Modelling induced seismicity in Groningen based on subcritically stressed faults and time-dependent stress response

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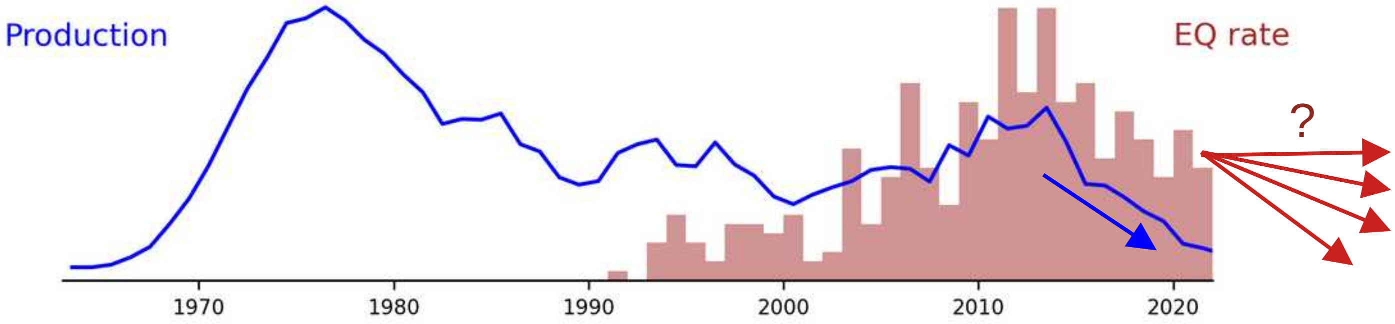

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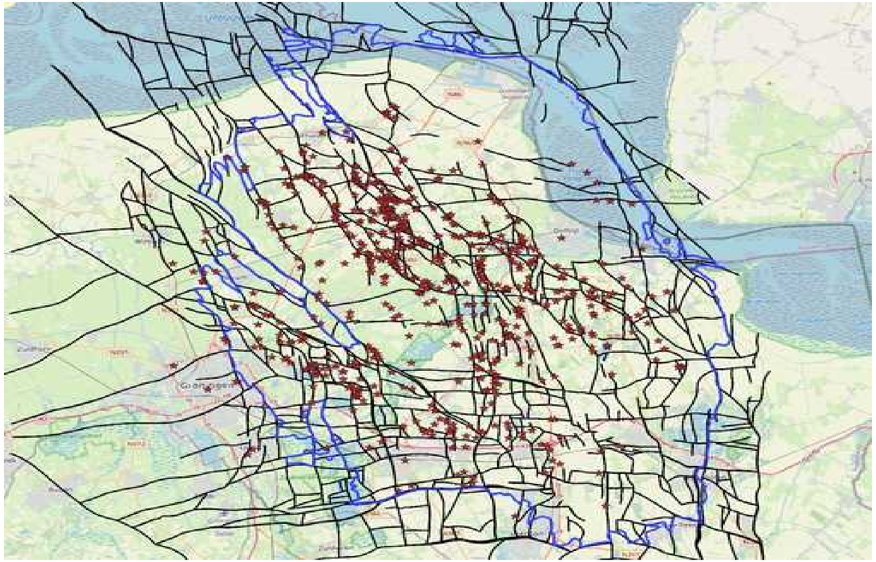
Hainzl et al. GJI (2025)

Universität Potsdam

Groningen is Europe’s largest gas field which is now shutdown

… but earthquake activity continues and appropriate seismicity models are required for seismic hazard assessment.



Many existing models:
(see review of Kühn et al. NJG 2022)

Coulomb-Failure models
(e.g. Bourne & Oates, 2017, 2018, Dempsey & Suckale 2017, 2023, Smith et al. 2022)

Rate-State models
(e.g. Candela et al. 2019, Richter et al. 2020, Acosta et al. 2023)

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+ borehole / field / lab data


We apply the new Time Dependent Stress Response (TDSR) model

Dahm & Hainzl, JGR 2022

because

... Coulomb Failure (CF) models assume unrealistic, instantaneous failure

... Rate-State (RS) models cannot account for realistic, subcritical initial stress conditions

TDSR builds on:

(i) time-to-failure is an exponential function of stress

(ii) a given initial stress distribution

$$\overline{t_f} = t_0 \exp\left(\frac{-(S-C)}{A_\sigma}\right)$$

with S: Coulomb Failure stress
C: threshold/cohesion
t_0: $\overline{t_f}$ for $S=C$
A_σ: sensitivity parameter

$\Rightarrow$ CF = $\lim_{A\sigma \to 0}$ TDSR

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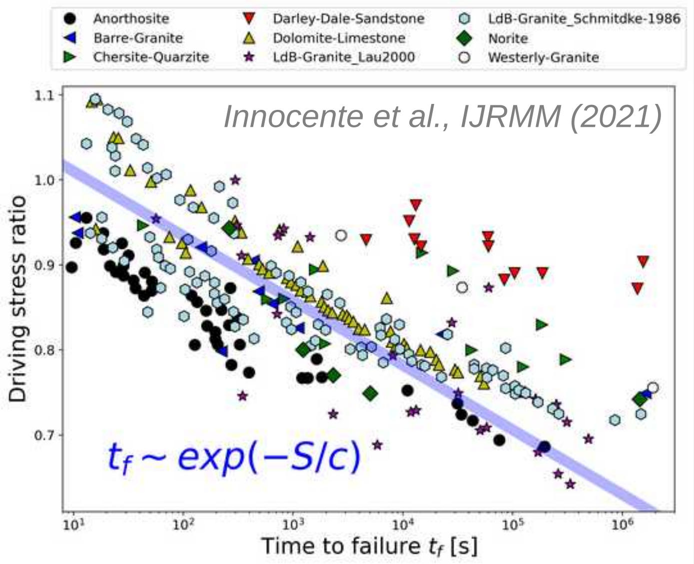
Rock experiments



Rate-State friction

Single fault: $t_f \sim \exp\left(-\frac{S}{A\sigma}\right)$

(Eq. A7 & A14, Dieterich 1994)

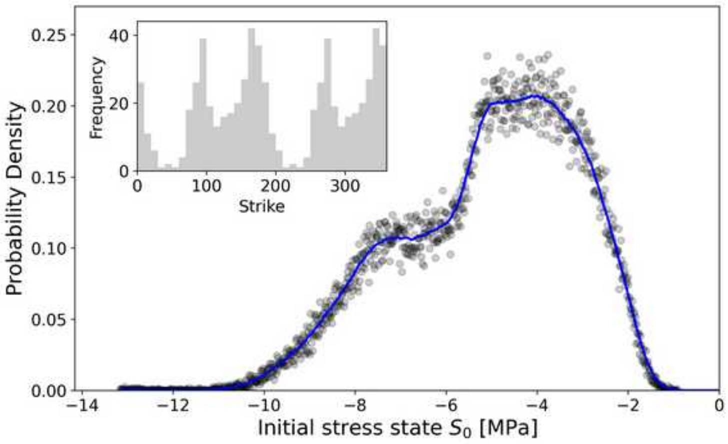
RS model (fault population):

Specific constraint: The initial condition is set that a constant (tectonic) stressing rate leads to a constant seismicity rate („critical initial stress“).

TDSR … reproduces the RS solutions for critical initial stress,

… but can also simulate the RS of fault populations with subcritical initial stress distribution!

Application to Groningen

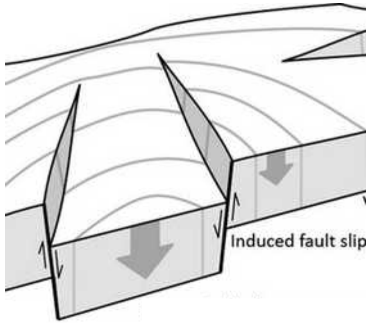


Initial stress condition:

- regional stress field (KEM-24, 2022)
- friction coefficient 0.59-0.62 (Hunfeld et al. 2017)
- cohesion: 7 MPa (KEM-24, 2022)
- fault strikes (Dempsey & Suckale 2017)
- fault dip 78° +- 7° (Kartekaas & Jaarsma 2017)

Elastic thin sheet model:

(Bourne & Oates, JGR 2017)



