SAND2016-12324C

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On subsurface fracture opening and closure

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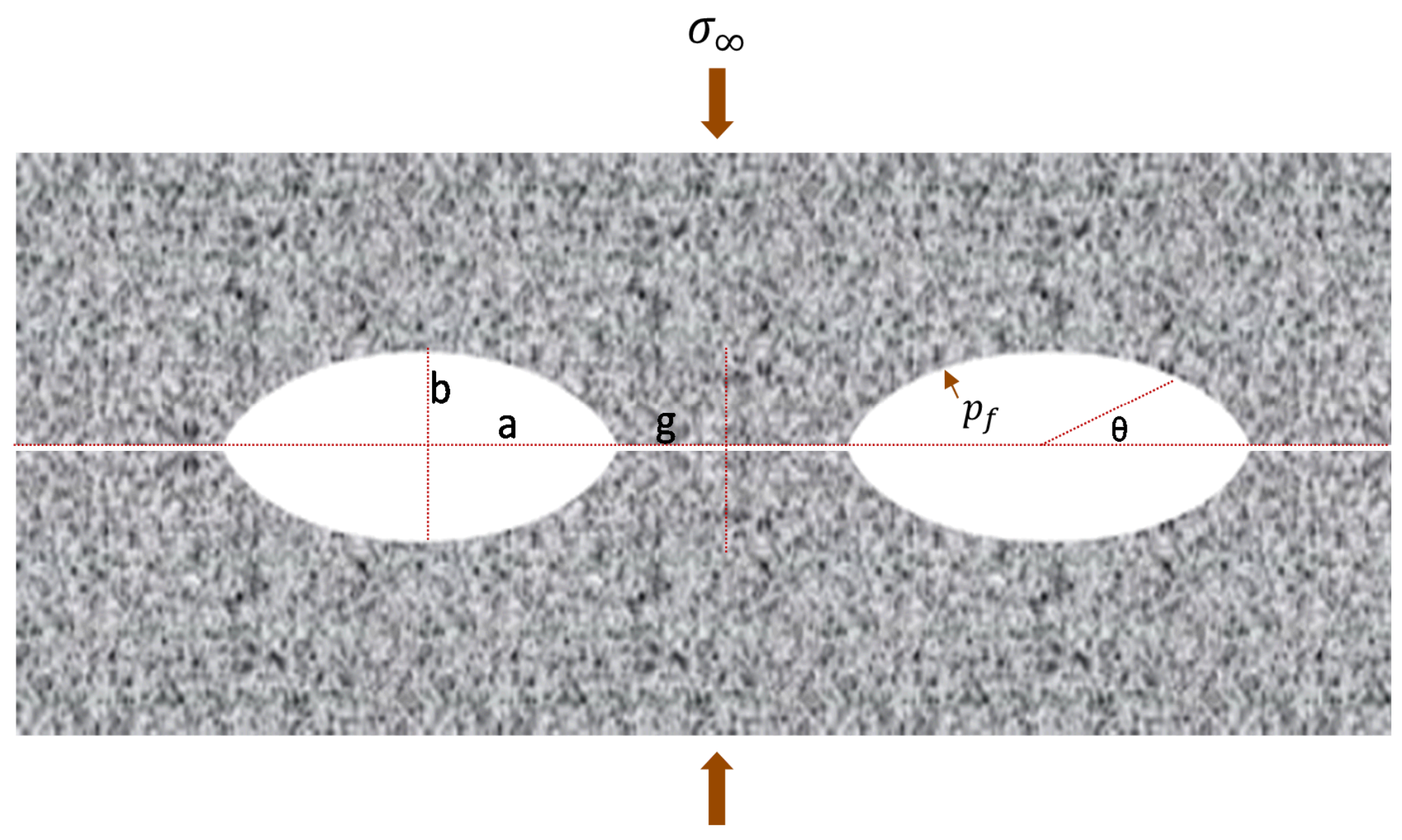
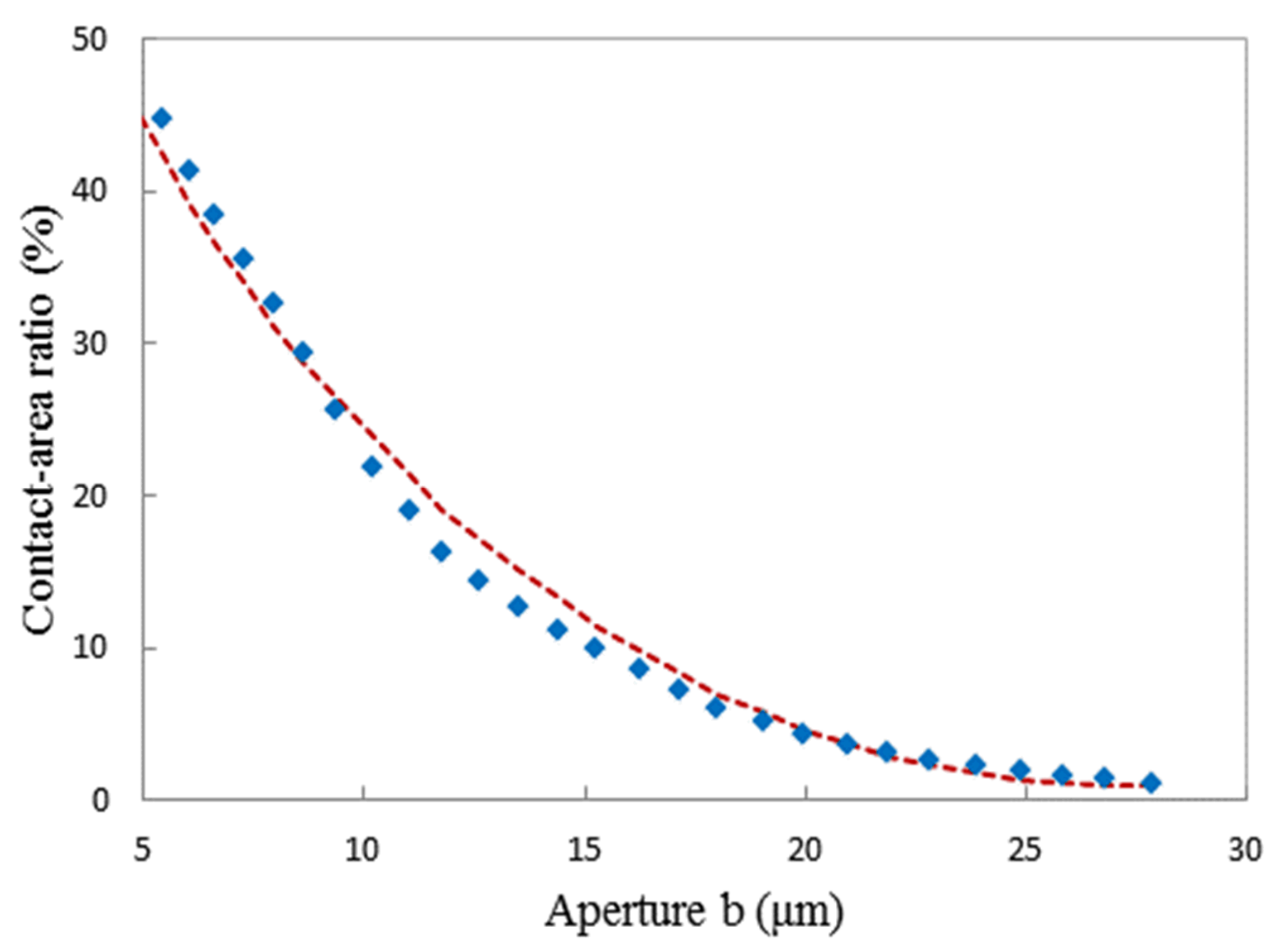
ABSTRACT

