-scale and basin-scale coupling ratios, which he tabulated from observations collected worldwide, expecting them to serve as a predictor or a kind of 'index' for an induced-seismicity propensity.

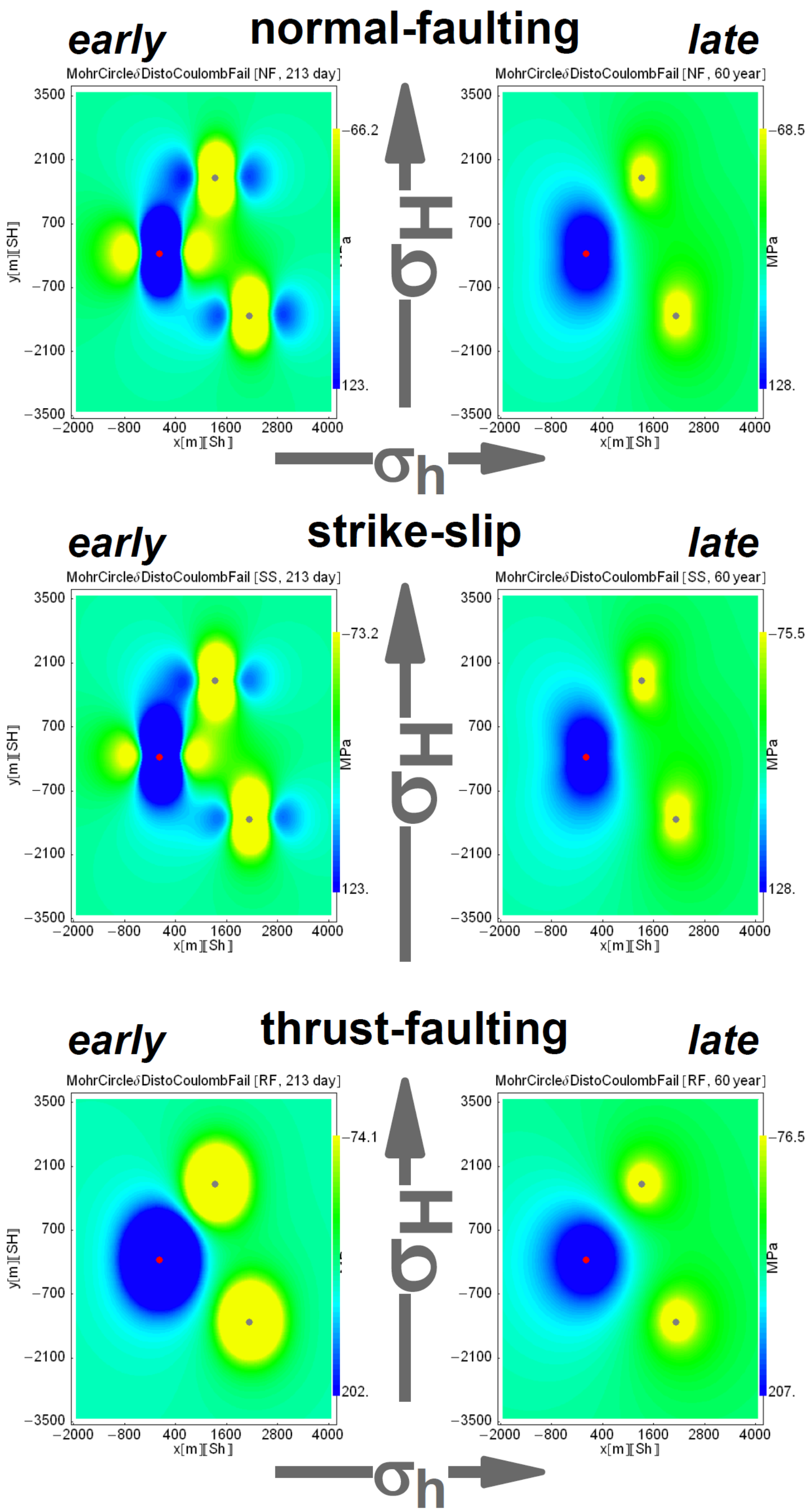

Figure 1: How will Mohr circle's alterations propagate in space and time, under possibly different tectonic regimes? Here, DMF changes are shown in the central horizontal plane containing all well-screens of the TRIPLET design, with the basic tectonic styles, all having σ_H along the *y* axis (roughly N-S in this Alpine foreland's spot of interest), at two distinct stages of reservoir operation (early ~ 6 months, late ~ 60 years since the start of forced-gradient circulation).