$\Delta S(t) = - f \, \Delta p(t)$ with $f = -\mu + \alpha \frac{1-2\nu}{2(1-\nu)}\left(\mu + \sqrt{1+\Gamma^2}\right)$

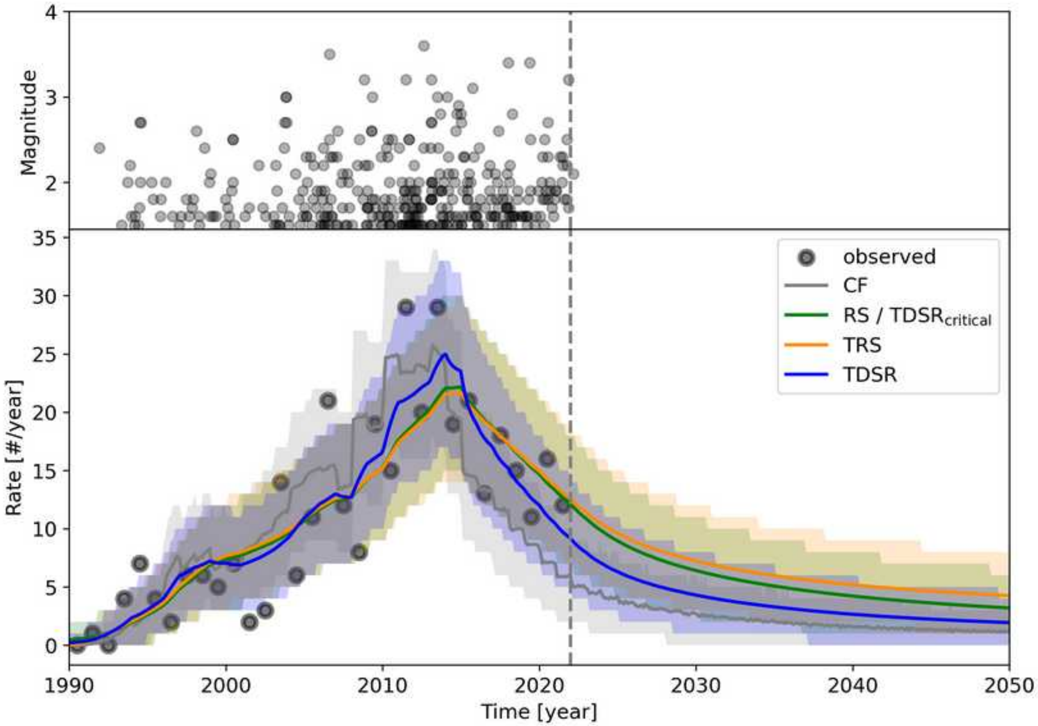
(friction coefficient μ, Biot’s constant α, Poisson ratio ν & spatial gradient Γ)

Pore pressure evolution Δp(t):

(NAM reservoir model, https://doi.org/10.24416/UU01-RHHRPY)

+ fault density and reservoir thickness

Results: Model comparison using maximum likelihood fits



CF: Coulomb Failure model (f, X_0)
… with initial stress distribution

RS: RS model (r, $A\sigma$, t_a)
(Dieterich 1994)

