Advection Heat Flow and the 1/F-Noise Fracture Nature of Crustal Rock

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ABSTRACT

Pervasive broadband (cm-Km) 1/*f*-noise power-law fluctuation scaling $S(k) \propto 1/k$ in well-logs and abundant support for poroperm fluctuation relation $\delta\varphi \approx \delta\log(\kappa)$ in clastic-reservoir well-core indicate that crustal rock is nearly everywhere permeable to percolating fluids. Percolating fluids can transport heat in parallel with thermal conduction if formation permeability is sufficiently high. We investigate the level of *in-situ* 1/*f*-noise permeability needed to bring advection of heat to levels comparable to those assumed for thermal conduction. The investigation centres on thermal gradient and neutron porosity well-logs recorded at 5,500-8,500 feet in a tight-gas province in western Colorado, USA. Formation core permeability is of order 10-20 μDarcy. The thermal gradient and porosity logs are 60% spatially correlated at zero lag, but the temperature gradient log has an underlying trend towards higher gradient values with depth/temperature in the well. Well-site core poroperm data are 60% cross-correlated, validating the relation $\delta\varphi \approx \delta\log(\kappa)$ for the tight gas foramtion and providing direct evidence for potential heat advection at all scale lengths. The temperature-gradient trend can be correlated with either a trend towards lower thermal conductivity with increasing depth/temperature, or with an advection term proportional to temperature. For the observed formation permeability, it is entirely possible that thermal advection is comparable to thermal conduction in the tight-gas formation. The tight-gas formation well-log data clearly suggest that higher permeability crustal rock can support advection heat transport where heretofore it has not been considered.

1/F-NOISE FRACTURE NATURE OF CRUSTAL ROCK

The Fourier power spectra of virtually all geophysical well-logs scale inversely with spatial wavenumber k, $S(k) \propto 1/k^{\beta}$, $\beta \approx 1 \pm 0.2$ (Leary 2002). The "1/*f*-noise" scaling law for *in-situ* geophysical fluctuations holds for sonic, resistivity, gamma activity, mass density, neutron scattering and chemical abundances over 5 decades of scale length (~cm to ~ km) in sedimentary and crystalline rock for both horizontal and vertical wells. The power-law nature of *in-situ* geophysical property fluctuations can be understood as arising from long-range spatial-correlation of grain-scale percolation-fracture density fluctuations in analogy with critical-state phenomena such as the organisation of mm-scale domains by Angstrom-scale iron atom magnetic dipoles. In this analogy, grain-scale fracture density plays the role of thermodynamic energy usually associated with temperature; at a critical density n_0 of grain-scale fractures, percolation pathways become effectively infinite in extent, the spatial correlation length goes critical, $\xi \propto 1/\sqrt{|n-n_0|} \to \infty$, and the spatial correlation function becomes power-law, $\chi(r) \propto 1/r^P \exp(-r/\xi) \to 1/r^P$.

The grain-scale percolation-fracture density nature of *in-situ* geophysical fluctuations is further testified to by the well-core poroperm fluctuation relation $\delta\varphi\iota \approx \delta\log(\kappa\iota)$, where $\delta\varphi\iota$ and $\delta\log(\kappa\iota)$ are, respectively, zero-mean-unit-variance fluctuation sequences $\iota = 1,2,3\ldots$ of well-core plug porosity and log(permeability). The poroperm fluctuation relation, observed at 85% ± 8% cross-correlation level for some thousands of well-core plugs from clastic reservoir rock, is physically equivalent to the mathematical statement $\delta n \approx \delta\log(n!)$ for n the number of grain-scale fractures in a unit volume and factorial $n!$ expressing the combinatorial nature of fracture-connectivity for percolation flow via grain-scale fracture populations (Leary & Walter 2008).

WELL-LOG POROSITY FLUCTUATIONS AND THE WELL-BORE THERMAL GRADIENT

Figure 1 illustrates the close association between neutron porosity and thermal gradient recorded in a well in the tight-gas formations of western Colorado, USA. The well was drilled and logged during a tight-gas production stimulation hydrofrac project (Branagan et al. 1996). Fluctuations in temperature gradient (red) are superposed on fluctuations in neutron porosity (blue). Apart from the trend toward increasing temperature gradient with depth, a close correspondence exists between variations in thermal gradient and porosity for 5,000 data points over 2,500 feet of formation. The two logs have a 60% cross-correlation coefficient at zero lag (with fluctuation standard deviation of 8%, a 60% cross-correlation peak is 8 standard deviations from being a chance occurrence).

