Episodic mineralising fluid injection through chemical shear zones

Thomas Poulet *
CSIRO Mineral Resources
Sydney, Australia
thomas.poulet@csiro.au

Sotiris Alevizos
UNSW Petroleum Engineering
Sydney, Australia
s.alevizos@unsw.edu.au

Manolis Veveakis
UNSW Petroleum Engineering
Sydney, Australia
e.veveakis@unsw.edu.au

Victor Boussange
INSA Lyon
Villeurbanne, France
victor.boussange@insa-lyon.fr

Klaus Regenauer-Lieb
UNSW Petroleum Engineering
Sydney, Australia
klaus@unsw.edu.au

SUMMARY

The nature of the geological mechanisms allowing mineralising fluids to flow from depth and form localized mineral deposits is uncertain and a matter of debate. Traditional assumptions of fluids travelling through highly permeable faults raise interesting questions about the existence of highly permeable faults at depths below the brittle-ductile transition, for example. A recent model of multi-physics oscillation can explain the behaviour of impermeable shear zones in such environments, under specific conditions where temperature sensitive endothermal reactions trigger in-situ release of fluids that lubricate the fault and lead to their reactivation. The response of such systems can be of various nature, including slow creep, one-off reactivation events, or episodic reactivation events during which the permeability increases by several orders of magnitudes and allows fluids from depth to flow upwards. In this contribution, we review briefly the previous studies on this chemo-mechanical oscillator and place the findings in the context of mineral exploration. We extend the parameter sensitivity analysis to the main two dimensionless parameters controlling the chemical reactions, the Arrhenius and Damköhler numbers, to understand how they affect the location of episodic slip instabilities in the global parameter space. We show that lower values of the Damköhler number reduce the range of Gruntfest values in which the oscillator operates and we propose some fitting relationships between the main parameters in various interesting areas of the parameter space.

Key words: episodic instability, chemo-mechanical oscillator, modelling, parameter sensitivity analysis.

INTRODUCTION

The formation of large mineral deposits is now widely recognised as a relatively fast process from a geological perspective (Cox, 2016). The involved timeframes could be as short as 10^4 to 10^5 years to accumulate fault-hosted lodes (Cox, 2016), with some researchers proposing even shorter periods of thousands of years or less to form 5 Moz goldfields (Micklethwaite, et al., 2015). Such timeframes are linked to the very localised nature, both spatially and temporally, of the controlling mechanisms involved. Fluids and mineralisation processes have been conceptionally pictured as "inverted lightning rods" from depth (Hronsky, et al., 2012) . Episodic fault slip events (Cox, 2016) involving highly-pressurized fluids (Sibson, et al., 1988) have been invoked. As such, shear zones and faults are of high interest, recognised for their transient enhancement of permeability (Rojstaczer, et al., 1995). Sibson (1981) described early on with his "fault-valve" model the coupling between fluid-pressure and permeability responsible for the opening of fluid pathways in very low permeability rocks. In between slip events, the partial to complete sealing of those fault zones can occur by precipitation of hydrothermal minerals (Cox, 2016). Slip events can increase the permeability by five to ten orders of magnitude (Ingebritsen & Manning, 2010) and this dynamic permeability (Cathles & Adams, 2005) leads to time-integrated permeability values high enough to form giant ore deposits from small volumes of metal-rich fluids (Wilkinson, et al., 2013).

The dynamics of hydrothermal ore systems is then fundamentally linked to these episodic slip events in faults and shear zones, which have been qualitatively compared to non-equilibrium open chemical reactors (Hobbs & Ord, 2016). A quantitative description of the complex Thermo-Hydro-Mechanical-Chemical couplings taking place in these environments have been formulated as a multi-physics oscillator (Alevizos, et al., 2014) occurring in shear zones under constant stress boundary conditions. This material instability approach applies to fluid-saturated faults under creep by modelling them as temperature- and rate-dependent frictional materials. It accounts for reversible fluid-release through chemical reactions and captures the corresponding excess pore pressure generation, leading to an increase in porosity and therefore permeability. The occurrence of such slip events, turning a sealed fault zone with barely any permeability into an intermittent fluid pathway, is dependent on the numerical values of the material properties and boundary conditions involved in the definition of the underlying system of partial differential equations. A stability analysis (Alevizos, et al., 2014) showed that, depending on those parameters, this system of equations can either lead to a permanent state of episodic slip events, a finite number of slip events, or slow geological creep. In particular, the oscillator regime captures well the permeability evolution of orders of magnitude during slip events (Poulet, et al., 2017), the temporal evolution of episodic tremor and slip events (Poulet, et al., 2014), as well as the corresponding spatial signatures visible now on exposed thrusts (Poulet, et al., 2014), as can be observed in several locations around the globe (see references in (Alevizos, et al., 2017)). A review of the applications of this model can be found in (Veveakis, et al., 2017).

