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

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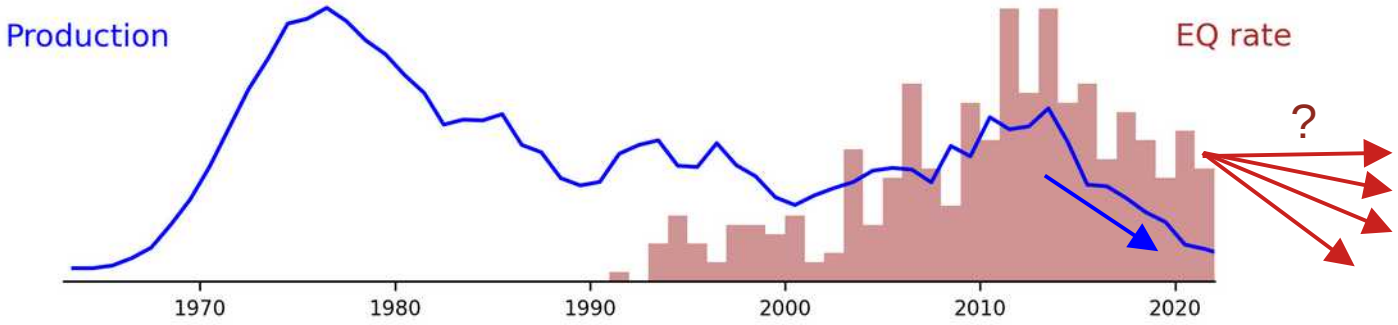

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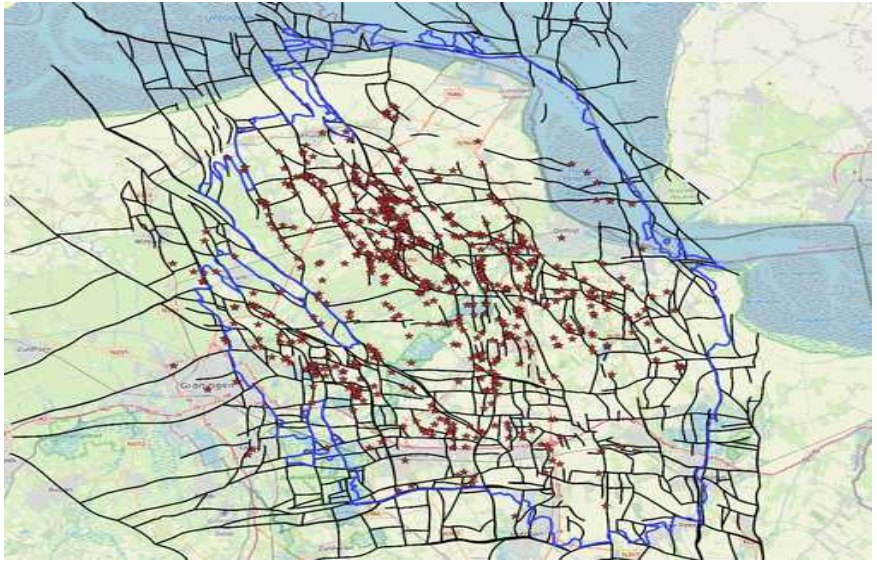
Hainzl et al. GJI (2025)

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

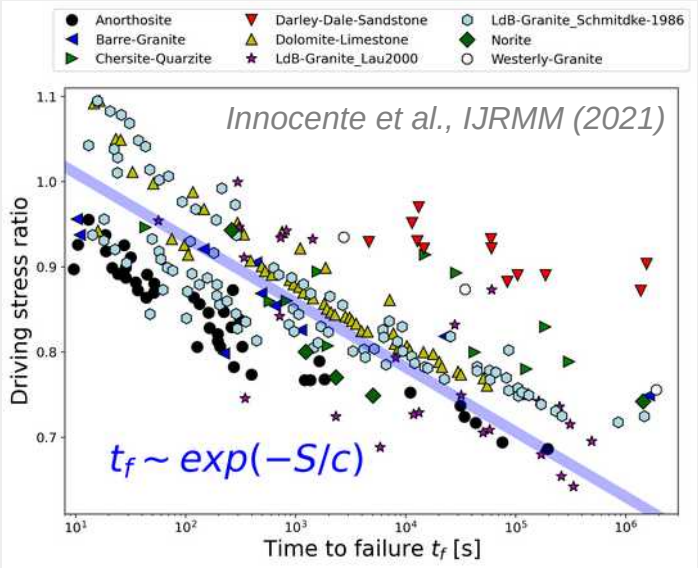
(ii) a given initial stress distribution

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

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

⇨ CF = $\lim_{A\sigma \to 0}$ TDSR

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“).