Figure 1 establishes that porosity can be closely associated with *in-situ* thermal gradients. Because water and gas are poor conductors compared with mineral grains (0.02 and 0.6 $Wm^{-1}K^{-1}$ for gas and water versus 2-8 $Wm^{-1}K^{-1}$ for minerals, Clauser & Huenges, 1995), positive porosity fluctuations are associated with negative thermal conductivity fluctuations. Expressing thermal conductivity as $K \approx K_0 - K_1\varphi$, with $K_0 \approx 3$ and $K_1 \approx 10$ for $0.0 < \varphi < 0.1$ (Clauser & Huenges 1995), positive porosity fluctuations yield negative conductivity $\delta K = -K_1\delta\varphi$. For steady-state conduction heat flow Q =

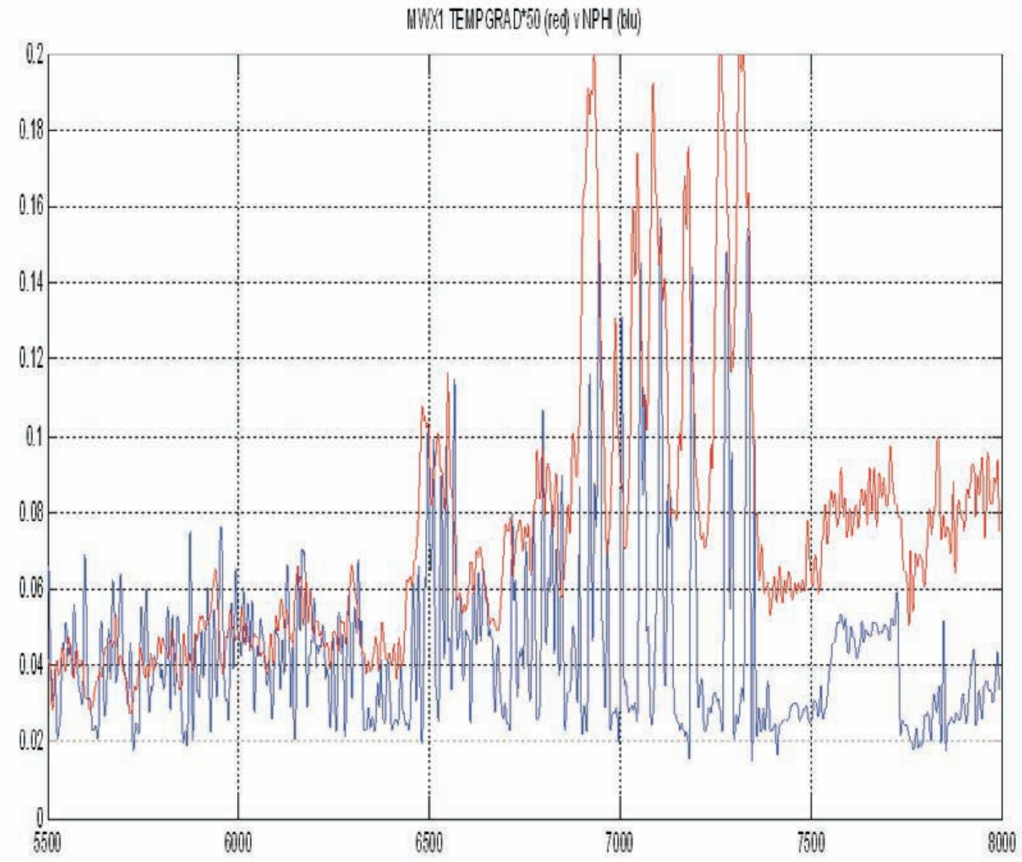

Figure 1. Well-log neutron porosity (blue) and thermal gradient (red) fluctuations recorded in a tight gas formation at the MWX hydrofrac gas production stimulation experimental site in western CO, USA (Branagan et. al. 1996). Horizontal axis: 5500:500:8000 ft; vertical scale for porosity: 0:0.02:0.2; temperature gradient data scaled for visual purposes.

const = $K\nabla T$, positive gradient fluctuations are associated with positive porosity fluctuations. From $\delta\nabla T/\nabla T + \delta K/K \approx 0$,

$$\delta\nabla T/\nabla T \approx \delta\nabla T/\underline{\nabla T} \approx -\delta K/K \approx K_1\delta\varphi/K_0 \quad (1)$$

where $\underline{\nabla T}$ is the mean temperature gradient. Equation 1 shows, however, that Figure 1 porosity can not alone account for the observed upward trend in thermal gradient fluctuations. We can introduce a rising trend into the porosity dependence by giving thermal conductivity a temperature dependence. Again from Clauser & Huenges (1995), temperature dependence of thermal conductivity is of order $K_0(T) \approx K_0(0)\ (1 - 5\ 10^{-3}\ T)$ for $0 < T < 100$ °C, hence

$$\delta\nabla \approx \underline{\nabla T}\,\delta\varphi(1 + 5\ 10^{-3}\ T)\ K_1/K_0 \approx 3\ \underline{\nabla T}\,(1 + 5\ 10^{-3}\ T)\delta\varphi \quad (2)$$

