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Identifying dominant barometric frequencies driving gas transport in fractured rock

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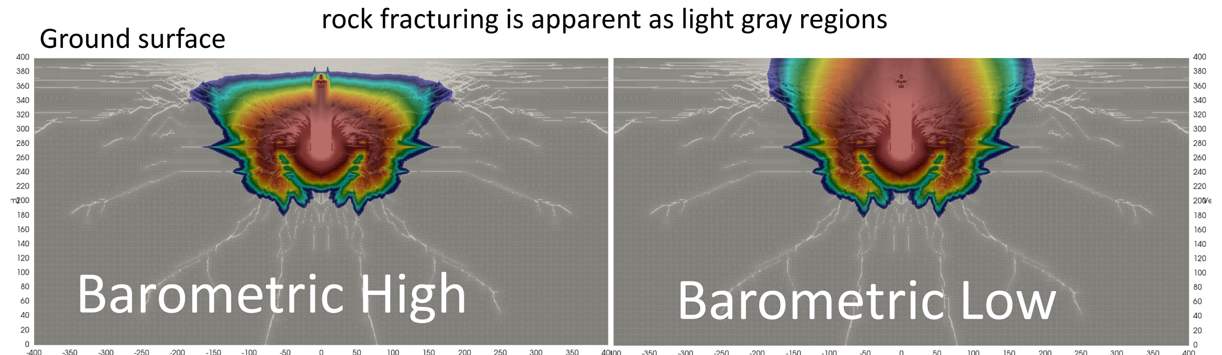
ABSTRACT

Barometric pressure variations are often one of the main drivers of gas transport in fractured rock, a process that is referred to as barometric pumping. Barometric pressure variations are complex, multi-frequency signals influenced by latitude, weather, elevation, lunar phase, time of year, and diurnal and semi-diurnal earth tides. As a result, gas transport due to barometric pumping can be difficult to characterize. However, our numerical and analytical analyses indicate that there may be a dominant transport frequency that leads to the vast majority of transport. Based on analytical arguments, the dominant transport frequency will maximize the breathing (air exchange) and diffusion exchange (immobile/mobile phase exchange) efficiencies. Identifying the dominant transport frequency allow us to more simply characterize future gas transport for which the barometric pressure variations are unknown and has implications for passive soil vapor extraction, CO_2 leakage from geosequestration operations, and radionuclide gas seepage from underground nuclear explosions and nuclear waste storage.

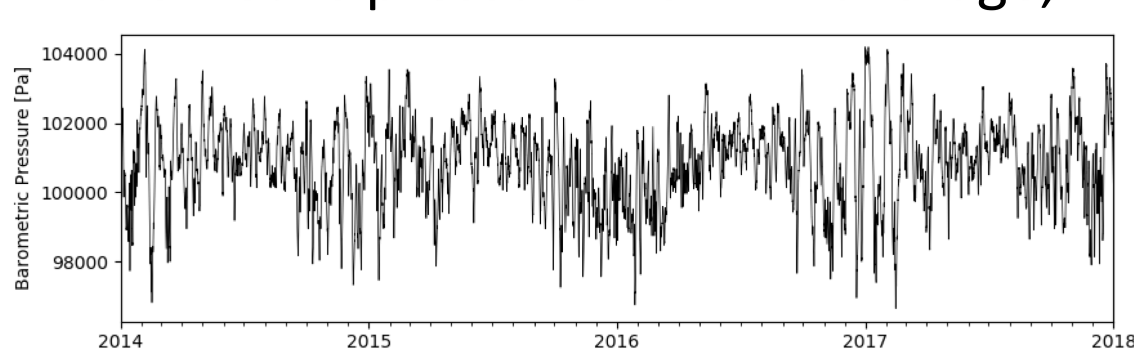
Simulated barometric pumping of gas in fractured rock

Gray scale is permeability field; explosion induced rock fracturing is apparent as light gray regions