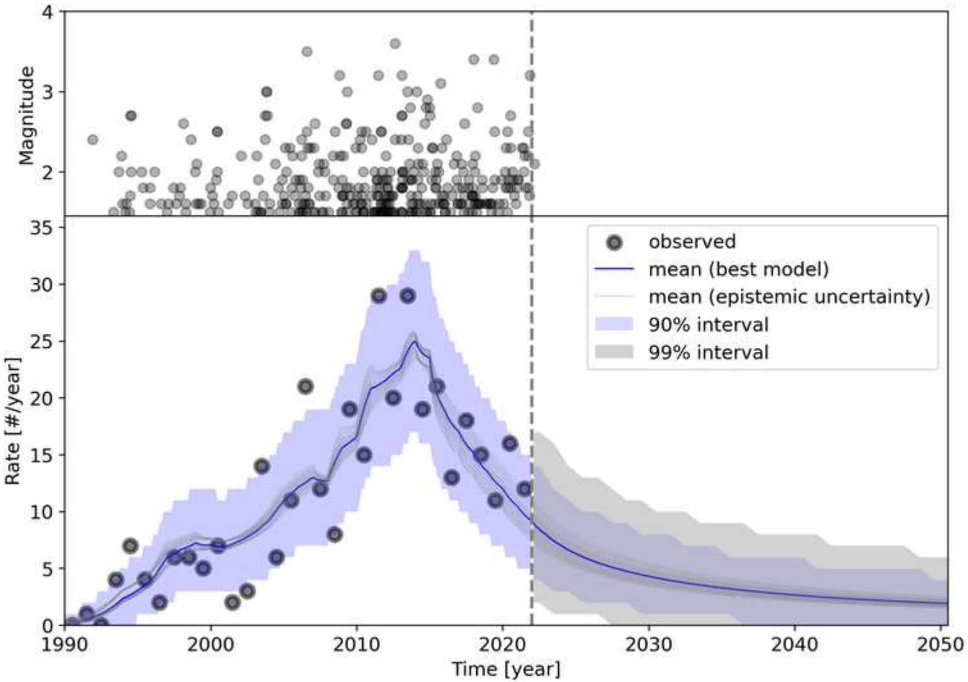
TRS: Threshold RS model (r, $A\sigma$, t_a, ΔS)
(Heimisson et al. 2022)

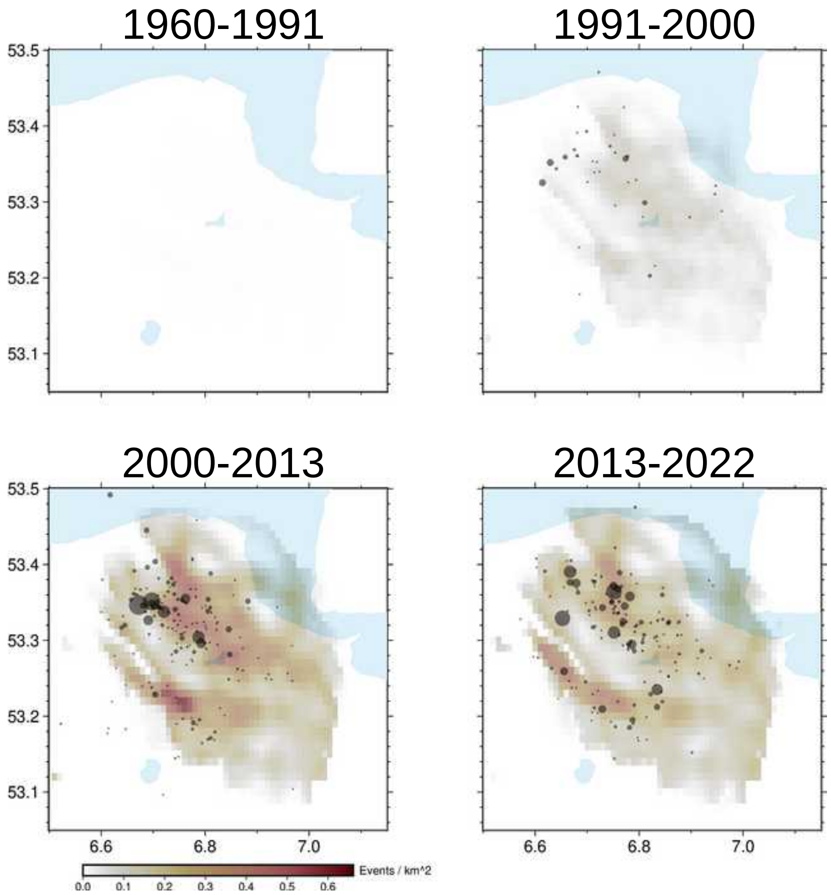
TDSR: This study (f, $X_{0,}$ A_σ)
… with initial stress distribution

AIC values:

TDSR yields best fit

Results: Spatiotemporal TDSR forecast





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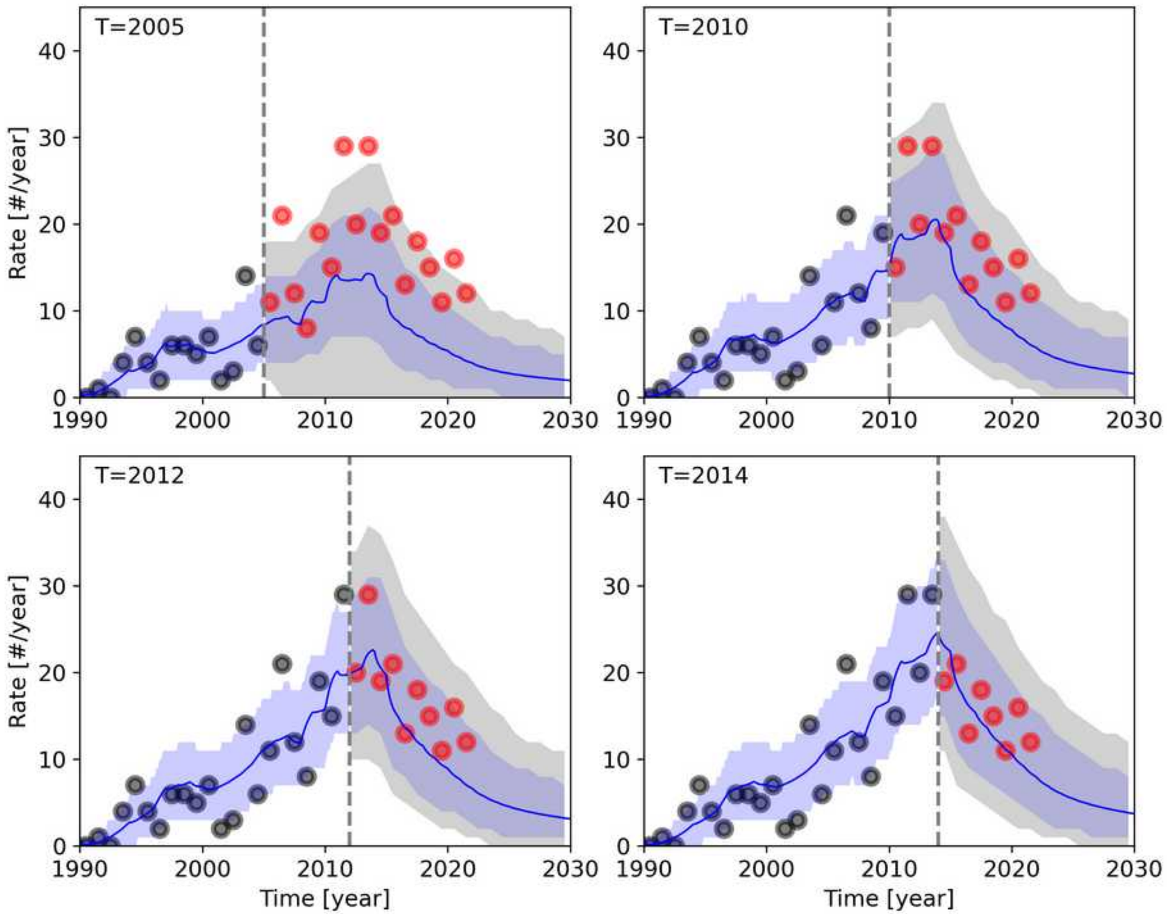
Result:
Forecast experiment