Alternatively, site well-log evidence indicates that porosity is strongly associated with permeability via grain-scale fracture percolation pathways throughout crustal rock. Advection introduces a temperature trend that can, in principle, also explain the divergence of Figure 1 curves. For largely vertical groundwater flow of rate ν, $[\nu]$ = m/s, steady-state advection heat transport is governed (Carslaw & Jaeger 1959) by $K\partial_z^2 T \approx C\rho\nu\partial_z T$, $C\rho$ = volume heat capacity of water. The combined advection and conduction heat flow Q is given by

$$Q \approx K\partial_z T - C\rho\nu\ (T - T_0), \quad (3)$$

Where T_0 is an integration constant. With groundwater diffusion flow forced by topography, $\nu \approx \kappa/\eta\nabla P \approx \kappa\rho g/\eta$, (3) gives thermal gradient ∇T in terms of advection and conduction (Jessop 1990),

$$\nabla T \approx C\rho^2 g\kappa/\eta K\ (T - T_0) + Q/K \quad (4)$$

Assuming for convenience a constant thermal conduction K, fluctuations in permeability generate fluctuations in thermal gradient proportional to fluctuations in porosity, $\delta\kappa \approx \kappa_0\delta\exp(\varphi) = \kappa_0\exp(\varphi)\delta\varphi = \kappa\delta\varphi$,

$$\delta\nabla T \approx C\rho^2 g/\eta K\ (T - T_0)\delta\kappa \approx C\rho^2 g\kappa/\eta K\ (T - T_0)\delta\varphi \quad (5)$$

Equation 5 is given a vertical scale length h in terms of the dimensionless Peclet number $Pe = C\rho^2 g\kappa\eta/\eta K$,

$$\delta\nabla T \approx Pe\ (T - T_0)/\eta\ \delta\varphi \quad (6)$$

The natural value for scale dimension h is the length of the temperature gradient log, h = 2500ft ≈ 756m. Integrating the thermal gradient field ∇T to get the temperature distribution, $T = \int\nabla T dz$, over the log length h fixes all parameters in equation 6 except for mean formation permeability κ_0. If κ_0 is large enough, the Peclet number will be large enough for advection (equation 6) to account for the thermal gradient fluctuations. If κ_0 is small, the advection process (equation 6) will not account for the thermal gradient fluctuations.

The terms of the Peclet number are:

- volume heat capacity of water $C\rho \approx$ 4MJ/kg-°C 1000kg/m^3 = 4GJ/m^3-°C;
- pressure gradient of gravity ρg = 1000kg/m^3 10m/s^2 = 104 Nt/m^3;
- dynamic viscosity of water η = 0.1kg/m-s;
- thermal conductivity K = 3Wm^{-1}K^{-1};
- mean formation permeability κ_0 in m^2; 1 μDarcy = 10^{-18}m^2;
- scale length h = 756m.

For $\kappa_0 \approx 1$ μDarcy, $Pe \approx 0.1$. However, well-site core permeability data indicate that tight-gas formation permeabilities have mean and median values in the range 10 to 20 μDarcy, hence the effective Peclet number is potentially of order unity $Pe \approx 1$ in the 5,500-8,000ft depth range surveyed for thermal gradient. Values of order $Pe \approx 1$ indicate that advection (equation 6) as well as conduction (equation 2) can plausibly account for the 60% thermal-gradient/neutron-porosity cross-correlation in Figure 1.

SUMMARY AND CONCLUSIONS

While heat flow in the crust is almost everywhere thought of in terms of thermal conduction, the broadband $1/f$-noise phenomenology of well-log spectra and well-attested poroperm fluctuation relation $\delta\varphi \approx \delta\log(\kappa)$ in clastic reservoir core suggest that fluid percolation at scale lengths from cm to km is a viable means of heat transport heat in crustal rock. Evidence for possible advection heat flow is seen in well-logs of highly correlated thermal gradient and neutron porosity fluctuations recorded over 750m in a tight-gas formation. Well core evidence for formation permeability returns a Peclet number $Pe \approx 1$-2 in a volume of 750m scale dimension. In these circumstances, both the trend and the fluctuations in the thermal gradient well-log data can be directly explained by fluctuations in formation porosity in the presence of an overall temperature trend. The potential for heat advection in more permeable rock is proportionately stronger. If heat flow inferred from well temperature data is more dependent on crustal percolation permeability than on thermal conduction, there may be a need to reassess existing heat flow maps.

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