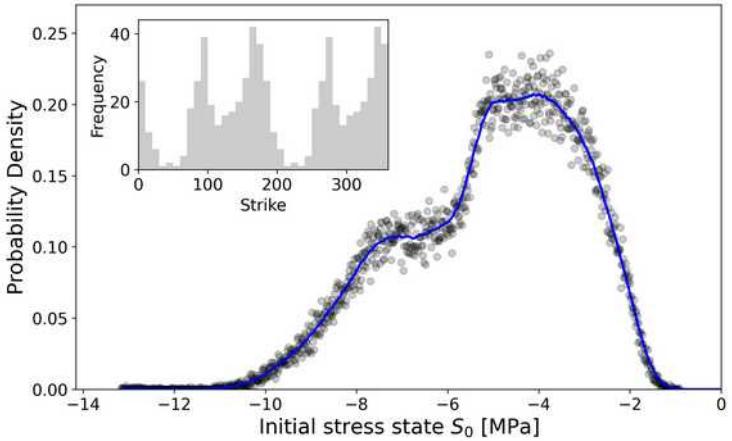
TDSR ... reproduces the RS solutions for critical initial stress,

... 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)

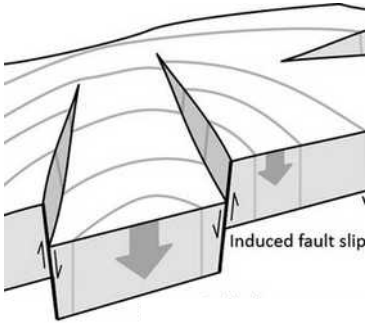


Elastic thin sheet model:

(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

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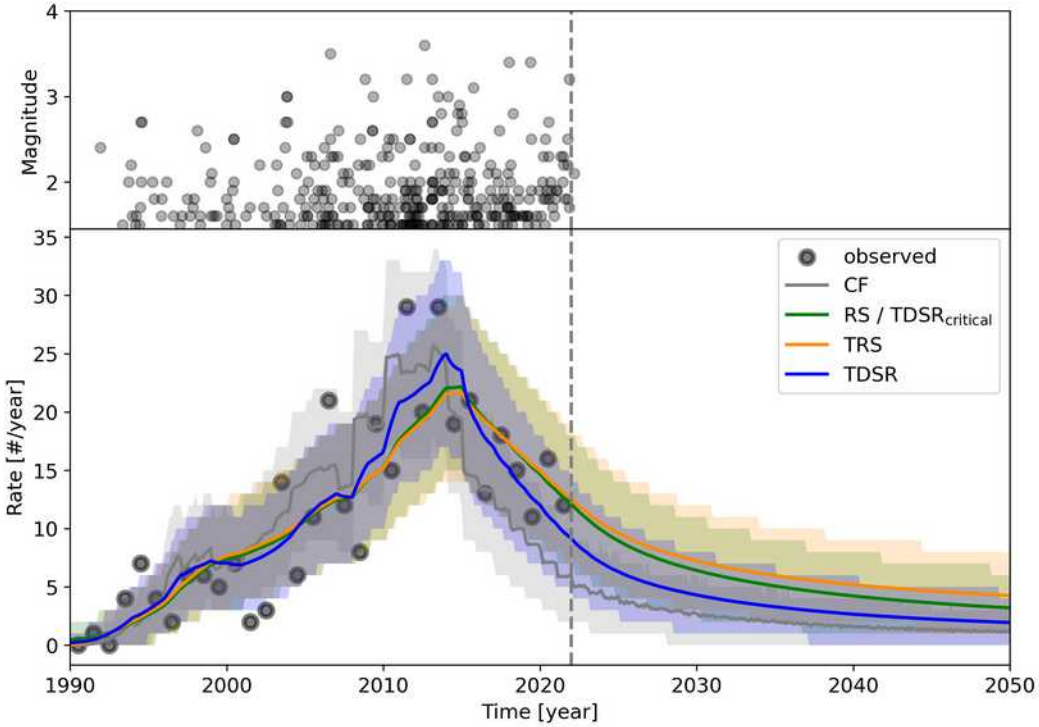
Results: Model comparison using maximum likelihood fits