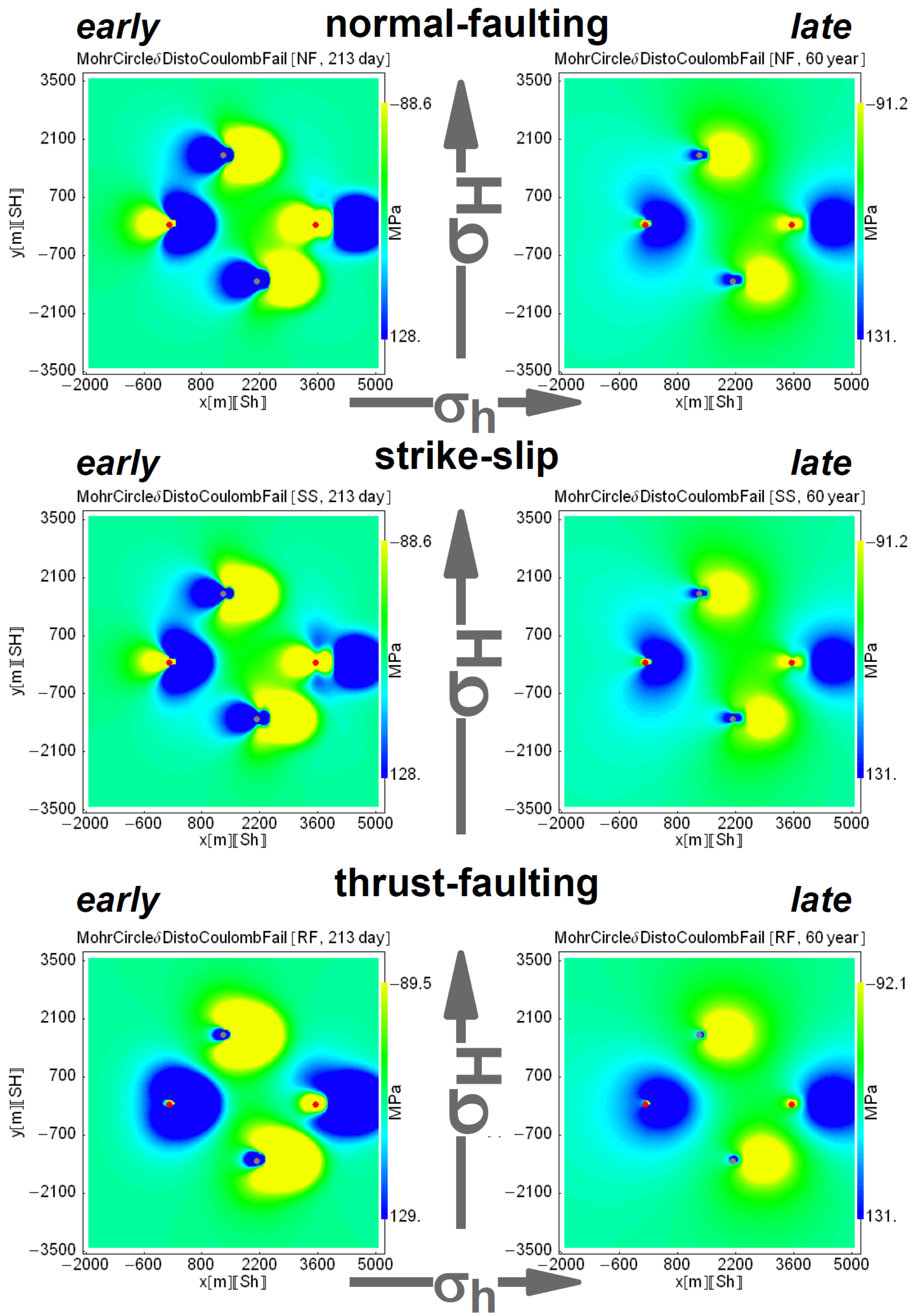

Figure 2: DMF changes shown in the central horizontal plane containing all well-screens of the QUADRUPLET design, with the basic tectonic styles, all having σ_H along the *y* axis (roughly N-S in this Alpine foreland's spot of interest), at two distinct stages of reservoir operation (early ~ 6 months, late ~ 60 years since the start of forced-gradient circulation).

A geothermal multi-well setting of fluid turnover, however, weakens the predictive ability of this "coupling ratio", which now becomes strongly variable across the reservoir as well as with operation time (not a reservoir "characteristic" any more).

Interestingly, the quadruplet configuration shows less than half the maximum "coupling ratio" value, compared to the triplet configuration for the *horizontal* stress components (one of which, as resulting from boreholes' alignment, would always be relevant under a normal-faulting regime), whereas for *vertical* stresses (which would become relevant in the case of a thrust-faulting regime) coupling is much stronger in the quadruplet than in the triplet configuration. With spatial patterns further inspected, the "coupling ratio" appears to loose its predictive ability for precisely those reservoir regions where the most significant effects are likely to occur.

Last not least, certain systematic features of Mohr circle's behavior are recognized in terms of DMF from figures 1 and 2, with some contrast, but also similarity between different tectonic styles, of which a synopsis is provided in table 3.

The chances for reservoir permeability enhancement are somewhat more pervasive, spatially, and DMF decrease amplitude at least 15 MPa larger in the quadruplet, than in the triplet configuration, despite the significantly lower amplitudes of stress *component* changes that were seen from table 2; however, in terms of stress magnitude change, few MPa may suffice for (Coulomb-type) failure, in whichever setting. To be recalled, the preference* identified by the last entry in table 3 makes sense only under the premise of injection-well alignment (roughly) along σ_H in both configurations, and production-well alignment along σ_h in the quadruplet configuration.