... using only m>1.5 earthquakes until time T to calibrate model parameters



mean rate
90% confidence
99% confidence
Eqs in fit period
Eqs in forecast period

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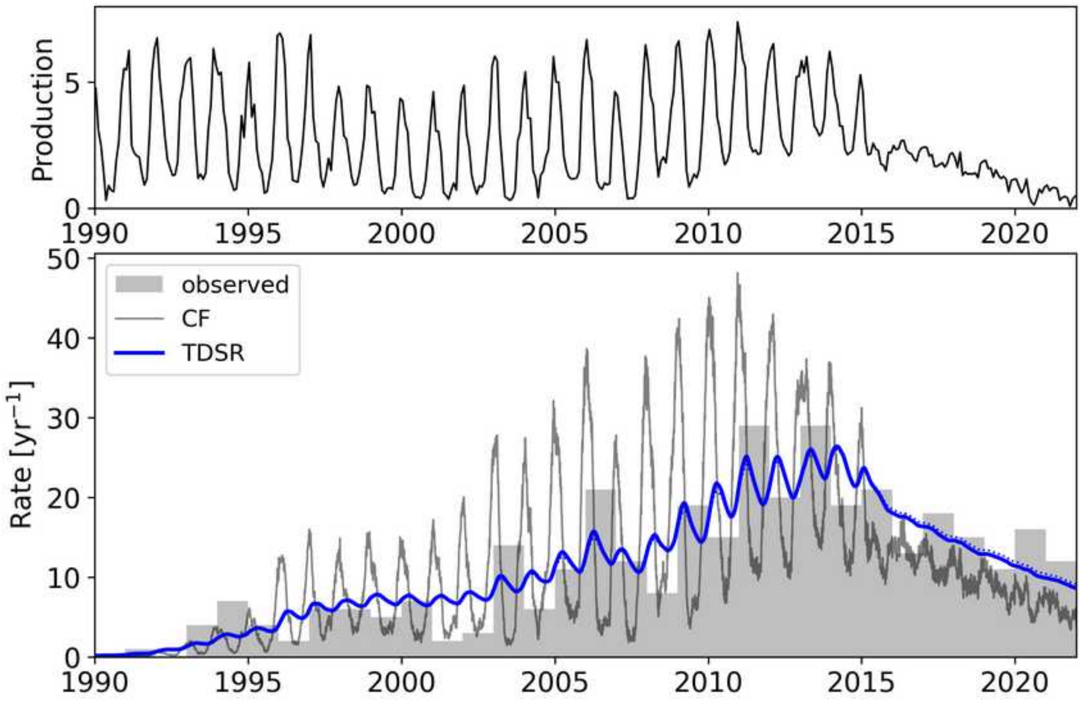
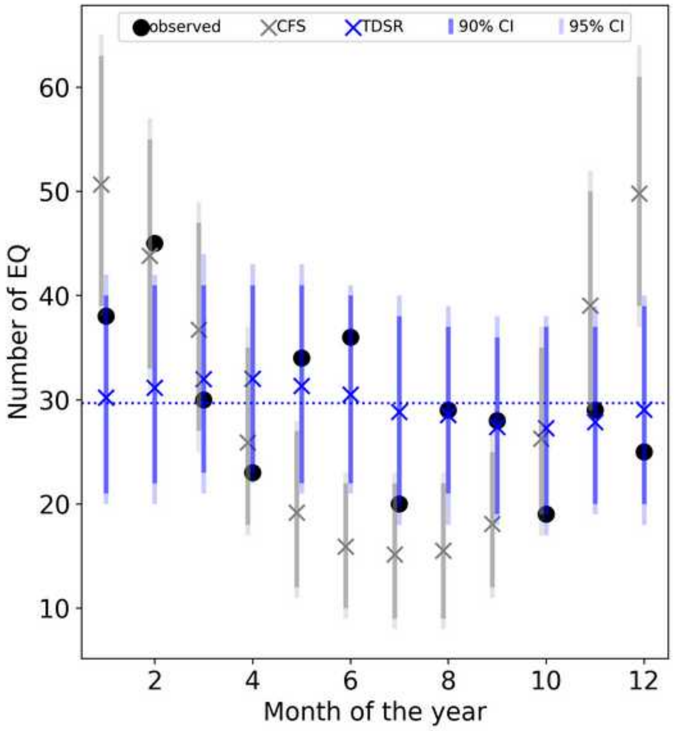
TDSR reproduces seasonality while CF does not do it.





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Summary

- An exponential dependence of the time-to-failure on stress is observed for
  (i) lab experiments for intact rock under constant stress and
  (ii) frictional nucleation of earthquakes.
- TDSR explicitly builds on it and can consider realistic initial conditions, not limited to specific conditions such as RS & TRS.
- Rock experiments and in-situ stress/fault data can be used to constrain forecasts.
- Application to Groningen shows good forecasting ability based only on a few free parameters.
- Seismicity in Groningen will continue in the next decades.

More details:

Hainzl et al., Modelling induced seismicity in Groningen based on subcritical stressed faults, GJI 241, 840–851 (2025). https://doi.org/10.1093/gji/ggaf064

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