A parameter sensitivity analysis for all parameters involved in the definition of this oscillator is then of critical importance to understand when dynamic instabilities take place. Previous studies have shown that the response of the system is strongly dependent on the values of two parameters: the Gruntfest number (*Gr*) which represents the ratio of characteristic time scales of heat production over energy transfers (Alevizos, et al., 2014), and the Lewis number (*Le*) expressed as the ratio of heat diffusion over mass diffusion (Alevizos, et al., 2016). In this contribution, we focus now on the effect of chemical reactions and present some results about the influence of two of the dimensionless numbers characterising those reactions: the Arrhenius number (Ar_c) defining the activation enthalpy of the effective chemical reaction, and Damköhler number (*Da*) that quantifies the reaction rate with respect to the convective transport rate.

PHYSICAL MODEL

Based on the very localised spatial signature of the chemo-mechanical oscillator (Poulet, et al., 2014), such chemical shear zones can be modelled in 1D across their thickness and their behaviour expressed mathematically as a system of partial differential equations for the temperature T and excess pore pressure ΔP across the shear zone (Alevizos, et al., 2014):

$$\begin{aligned} \frac{\partial \Delta P}{\partial t} &= \frac{\partial}{\partial z}\left[\frac{1}{Le}\frac{\partial \Delta P}{\partial z}\right] + \mu_r Da(1-\phi)(1-s)e^{\frac{-Ar_c}{1+\delta T}} \\ \frac{\partial \mathrm{T}}{\partial t} &= \frac{\partial T}{\partial z^2} + Gr\, e^{\left(-\alpha \Delta P + \frac{Ar_m \delta T}{1+\delta T}\right)} - Da(1-\phi)(1-s)e^{\frac{-Ar_c}{1+\delta T}} \end{aligned} \quad (1.)$$

All dimensionless groups are defined in (Alevizos, et al., 2014), including the Gruntfest number *Gr*, Lewis number *Le*, Arrhenius number for the chemistry Ar_c, and Damköhler number *Da*. A stability analysis with respect to *Gr* (Alevizos, et al., 2014) showed a steady-state response of the system in the shape of an “S-curve”, with a lower branch representing the steady-state response of the fault creeping at geological strain rate, and an upper branch characterising fast slip events, either in the form one continuous slip or as episodic stick-slip events. A further study (Alevizos, et al., 2016) showed the importance of *Le*, whose values affect strongly the shape and stability regime of the S-curve. In particular, that work showed the existence of a critical value Le_c below which oscillations can’t exist, regardless of the value of *Gr*. Given the definition of the Lewis number (Alevizos, et al., 2014), this threshold Le_c can be interpreted as a maximum value of permeability above which the system will never enter a slip regime since any fluid created will simply diffuses away too quickly. This behaviour is quite intuitive as one expects indeed a low enough background permeability for the fluid generated in situ to exert enough excess pore pressure to lubricate the fault and accelerate its slipping. For larger values of $Le > Le_c$, there exist a range of values for *Gr* where the system converges towards an attractor, i.e. the fault follows an episodic stick-slip motion indefinitely. Note that the behaviour of the system for *Gr* within this range can sometimes depend on the initial conditions of the temperature and pore pressure across the shear zone when two limit cycles exist for a single value of *Gr*, one stable and one unstable (Alevizos, et al., 2017).