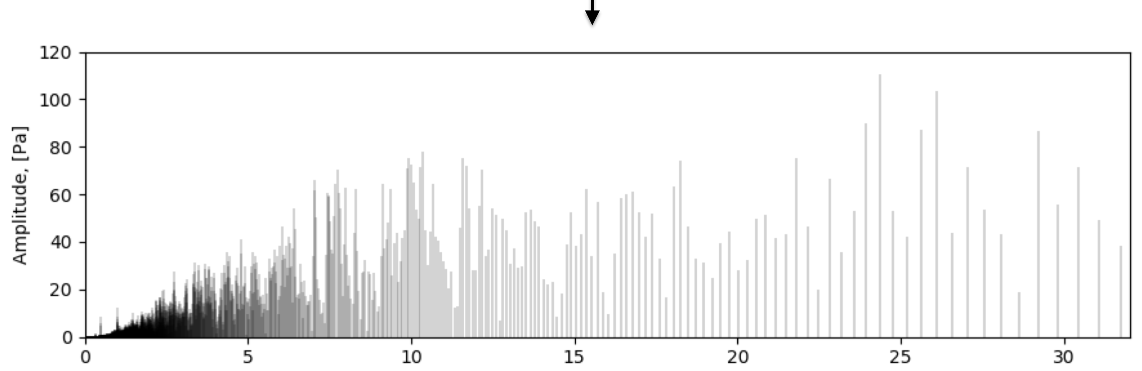


Decomposing barometric pressure signals

Barometric pressure from Anchorage, AK



Fast Fourier Transform decomposes signal into frequencies (periods) and associated amplitudes



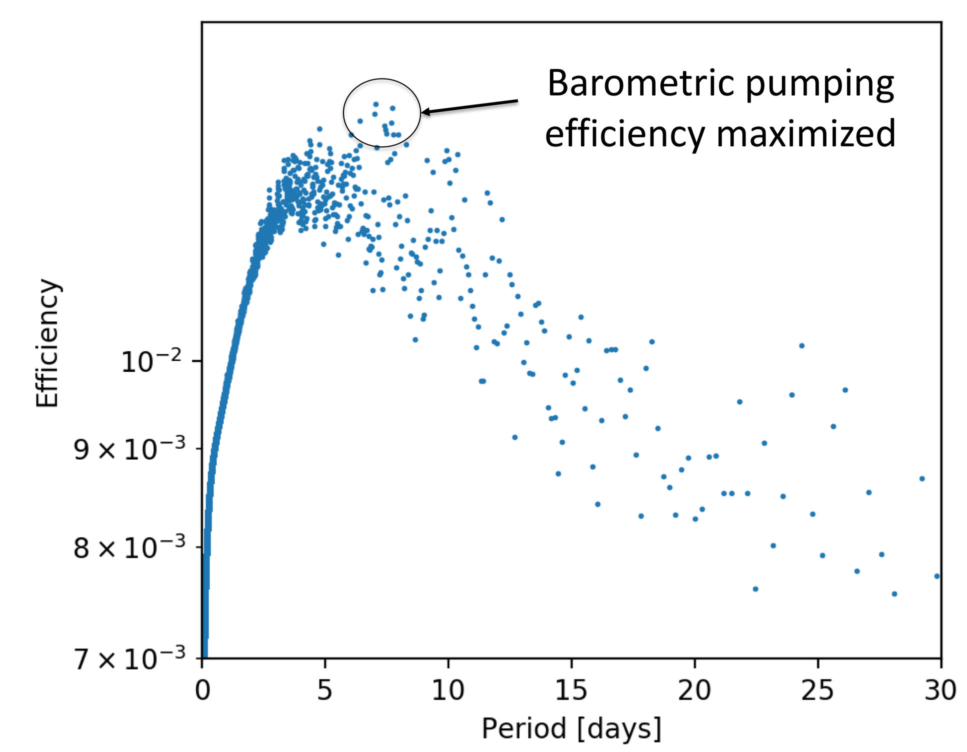
Analytical efficiency analysis based on Nilson et al. (1991)

Breathing efficiency: $\eta_B = \frac{\Delta V}{\Delta V_{max}} = \frac{\delta_f}{(\delta_f+\phi_m\delta_m)} mod \left[\frac{\lambda_{fm}^2}{\lambda_f^2}\frac{\tanh \lambda_{fm}\sqrt{i}}{\lambda_{fm}\sqrt{i}}\right]$