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

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

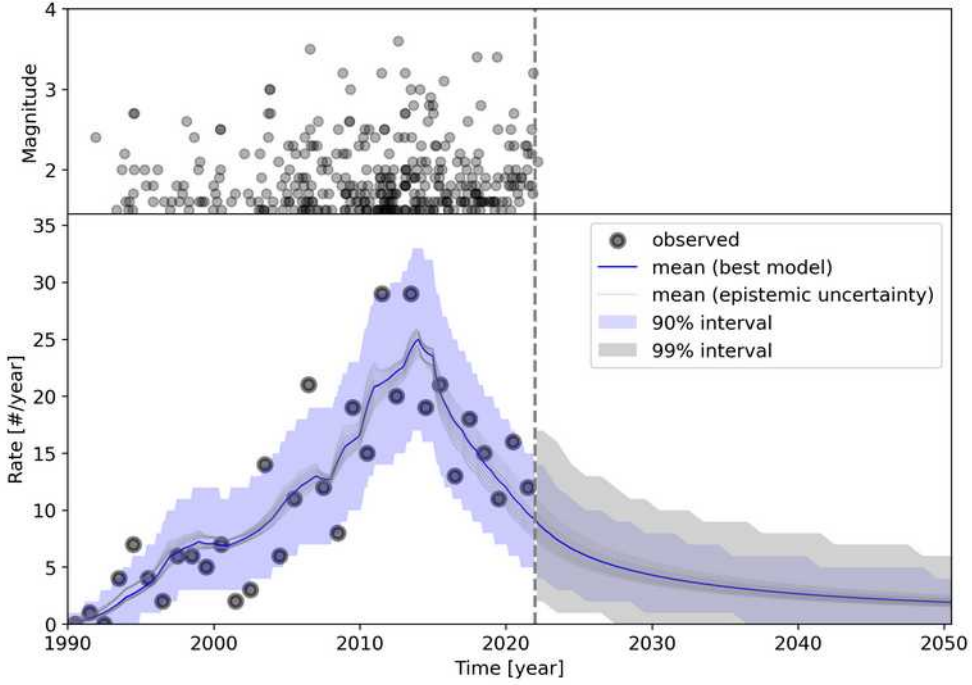
TRS: Threshold RS model (r, $A\sigma$, t_a, ΔS)
(Heimisson et al. 2022)

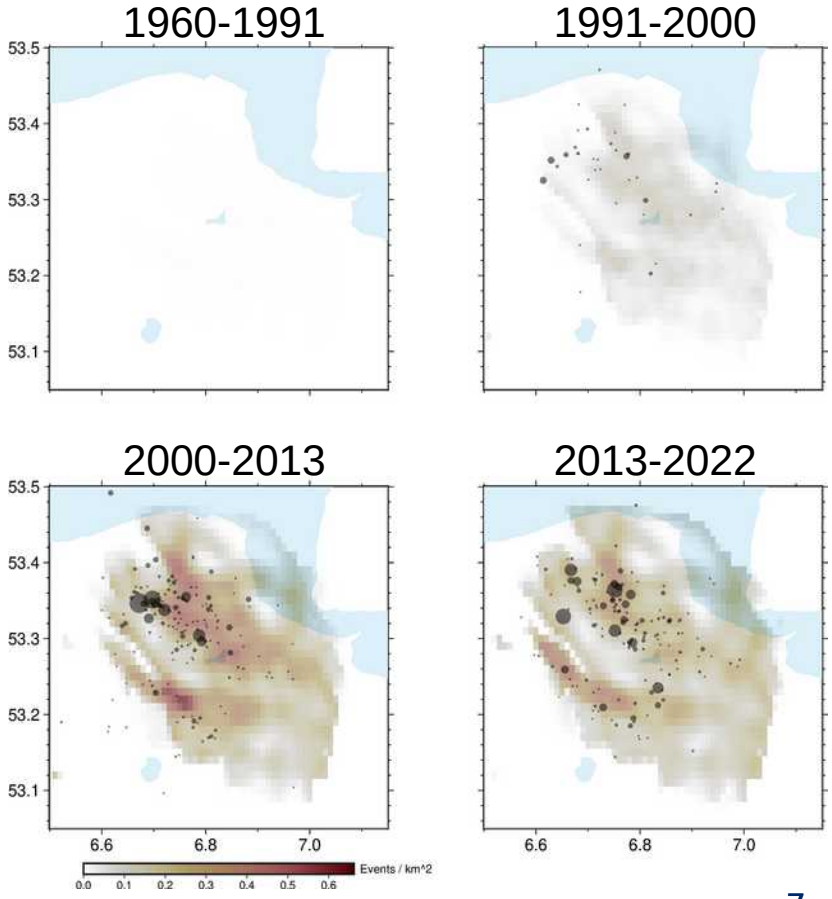
TDSR: This study (f, X_0, A_σ)
… with initial stress distribution