METHOD AND RESULTS

In order to build on the previous studies and perform more parameter sensitivity analyses, we extended the capability of our pseudo-arc-length continuation algorithm built on spectral methods (Alevizos, et al., 2014; Veveakis, et al., 2014) to include the automatic detection of the singularities and bifurcation points within a given tolerance by dichotomy. These include Saddle Points (SP), Hopf Points (HP), and Exchange of Stability Points (ESP). A saddle point is a point in the bifurcation diagram where the solution branch folds back onto itself, as can be observed twice when the bifurcation diagram in the shape of an S-curve. It is detected by tracking the eigenvalues of the Jacobian of the extended system of equations (including the extra equation for the continuation parameter) and monitoring when a real one changes sign. A Hopf Point is the manifestation of a periodic bifurcation and occurs when a limit cycle is born from a stationary solution. It can be characterised by a set of conjugate complex eigenvalues of the steady state solution crossing the imaginary axis from negative to positive. In the context of this study, we define as an Exchange of Stability Point the threshold where a periodic solution transitions to a stable steady state, which is the opposite case of the Hopf point as a couple of conjugate complex eigenvalues across the imaginary axis from positive to negative. For a continuation in *Gr*, the zone of oscillation is then often located in range of *Gr* values bounded by a Hopf Point on the lower side and an Exchange of Stability Point on the upper side. To test the detection feature of our algorithm, which is still limited to a single continuation parameter, we investigate the behaviour of the system around the threshold value Le_c. We perform some continuation analyses along *Gr* (i.e. using *Gr* as the continuation parameter) for various values of *Le*, as well as some continuation analyses along *Le* for various values of *Gr*. Figure 1A shows that

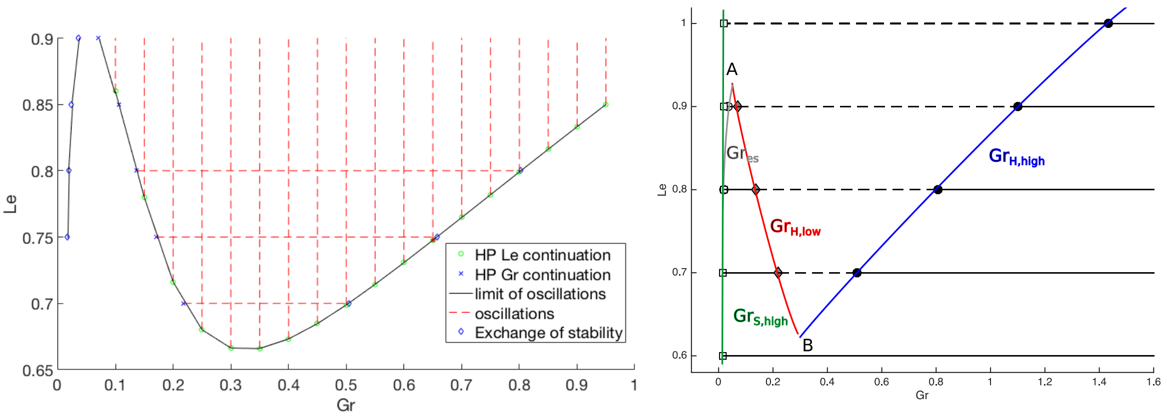

Figure 1: A) Continuations along Gr (horizontal red dashed lines) and Le (vertical red dashed lines), marking the zone of oscillation (red dashes) between HP and ESP; B) Initial approximation for the same zone in the *Gr*-*Le* parameter space as published in (Alevizos, et al., 2016).

both series lead to the determination of the same boundary for the zone of oscillations and contribute to refine the original picture shown on Figure 1B, originally obtained (Alevizos, et al., 2016) with a limited series of continuations for $Le = 0.6, 0.7, 0.8, 0.9, 1.0$.

With the framework ready for automatic detection of bifurcation points, we can now run a parameter sensitivity analysis with respect to Ar_c by performing numerous continuations along Gr for different values of Le and Ar_c and plotting the identified bifurcation points in the (Gr, Le, Ar_c) parameter space as shown in Figure 2. Results show that Ar_c only affects the location of the second saddle point (occurring for lower values of Gr due to the shape of the S-curve) for increasing values of Le. This second saddle point can even collide with the first saddle point for large values of Le and low values of Ar_c, leading to a stretched S-curve and the apparition of a new Hopf point. Figure 3A shows a projection in the Le- Ar_c plane of this curve marking the apparition of this Hopf point, displaying a constant threshold for Le at lower values of Ar_c and a rapid growth of Le with respect to Ar_c when $Ar_c > 20$. This curve can be matched nicely with an exponential fit. Another fit, shown in Figure 3B, is performed on the location of the Exchange of Stability Points marking the end of oscillations, which are independent of Ar_c. This fit shows a power dependency between Le and Gr.

