Why We Have Earthquakes in the Eastern United States

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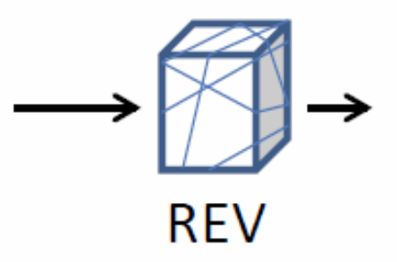
Introduction: It is increasingly recognized that there are only two types (Figure 1) of naturally-occurring earthquakes anywhere on the Earth (Costain and Bollinger, 2010): 1) those associated with the dynamics of plate tectonics and 2) those associated with the dynamics of the hydrologic cycle. The first type (Type I) is characteristic of an ***INTER***plate setting (like the San Andreas Fault in California). The second (Type II) is characteristic of an ***INTRA***plate setting (like the Virginia magnitude 5.7 earthquake of August 23, 2011, or the earthquakes of the New Madrid, MO seismic zone). The second type is caused by the dynamics of groundwater recharge from rainfall, hurricanes, and typhoons, which trigger the intraplate earthquakes. The Earth's crust is generally accepted to be in a self-organized critical (SOC) state and fractured with connected hydraulic continuity from the surface down to 15-18 km. Thus, the fluid (meteoric water) filling the cracks is under hydrostatic, not lithostatic pressure. It is generally accepted that it takes only 0.01-0.1 MPa (0.1-1.0 bar) of pore-fluid overpressure to trigger an ***intra***plate earthquake.

The central Virginia seismic zone (CVSZ), and the New Madrid, MO, intraplate seismic zones are both bisected by major river systems. A hydrograph separation (Figure 2) to obtain base flow (groundwater recharge) was obtained at stream gaging station 02.0350.00 in the CVSZ. The derivative of the response of the crust to a unit step function increase in pore-fluid pressure at the surface of the Earth (by groundwater recharge) is, by definition, the impulse response of a hydraulically conductive crust. The time sequence of groundwater recharge (baseflow) can then be convolved with the impulse response to give the pore-fluid overpressure (pressure above hydrostatic) at depth. The pore-fluid pressure is governed by the equations shown below in Figure 3.



$$\boxed{\rho\, S\frac{\partial p}{\partial t} - \nabla\cdot\left(\rho\,\frac{k}{\mu}\,\nabla p\right) = 0}$$

Starting point. *p* is pore-fluid overpressure (above hydrostatic)

$$\frac{p(z,t)}{p(0,t)} = 1 - \mathrm{Erf}\left(\frac{z}{2\sqrt{D\,t}}\right)$$

Solution of DE for a step function Increase in *po* due to recharge.
D is crustal hydraulic diffusivity
z is diffusion distance

$$\lim_{\Delta t\to 0}\left[\frac{p_0\,\mathrm{Erf}\left(\frac{z}{2\sqrt{(t-\Delta t)\,D}}\right) - p_0\,\mathrm{Erf}\left(\frac{z}{2\sqrt{t\,D}}\right)}{\Delta t}\right] = \boxed{\frac{\partial p}{\partial t} = \frac{p_o\,D\,e^{-\frac{z^2}{4\,D\,t}}\,z}{2\sqrt{\pi}\,(D\,t)^{3/2}}}$$

This turns recharge on and off (before taking the limit)

Hydraulic impulse response

$$\frac{\partial^2 p}{\partial t^2} = -\mathrm{po}\left(\frac{3e^{-\frac{z^2}{4tD}}\,D^2\,z}{4\sqrt{\pi}(t\,D)^{5/2}} - \frac{e^{-\frac{z^2}{4tD}}\,z^3}{8\sqrt{\pi}t^2(t\,D)^{3/2}}\right) = 0$$