AIC values:

TDSR yields best fit

Results: Spatiotemporal TDSR forecast





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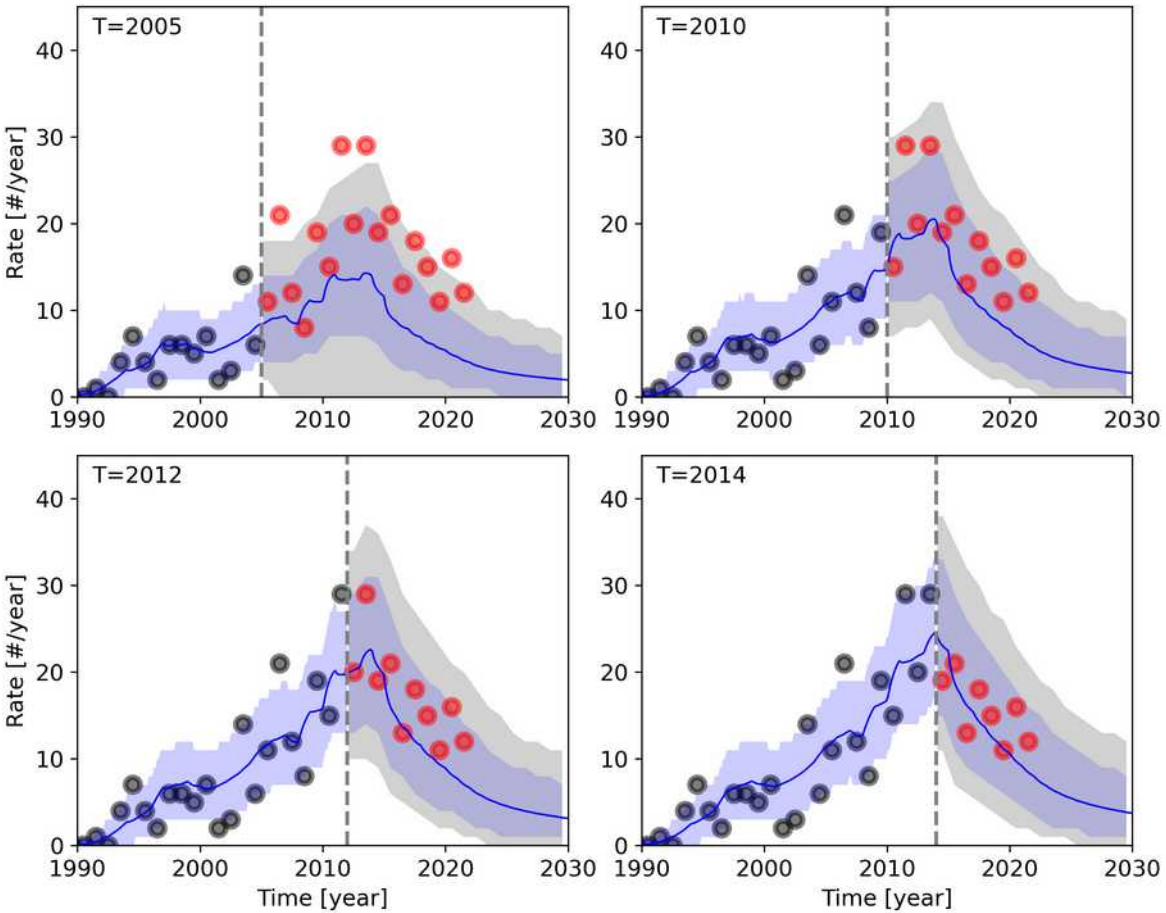
Result:
Forecast experiment