Table 3 : Synopsis of typical Mohr-circle alterations in the triplet and quadruplet configuration

<table>
<tr><th>Mohr circle's property</th><th>near-well behavior</th><th>propagation style</th><th>tectonic style influence</th></tr>
<tr><td>radius
(½ of differential stress)</td><td>zero
at the well</td><td>tetra-lobes of alternating decrease and increase along two orthogonal axes,
of opposite sign for inj. vs. prod. wells</td><td rowspan="2">preferred lobe growth direction complementary between NF and TRF, but no preferred growth direction in SS</td></tr>
<tr><td>center distance
(ave. normal stress)</td><td>maximum |±value|
at the well</td><td rowspan="2">spherically or elliptically
from the wells outwards:
increase around prod. wells,
decrease around inj. wells, …</td></tr>
<tr><td rowspan="2">DMF
(Mohr circle's distance to Coulomb failure)</td><td rowspan="2">maximum |±value|
at the well</td><td rowspan="2">general preference* for σ_H axis under all tectonic regimes (more pronounced in NF and SS, less pronounced in TRF), but much less in quadruplet than in triplet configuration</td></tr>
<tr><td>… superimposed on weaker overshooting lobes reminiscent from early time stages</td></tr>
</table>

Ultimately, the most interesting surprise is that of localized self-stimulating 'isles' around production wells, occurring only in the quadruplet (fig. 2), and not in the triplet (fig. 1) configuration. Their *early* occurrence, along with their persistently *localized* character (closely confined to the wells at late stages, too, i. e., not evolving to a large-scale 'hazard' of fluid-induced seismicity) is a fortunate trait, since the applicability of the available analytical solutions (valid for the 'infinite reservoir') decreases, generally, with increasing duration of multi-well operation, and with increasing distance from the wells (such 'self-stimulating' would be rather questionable if it would occur at (physical) reservoir margins, and/or only at late operation stages). These producer-centered stimulation 'isles' of the quadruplet setting are not a calculation artifact, and a further fortunate trait is their occurrence under any tectonic regime, with almost no difference between normal-faulting and strike-slip styles, and with somewhat less pronounced 'stimulation' propensity under the thrust faulting regime (the latter being unlikely to be encountered at the investigated Alpine foreland's spot).

3. OUTLOOK: SOME ADDED BENEFITS OF THE QUADRUPLET SETTING

Apart from emergent shear, and some 'overshooting' at incipient operation stages, poroelastic coupling effects are rather slow to develop and propagate at the reservoir's large scale, because the balanced character of multi-well fluid turnover keeps them localized around the wells (unlike in hydrocarbon reservoir depletion, where fluid abstraction imbalance can but keep growing in space and time).

Furthermore, coupling effects appear to be of lower amplitude, and generally smoother at reservoir scale for the quadruplet, than for the triplet design. Stress tensor *rotation* is bound to occur in both, but the new (fluid-induced) shear stresses in the (formerly principal) horizontal plane will result only about half as strong for the quadruplet than for the triplet setting.

The most striking finding is that of early, well-centered 'self-stimulating isles' around the 'depletor' wells, seen to develop in the quadruplet, but not in the triplet setting (fig. 2 versus fig. 1). For the quadruplet setting, however, they are found to occur with any tectonic style. They can be regarded as a correlate to the previously-mentioned anomalous shifting of pore pressure (drawdown) 'fronts' (traceable all along their so-called "stress coupling ratios", as well) that had been found for the quadruplet, but not for the triplet configuration, i. e., as a *geometrical rather than tectonic* effect. On the other hand, they are a genuine poroelastic effect indeed – since by Terzaghi's 'effective stress' concept alone (without Biot's poroelastic coupling α) one would hardly obtain a DMF decrease around a depleting well.

A more general explanation for this counter-intuitive phenomenon was offered by Behrens et al. (2020), who also demonstrated that 'misaligned stimulation' effects are more likely to occur at production wells of geothermal well systems, at their early operation stages (cf. figs. 8, 9, 10 of ibid.), and illustrated such effects for a nine-well ensemble. Under certain circumstances, such effects vanish at later operation stages (cf. figs. 10, 11, 12 of ibid.).

The significant differences found between poroelastic effects in quadruplet versus triplet settings, in turn, demonstrate that well-field design- and site-specific analyses (as also endeavored by Yamah 2020, besides Adu 2019) are indispensable. At the end of the day, not only was the exercise worth conducting – but, also, for this particular site in the Alpine foreland basin it seems worth drilling a fourth well.

Within the ongoing study, hydraulic and poroelastic evaluations are to be complemented by a comparison of *fluid residence time distribution* patterns (cf. fig. 4 of Behrens et al. 2020) along with *thermal lifetime expectations* (cf. fig. 3 of ibid.) between triplet and quadruplet settings, revealing further benefits of the latter, which pay up for the additional drilling costs.

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