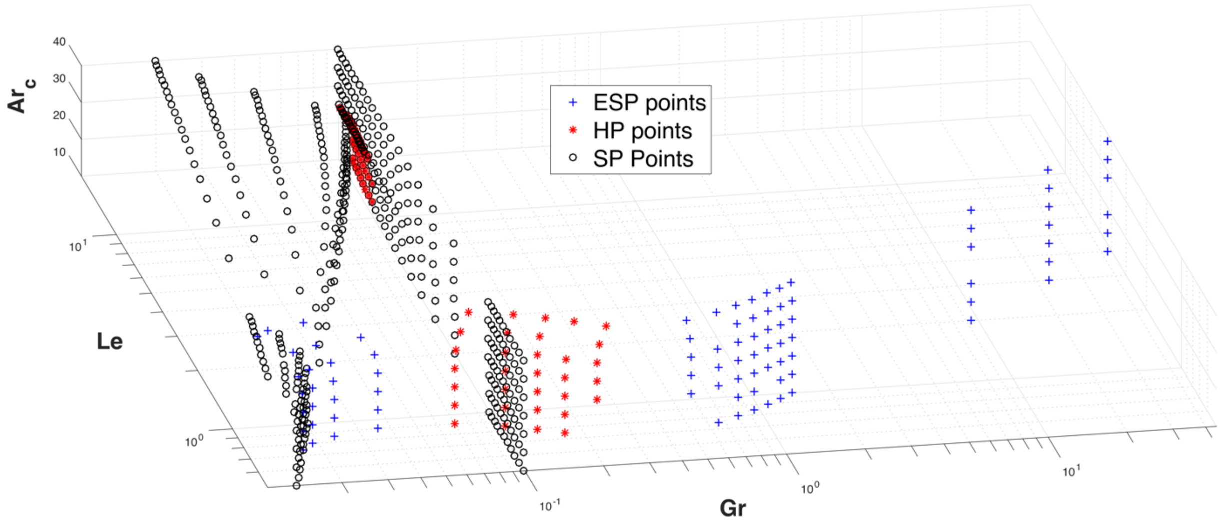

Figure 2: 3D Map of characteristic stability points – Exchange of Stability Points (ESP), Hopf Points (HP), Saddle Points (SP) – of the system showing the sensitivity of the Gruntfest (Gr), Lewis (Le), and chemical Arrhenius (Ar_c) parameters.

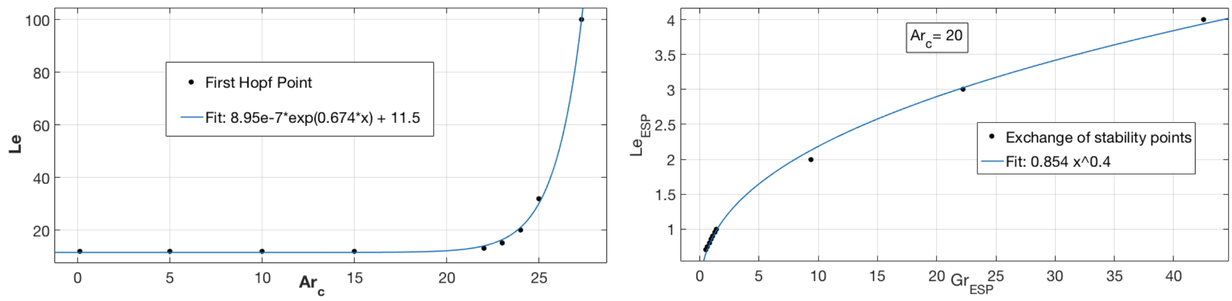

Figure 3: A) Projection in the Ar_c-Le plane of the extra Hopf points appearing for high values of Le and low values of Ar_c, matched by an exponential fit; B) Projection in the *Gr*-*Le* plane of the exchange of stability points marking the end of oscillations, matched by a power law fit.

We ran a parameter sensitivity analysis for Da following the same methodology, with numerous continuations along Gr for different values of Le and Da and a plot of the identified bifurcation points in the (Gr, Le, Da) parameter space shown in Figure 4. Results show the apparition of Hopf points for high values of Le, as observed for the previous Ar_c analysis. Figure 5 shows a projection of those points in the Le-Da plane, matched by exponential decay fit. The impact of Da on the response of the system can also be seen on the location of the Hopf and exchange of stability points for lower values of Le, with a reduced range of Gr values leading to oscillations for lower values of Da.