… 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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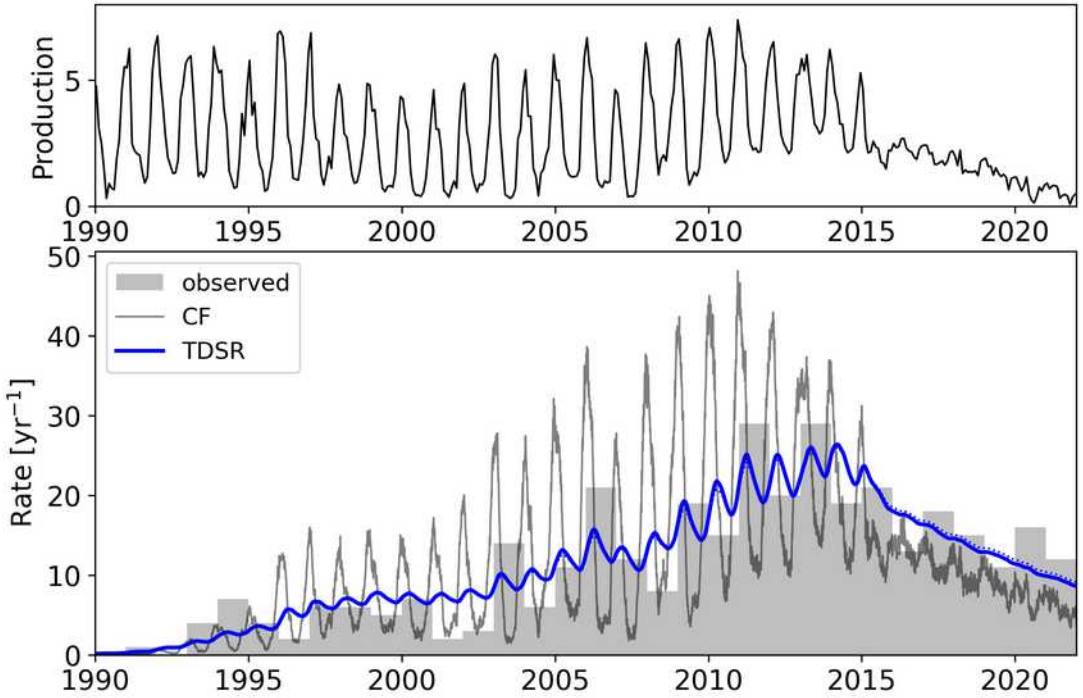
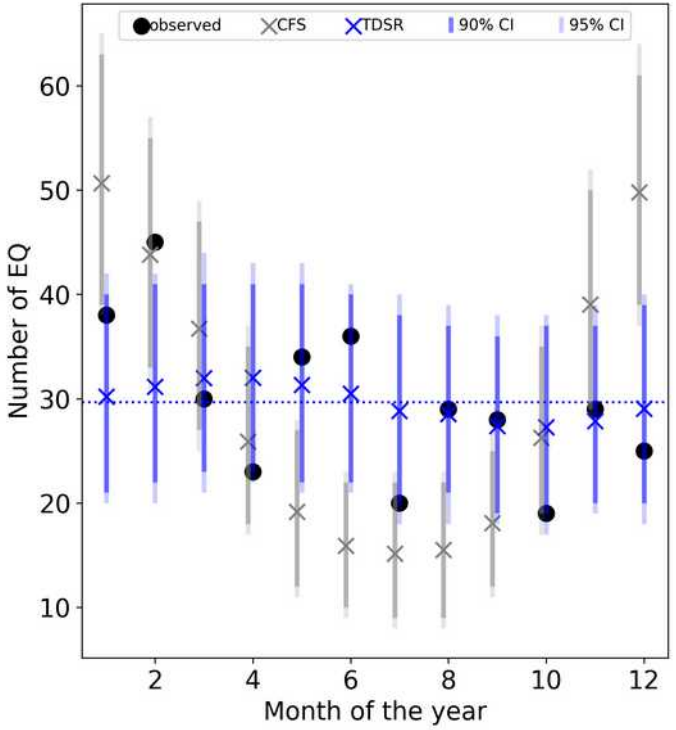
TDSR reproduces seasonality while CF does not do it.





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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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