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Assessment of geological factors potentially affecting production-induced seismicity in North German gas fields

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HIGHLIGHTS

- Modelling study on geological factors controlling production-induced seismicity in North German gas fields.
- Preferred reactivation of steeply dipping faults due to compaction driven fault loading.
- Pronounced fault reactivation potential below the flanks of a viscoelastic salt diapir.
- Increased production-induced fault loading in intercalated horizons between reservoir and salt layer.

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ABSTRACT

Recovery of hydrocarbons has triggered seismicity in some Rotliegend reservoirs in the Netherlands and in northern Germany. In Germany, these earthquakes have caused negligible structural damage, but raised public concerns in a region of low historic seismic activity. Production-induced seismicity has been successfully addressed by analytic poroelastic models that explain the development of critically stressed faults with pore fluid pressure depletion inside and around reservoirs. The available analytical approaches fail to account for the mechanical stratigraphy and structural complexities occurring in reality, i.e., reservoirs compartmentalized by faults. The present study aims to increase the quantitative understanding of the geological factors that potentially affect production-induced seismicity in North Germany. In the first part of the paper, a series of 2D finite element models is presented to investigate a parameter space for reservoir depth, reservoir thickness, mechanical reservoir and host rock properties, and compartment geometries typically observed in North German Rotliegend gas fields. The second part addresses the impact of mobile salt layers with variable thickness atop the reservoir on fault stability. The results indicate preferred fault reactivation for steeply dipping faults, large Biot–Willis coefficients, inhomogeneous overburden loads, large reservoir thicknesses, a shallow reservoir position and short distances of the salt layer to the reservoir. In the third part we investigate the effects of fault dip and throw along a fault loaded by three depletion scenarios in a compartmentalized intra-graben setting. Maximum fault loading was obtained for the case that fault throw is half of the reservoir thickness and production is exclusively from the footwall block. The main finding is a preferred reactivation of steeply dipping faults ($>60^\circ$) caused by the dominant contribution of reservoir compaction to fault loading. Compaction-loading constitutes the main difference to seismicity driven by far field tectonics dominated by horizontal strain, for which faults with dip angles of approximately 60° are predicted favourable for reactivation.

1. Introduction

Both, injection and extraction of fluids from permeable reservoirs have induced seismicity at the affected sites.[1–3] Seismicity results from compensation of mechanical disequilibria by fault reactivation that built up from differences in deformation driven by changes in pore fluid pressure P_f inside the reservoir and its surrounding. Reservoir deformation is frequently observed at the earth's surface by modern geodetic techniques.[4,5] Injection-induced seismicity driven by an increase in the pore fluid pressure has been documented for a variety of subsurface operations including (1) waste water disposal in deep formations,[6] (2) pressure maintenance in oil and gas fields,[7] (3) pore fluid pressure diffusion in the framework of hydraulic fracturing,[8–10] (4) injection into storage facilities,[11] and (5) stimulation[12] and operation of geothermal

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reservoirs.[13] Mechanisms leading to injection-induced seismicity include the decrease in effective normal stresses caused by the increase in P_f (e.g. Refs. 9, 14, 15), more complex models relate injection-induced seismicity to changes in total stress attributed to pore fluid pressure–stress coupling (e.g. Refs. 16–18), propagation of Coulomb stress perturbations (e.g. Refs. 19, 20) transient thermoelastic effects (e.g. Refs. 21, 22) or shear slip stress transfer.[23]

Seismicity caused by the withdrawal of oil or gas from deep permeable reservoirs, i.e. by a reduction in P_f, has received significantly less scientific attention, although important models for production-induced fault reactivation within or in vicinity to reservoirs were proposed in the last three decades. For instance, Pennington et al.[24] proposed that elastic strain accumulates along fault segments bounding reservoir compartments due to compaction of the reservoir rocks related to production. Segall[25,26] proposed that stress changes in the region surrounding a depleting reservoir may destabilize faults at some distance to the reservoir. Segall & Fitzgerald[27] demonstrated that fault loading and reactivation within the reservoir or in the hosting rocks depends strongly on the geometry of the reservoir, and on the rock mechanical parameters controlling the ratio of stress and pore fluid pressure changes.

However, all available analytical solutions are restricted to simple reservoir geometries and limited by assumptions of zero lateral strain or homogeneous distribution of material properties. Such solutions are incapable to solve for the production-induced strain field that arises from interaction with structural complexities in compartmentalized reservoirs. For instance, stress concentration related to offset of producing reservoirs along intra-field faults,[28,29] or juxtaposition of reservoir rocks with different mechanical properties at field-bounding faults cannot be addressed by any analytic solution.

Altmann et al.[18] affirmed that poroelastic stress changes, as predicted by Rudnicki's[30] analytic solutions for continuous fluid extraction from a poroelastic full-space, are matched by finite element simulations. Such numerical models have shown to be valuable tools to study production-induced stress redistributions considering complex reservoir geometries and rock property distributions. For instance, Orlic & Wassing[29] used finite element methods to simulate stress changes and fault slip in faulted reservoirs, and such overlain by elastic and viscoelastic caprocks in the Dutch part of the North German Basin. Their results clearly highlight the importance of reservoir geometry for production-induced stress redistribution.