Understanding of subsurface fracture opening and closure is of great importance to oil/gas production, geothermal energy extraction, radioactive waste disposal, and carbon sequestration and storage. Fracture opening and closure involve a complex set of thermal, hydrologic, mechanical and chemical (THMC) processes. In this paper, a fully coupled THMC model for fracture opening and closure is formulated by explicitly accounting for the stress concentration on aperture surface, stress-activated mineral dissolution, pressure solution at contacting asperities, and channel flow dynamics. A model analysis, together with reported laboratory observations, shows that a tangential surface stress created by a far-field compressive normal stress may play an important role in controlling fracture aperture evolution in a stressed geologic medium, a mechanism that has not been considered in any existing models. Based on the model analysis, a necessary condition for aperture opening has been derived. The model provides a reasonable explanation for many salient features of fracture evolution in laboratory experiments, including a spontaneous switch from a permeability reduction to a permeability increase in a static limestone experiment. The work may also help develop a new method for estimating in-situ stress in a reservoir.

A fracture plane is represented by stripes of contacting areas (asperities) surrounded by aperture channels The cross section of an individual aperture channel is described by a truncated ellipse defined by the intersection of two identical ellipses.





At a fracture contact, the chemical potential of the solid can be expressed as:

$$\mu_s = \mu_s^0 + \frac{1}{2}(\sigma_c^n + \sigma_c^t)v_s + \Delta G_s(contact)$$

At the aperture surface, the chemical potential of the solid at a specific point can be described by:

$$\mu_s(\theta) = \mu_s^0 + \frac{1}{2}[\sigma_p^n(\theta) + \sigma_p^t(\theta)]v_s + \Delta G_s(\theta)$$

Based on the transition state theory, the dissolution rate at an aperture surface can be described by:

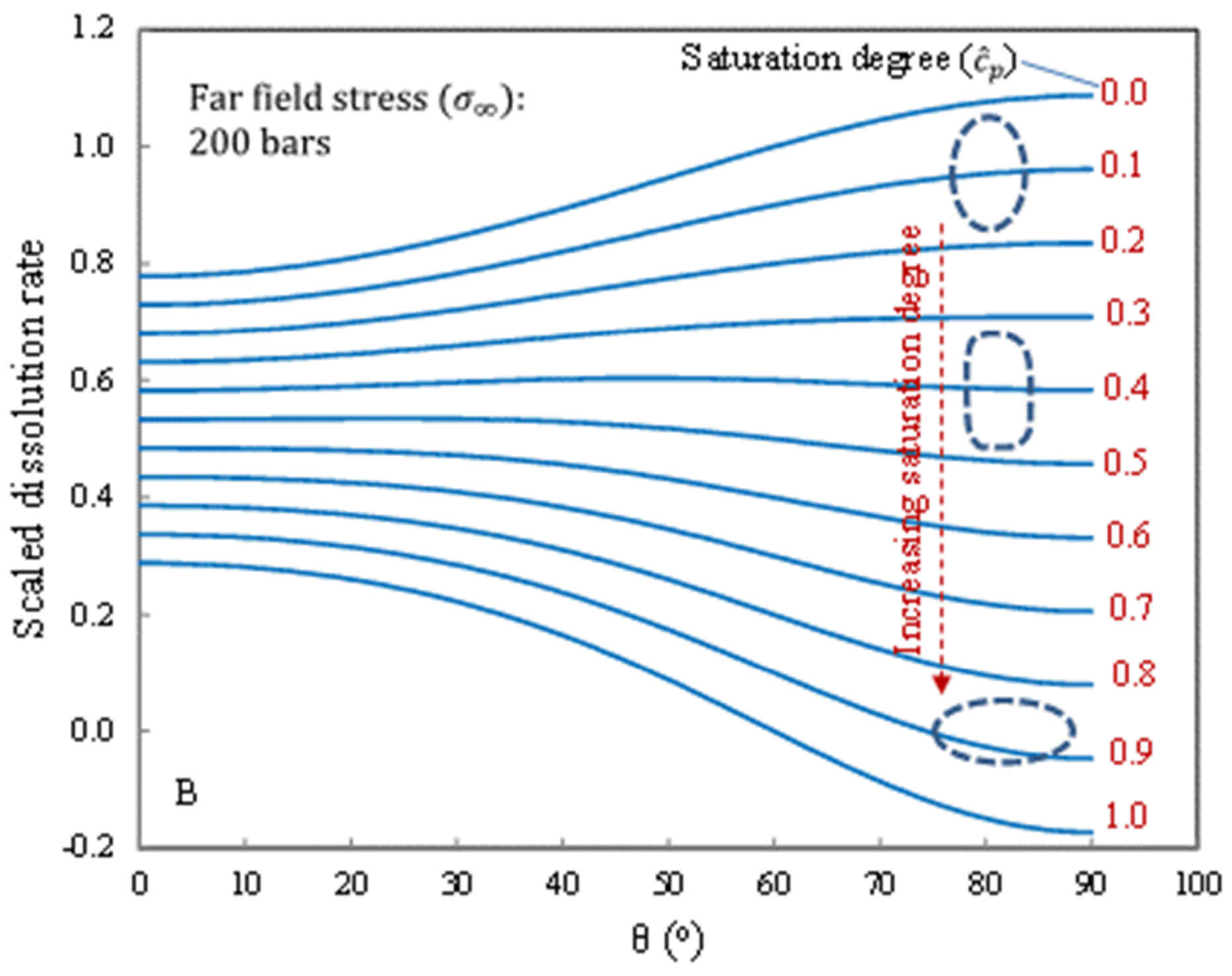
$$R(\theta) = ke^{-\frac{\Delta G^{\#}+\sigma_p^t(\theta)v^{\#}}{RT}}\left(1 - e^{-\frac{A_p}{RT}}\right)$$