Exchange efficiency: $\eta_D = -\frac{\pi}{4} Re\left[\frac{iW_a\sqrt{i}}{W_a\sqrt{i}+\tanh \beta W_a\sqrt{i}}\right]$

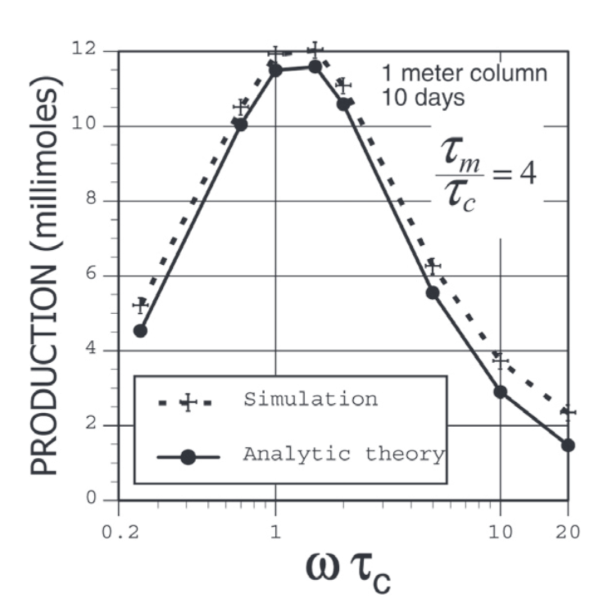
Total efficiency: $\eta = \eta_B\eta_D = \left(\frac{\Delta V}{\Delta V_{max}}\right)\left(\frac{\Delta M_c}{C_B\,\Delta V}\right) = \frac{\Delta M_c}{C_B\,\Delta V_{max}}$

Pumping efficiency of Anchorage period/amplitude pairs plotted as a function of barometric period with matrix perm 1e-15 m^2, matrix porosity 0.1, fracture aperture 0.001 m, fracture spacing 10 m. – Results are highly dependent on rock/fluid properties!