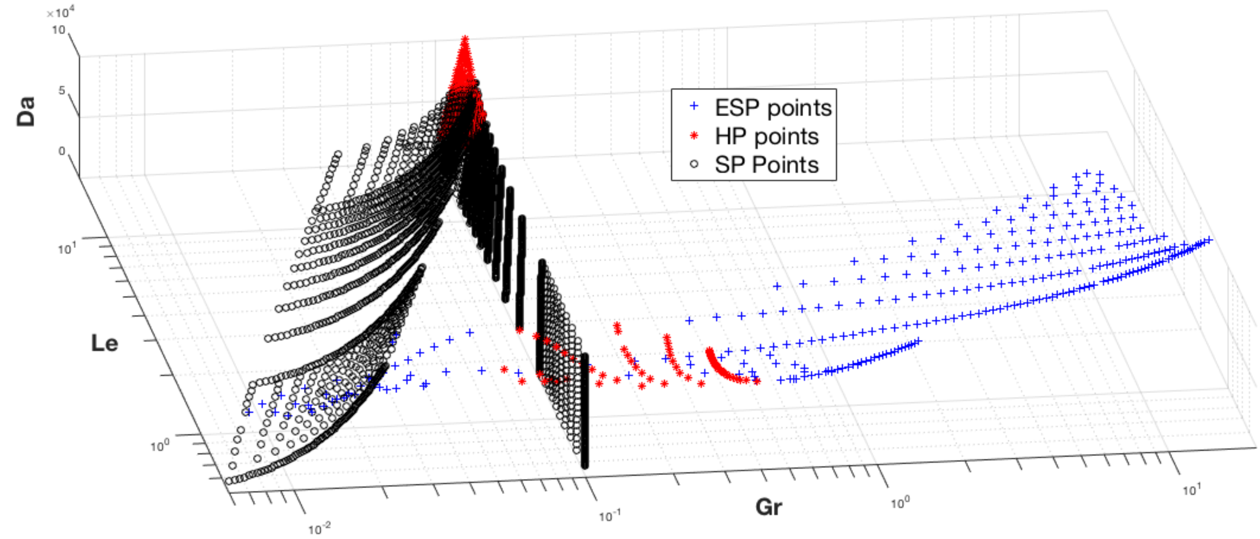

Figure 4: Preliminary 3D Map of characteristic stability points – Exchange of Stability Points (ESP), Hopf Points (HP), Saddle Points (SP) – of the system showing the sensitivity of the Gruntfest (Gr), Lewis (Le), and Damköhler (Da) parameters.

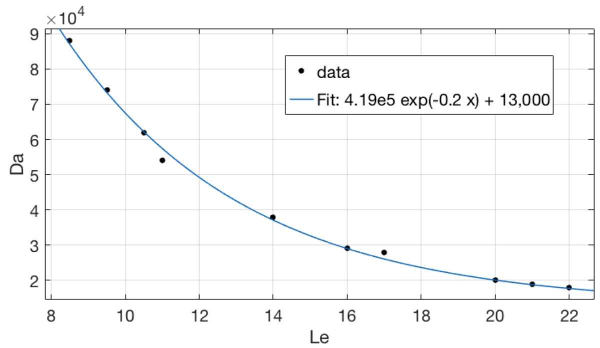

Figure 5: Identification in the Lewis (Le) – Damköhler space of the boundary (for high values of Le on Figure 4) delimiting the zone of Hopf Points (HP).

CONCLUSIONS

The chemo-mechanical oscillator introduced by (Alevizos, et al., 2014) proposes a quantitative approach to model the episodic slip behaviour of chemical shear zones, linked to drastic increases of permeability enabling mineralising fluids to propagate and ore deposits to form. A key aspect of this approach is the fact that over-pressurised fluids get generated in-situ by the fault slip and do not need to be assumed present in external reservoirs. The behaviour of this model is dictated by the values of its dimensionless parameters, with only specific combinations of parameters leading to the interesting episodic instabilities. While the start of the oscillations usually occurs for *Gr* beyond the lower saddle point, the shape of the parameter space for the oscillations is more complex and we analysed in this study the impact of two of the chemical parameters, Ar_c and *Da*. While Ar_c does not impact very much the zone of oscillations, *Da* has a much more pronounced effect at lower values of *Le*. Several fits were proposed to characterise the relationships between some of the parameters in parts of the parameter space. This progresses our understanding of this system of chemical shear zones which looks deceptively simple and yet hides so much complexity.