$$= ke^{-\frac{\Delta G^{\#}+\sigma_p^t(\theta)v^{\#}}{RT}}\left[1 - \frac{C_p}{K(\theta)}\right]$$

where k is the reaction rate constant; $\Delta G^{\#}$ is the activation energy to account for the temperature effect on the reaction rate; $v^{\#}$ is the activation volume to account for the effect of surface stress on the reaction rate; and $K(\theta)$ is the equilibrium constant of the dissolution reaction under stress:

$$K(\theta) = e^{\frac{\mu_s^0 - \mu_a^0 + \left\{\frac{1}{2}\left[\sigma_p^n(\theta)+\sigma_p^t(\theta)\right] + \beta\left[\sigma_p^n(\theta)^2 + \sigma_p^t(\theta)^2\right]\right\}v_s - p_f v_a}{RT}}$$

Model prediction



Experimental observations

Material & solution	Axial load (bars)	Hole shape
In salt solution		
Salt undersaturated 1	30	Flattened circle
Salt undersaturated 2	12	Flattened circle
Salt undersaturated 3	13	Flattened circle
Salt saturated 1	15	Ellipse perpendicular
Salt saturated 2	14	Ellipse perpendicular
	In dilute hydrochloric acid	
Solenhofen limestone 3	129	Ellipse parallel
Solenhofen limestone 4	66	Ellipse parallel
Solenhofen limestone 6	45	Ellipse perpendicular
Oak Hall limestone 1	297	Ellipse perpendicular
Oak Hall limestone 3	324	Ellipse perpendicular
Oak Hall limestone 4	170	Ellipse perpendicular
Oak Hall limestone 5	262	Ellipse perpendicular
Kasota limestone	59	Ellipse perpendicular
Marble 1	220	Flattened circle
Marble 2	187	Flattened circle
Marble 3	91	Flattened circle
Water lime 1	48	Irregular
Water lime 1	42	Irregular
Water lime 1	29	Irregular
Chalk 1, Kansas	39	Irregular
Chalk 2, Kansas	24	Irregular

A necessary condition for fracture opening is:

$$\frac{2g^2 k\sigma_\infty^\gamma}{\lambda K_{eq} D f_c^\gamma} > 1$$

The favorable conditions for fracture opening would include: a low solubility of the mineral (K_{eq}), a high reaction rate constant (k), and large contact areas (g).

CONCLUSION

A dynamic model for subsurface fracture opening and closure has been formulated. The model explicitly accounts for the stress concentration around individual aperture channels and the stress-activated mineral dissolution. It has been demonstrated that the surface stress-activated dissolution may play an important role in subsurface fracture evolution. Based on a model analysis, a necessary condition for fracture opening has been derived. The proposed model is able to explain key features of fracture evolution in laboratory experiments. The geologic implications of the model results have been discussed. The work presented here may help to develop a new method for estimating in-situ stress in a reservoir.

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