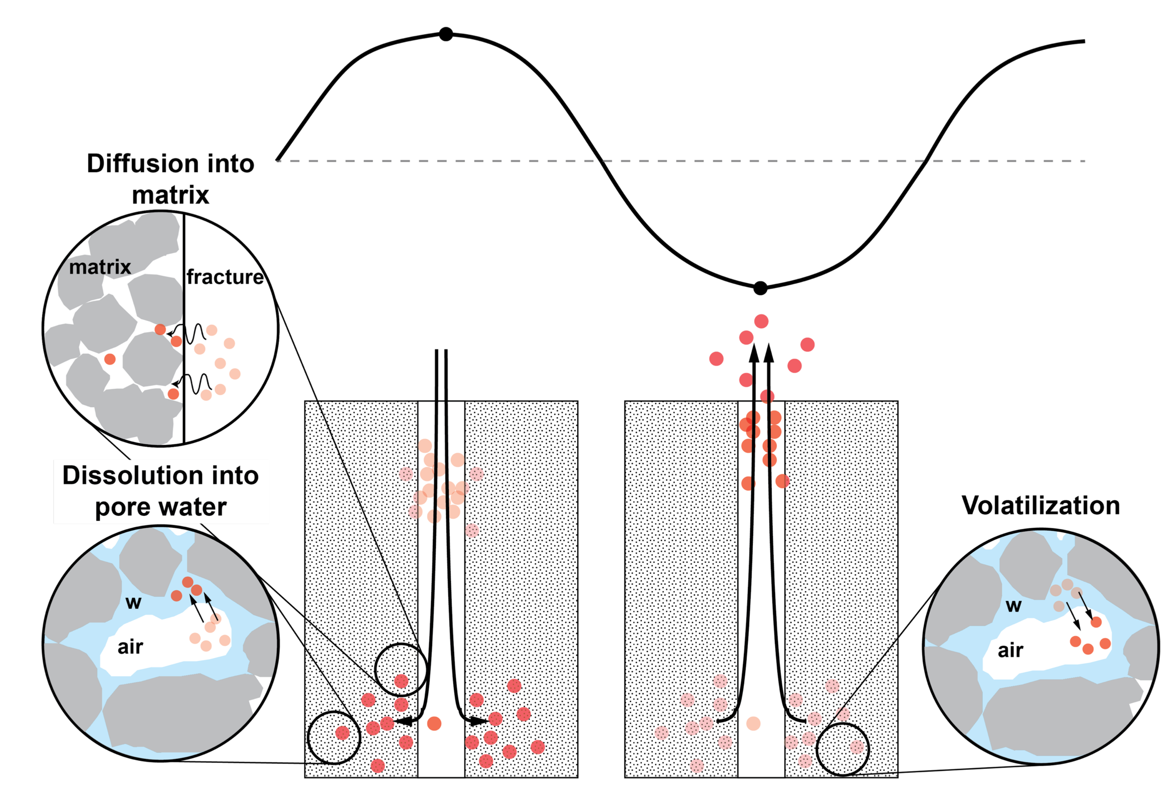


Analytical exchange diffusivity analysis (Neeper and Stauffer, 2011)

Neeper and Stauffer (2011) identified that the production due to barometric pumping is maximized when the barometric frequency times the time for the concentration in an initially clean fracture to stabilize with a contaminated matrix is around one.

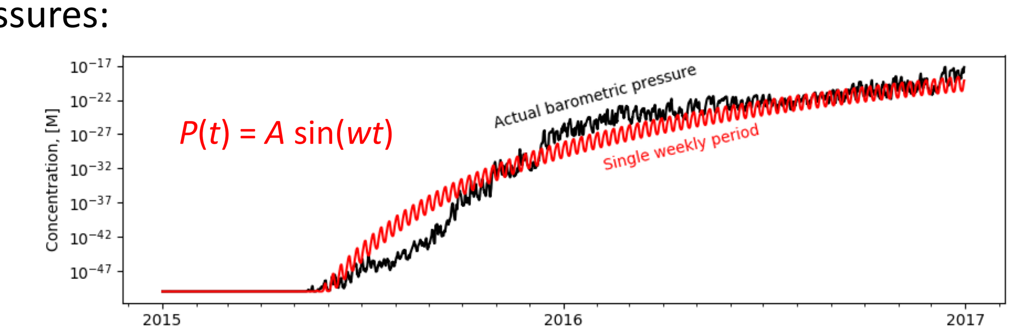


Physical processes include in numerical modeling of gas transport due to barometric pumping (Harp et al, 2018)