ACKNOWLEDGMENTS

K. Regenauer-Lieb, M. Veveakis, S. Alevizos and T. Poulet would like to acknowledge the support from the Australian Research Council (ARC Discovery grants no. DP140103015, DP170104550, DP170104557).

REFERENCES

Alevizos, S., Poulet, T. & Veveakis, E., 2014. Thermo-poro-mechanics of chemically active creeping faults. 1: Theory and steady state considerations. *Journal of Geophysical Research: Solid Earth,* Volume 119, pp. 4558-4582.

Alevizos, S., Poulet, T., Veveakis, M. & Regenauer-Lieb, K., 2016. Analysis of Dynamics in Multiphysics Modelling of Active Faults. *Mathematics,* Volume 4, p. 57.

Alevizos, S. et al., 2017. The dynamics of multiscale, multiphysics faults: Part II - Episodic stick-slip can turn the jelly sandwich into a crème brûlée. *Tectonophysics,* pp. -.

Cathles, L. M. I. I. I. & Adams, J. J., 2005. Fluid flow and petroleum and mineral resources in the upper (<20-km) continental crust. *Economic Geology; 100th Anniversary Volume,* pp. 77-110.

Cox, S. F., 2016. Injection-Driven Swarm Seismicity and Permeability Enhancement: Implications for the Dynamics of Hydrothermal Ore Systems in High Fluid-Flux, Overpressured Faulting Regimes - An Invited Paper. *Economic Geology,* Volume 111, pp. 559-587.

Hobbs, B. E. & Ord, A., 2016. Does non-hydrostatic stress influence the equilibrium of metamorphic reactions?. *Earth-Science Reviews,* Volume 163, pp. 190-233.
Hronsky, J. M. A., Groves, D. I., Loucks, R. R. & Begg, G. C., 2012. A unified model for gold mineralisation in accretionary orogens and implications for regional-scale exploration targeting methods. *Mineralium Deposita,* Volume 47, pp. 339-358.
Ingebritsen, S. E. & Manning, C. E., 2010. Permeability of the continental crust: dynamic variations inferred from seismicity and metamorphism. *Geofluids,* Volume 10, pp. 193-205.
Micklethwaite, S., Ford, A., Witt, W. & Sheldon, H. A., 2015. The where and how of faults, fluids and permeability – insights from fault stepovers, scaling properties and gold mineralisation. *Geofluids,* Volume 15, pp. 240-251.
Poulet, T., Paesold, M. & Veveakis, E., 2017. Multi-physics modelling of fault mechanics using REDBACK - A parallel open-source simulator for tightly coupled problems. *Rock Mechanics and Rock Engineering,* Volume 50, pp. 733-749.
Poulet, T., Veveakis, E., Regenauer-Lieb, K. & Yuen, D. A., 2014. Thermo-poro-mechanics of chemically active creeping faults: 3. The role of serpentinite in episodic tremor and slip sequences, and transition to chaos. *Journal of Geophysical Research: Solid Earth,* Volume 119, pp. 4606-4625.
Poulet, T. et al., 2014. Modeling episodic fluid-release events in the ductile carbonates of the Glarus thrust. *Geophysical Research Letters,* Volume 41, pp. 7121-7128.
Rojstaczer, S., Wolf, S. & Michel, R., 1995. Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes. *Nature,* jan, Volume 373, pp. 237-239.
Sibson, R. H., 1981. Fluid flow accompanying faulting: Field evidence and models. In: D. W. Simpson & P. G. Richards, eds. s.l.:American Geophysical Union, p. 593–603.
Sibson, R. H., Robert, F. & Poulsen, K. H., 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits. *Geology,* Volume 16, p. 551.
Veveakis, E., Alevizos, S. & Poulet, T., 2017. Episodic Tremor and Slip (ETS) as a chaotic multiphysics spring. *Physics of the Earth and Planetary Interiors,* Volume 264, pp. 20-34.
Veveakis, E., Poulet, T. & Alevizos, S., 2014. Thermo-poro-mechanics of chemically active creeping faults: 2. Transient considerations. *Journal of Geophysical Research: Solid Earth,* Volume 119, pp. 4583-4605.
Wilkinson, J. J., Simmons, S. F. & Stoffell, B., 2013. How metalliferous brines line Mexican epithermal veins with silver. *Nature Scientific Reports,* jun, Volume 3, p. 2057.