Production-induced seismicity has been observed in hydrocarbon fields worldwide, but recurring events have only been recorded in a small number of basins in which only few fields are pertained. The majority of worldwide oil and gas fields remains seismically quiescent.[1,31,32] Production-induced seismicity has been reported for the largest gas field in Western Europe, the Groningen field in the Netherlands and some smaller gas fields in the Lower Saxony region, Germany, also hosted by Rotliegend reservoir rocks. In both cases, first seismic events occurred about 2–3 decades after onset of hydrocarbon extraction.[33,34]

In Groningen, production started in the early 1960's, and first seismicity was recorded in 1991. Since then, 271 seismic events with Mw > 1.5 have been recorded until 2016.[35] Many geomechanical studies have been published that address the mechanisms of production-induced seismicity encountered in the Groningen field (e.g. Refs. 3, 28, 29, 36, 37). Bourne et al.[38] proposed that reservoir compaction observed as subsidence at the surface is the main mechanism that drives fault reactivation.

Differential compaction and offset along intra-field faults along with superposition of induced stress changes have been proposed as important factors for fault reactivation in production-induced seismicity (e.g. Refs. 28, 29), as well as for the assessment of fault stability in CCS operations.[39] Production from offset reservoir horizons induces non-continuous strain fields and moments across the fault, in the simplest case due to offset along the fault. However differences in displacement, frequently referred to as 'differential compaction'[3,28,40,41] can relate either to differences in total production, in production rates, reservoir thicknesses, elastic and poroelastic properties, or a combination of these parameters.

In Lower Saxony 77 seismic events with magnitudes between $M_L \approx 0.5$ and probably up to $M_L \approx 4.3$–4.4 associated to active gas fields have been recorded hitherto.[33] A similar suite of geomechanical models as available for the Groningen gas field is still missing for production-induced seismicity encountered in Lower Saxony, presumably due to the significantly higher recurrence intervals of seismic events (i.e. larger time span between two events of similar magnitude).[33,42]

A special feature of the Rotliegend gas fields in Lower Saxony is the variable thickness of the overlying Zechstein salt unit which ranges between a few metres and several kilometres (e.g. Ref. 43). This salt diapirism may cause a non-uniform overburden load to the Permian subsalt graben system in northern Germany. For instance Hoetz et al.[44] explain the increase of seismic velocities in the vicinity of salt welds by a simple "brick in the bath-tub" model predicting pronounced vertical loading in horst blocks below or next to thinning and welding salt layers. Recent publications address the numerical modelling of stresses in suprasalt formations adjacent to salt diapirs,[45–47] but the subsalt stress state remains widely unconstrained.

Apart from the non-homogeneous overburden load exerted by diapiric salt layers to underlying reservoirs, Orlic & Wassing[29] demonstrated that the presence of a viscoelastic caprock in direct vicinity of producing reservoirs modifies the pattern of production-induced stresses and thereby enhances fault slip. In addition their modelling results propose that production-induced shear stress relaxation can continue and affect fault stability long after production has ended.

The present publication deals with the quantitative understanding of the factors that affect production-induced stress changes and seismicity in Rotliegend gas fields located in Lower Saxony, Germany. For that, we present a series of 2D Finite Element models to investigate a parameter space for reservoir depth, reservoir thickness, mechanical reservoir and host rock properties, and compartment geometries typically observed in North German gas fields. The impact of salt diapirism on the subsalt reservoir stress state is addressed in an individual section. Our focus is on stress changes and fault loading in terms of shear and effective normal stresses, and not on the mechanical response of a fault to loading. Thus, it is important to notice that in no means our approach is applicable for earthquake prediction neither in space nor in time. Instead, the focus of this work is on development of a first-order understanding of the impact of factors on fault loading associated to pore fluid pressure decrease for the conditions specific to the North German basin.

2. Stress changes with pore fluid pressure depletion

In the following, compressive normal stresses and pore fluid pressures are denoted by positive values, as commonplace in geoscience. Absolute components of the stress tensor are written as σ_{ij}, and effective stress tensor components (Eq. (3)) are indicated by σ'_{ij}. Kronecker's δ_{ij} discriminates normal and shear stress components of the stress tensor, thus $\delta_{ij} = 1$ when $i = j$, and $\delta_{ij} = 0$ when $i \neq j$.

The theory of poroelasticity mainly formulated by Biot[48] predicts coupled changes of total stress with changes in pore fluid pressures P_f. Pore fluid pressure–stress coupling is obvious from series of in-situ stress measurements by hydraulic fracturing tests[49–51] performed at different stages of depletion, as, for instance, compiled by Ref. 18. Apart from in-situ measurements, coupling factors can be derived by differentiation of Eq. (1) which