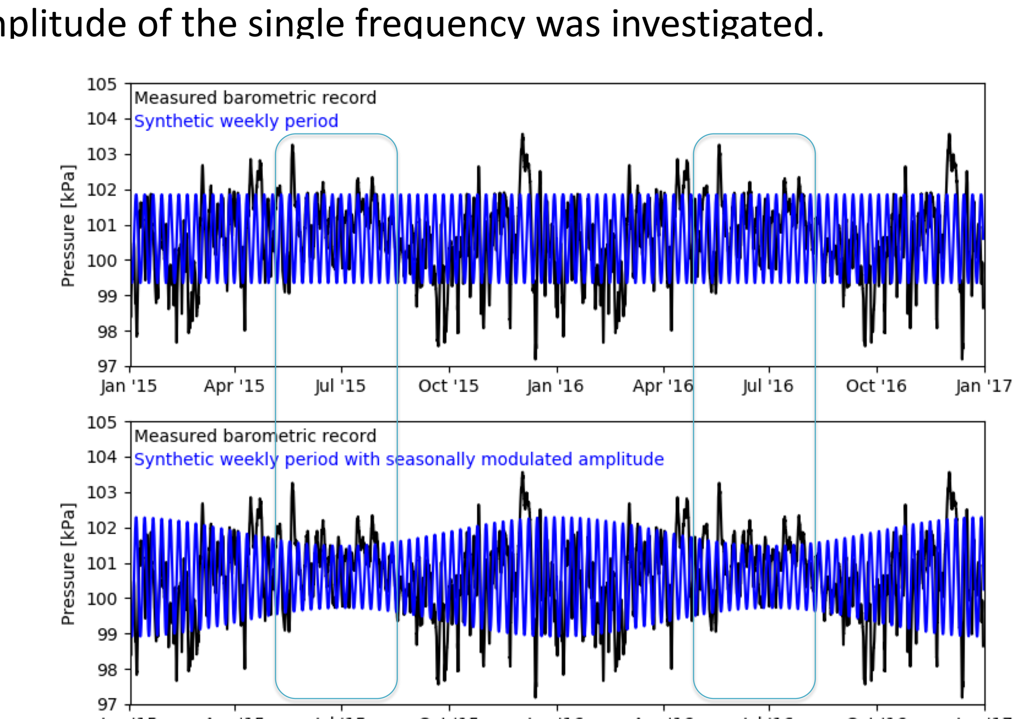


Finding the dominant frequency

We calibrated gas transport simulated using a pressure signal with a single frequency to gas transport using the Anchorage barometric pressures:

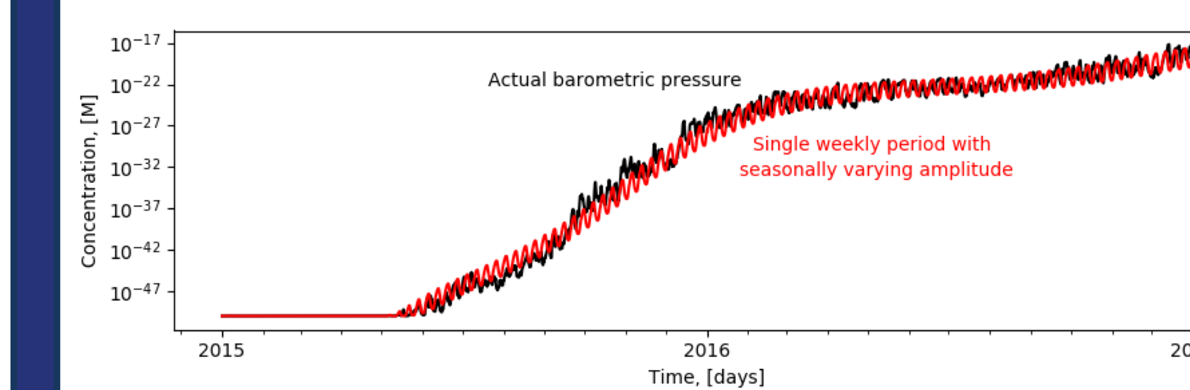


While the calibrated gas transport captured some of the characteristics of the gas transport simulated with the measured pressures, it was obvious that something was missing. By inspecting the mismatch in the gas transport and the seasonal characteristics of the amplitude of the pressure record below, modulating the amplitude of the single frequency was investigated.



Modulating the amplitude of the dominant frequency by season

The fit is significantly improved by seasonally modulating the single barometric frequency:



$P(t) = (A_w + A_s\sin(w_s t))\sin(w_w t)$

A_s – seasonal amplitude
A_w – weekly amplitude
w_s – seasonal frequency
w_w – weekly frequency

Conclusions

It has long been recognized based on analytical arguments that barometric frequencies will have different efficiencies in driving gas transport. We have demonstrated numerically that it is possible to represent gas transport driven by a real barometric pressure record using a single frequency modulated by season. Future work will investigate the sensitivity of the dominant frequency, amplitude and seasonal modulation and investigate analytical analyses to identify dominant gas transport frequencies from barometric pressure records.

References

Nilson, R.H., Peterson, E.W., Lie, K.H., Burkhard, N.R. and Hearst, J.R., 1991. Atmospheric pumping: A mechanism causing vertical transport of contaminated gases through fractured permeable media. *Journal of Geophysical Research: Solid Earth*, *96*(B13), pp.21933-21948.

Neeper, D.A. and Stauffer, P.H., 2012. Transport by oscillatory flow in soils with rate-limited mass transfer: 1. Theory. *Vadose Zone Journal*, *11*(2).

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