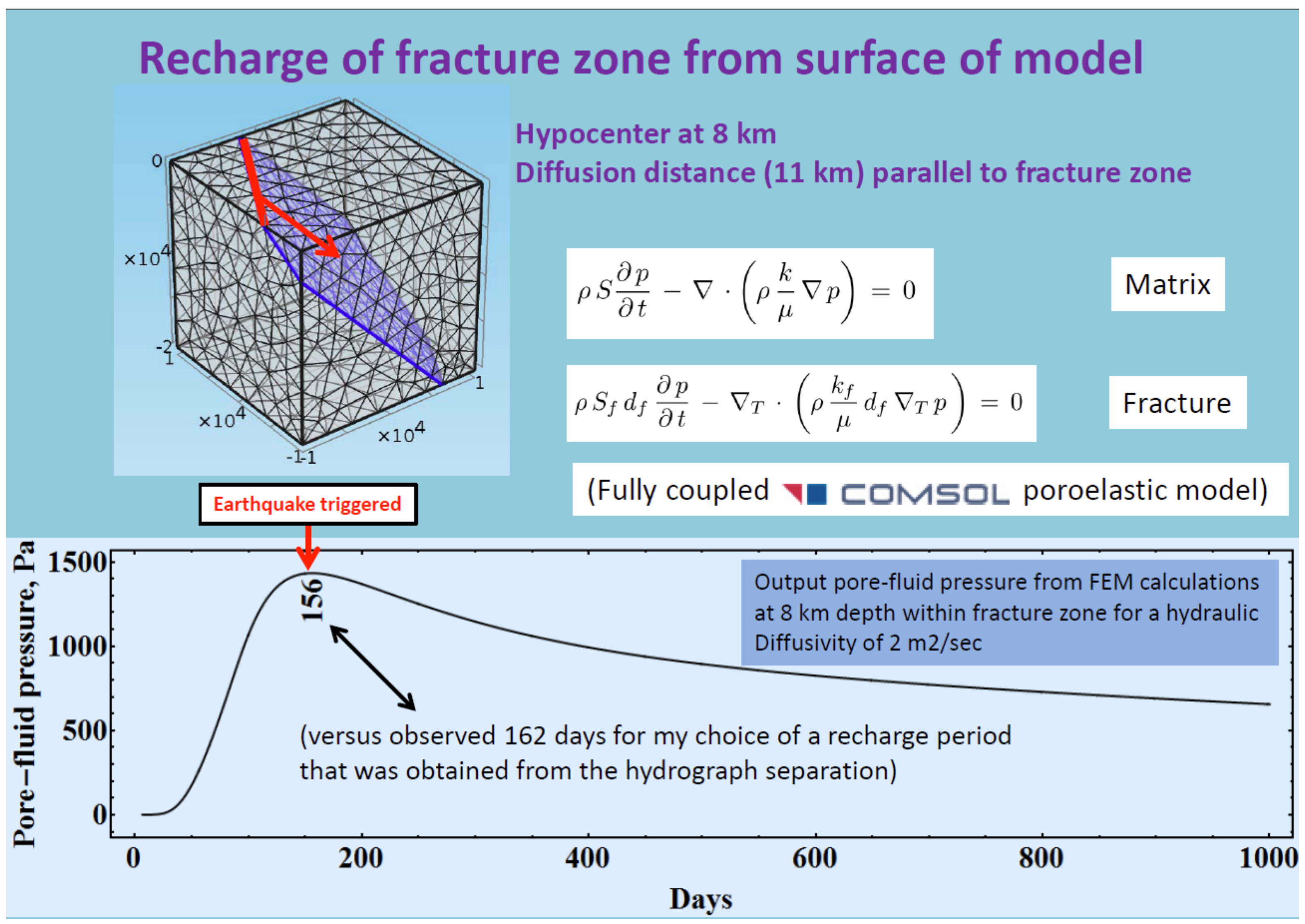
Derivative of above, set equal to zero and get time to peak of impulse response **(and assume the peak triggers earthquakes)**

$$\boxed{t \equiv \tau = \frac{z^2}{6\,D}}$$

$$p = \int_{t_1\approx 0}^{T}\frac{p_o\,D\,e^{-\frac{z^2}{4\,D\,t}}\,z}{2\sqrt{\pi}\,(D\,t)^{3/2}}\,dt = p_o\left(\frac{\sqrt{D}\,\mathrm{Erf}\left[\frac{z}{2\sqrt{D}}\right] - \frac{\sqrt{D\,t}\,\mathrm{Erf}\left[\frac{z}{2\sqrt{D}\sqrt{T}}\right]}{\sqrt{T}}}{\sqrt{D}}\right)$$

Integrate the impulses from start of recharge to end of recharge.
T = duration of recharge

Figure 3. The Darcy differential equation for groundwater flow in a fractured and permeable crust of the Earth. The solution for a step function increase in recharge is differentiated to obtain the impulse response of the hydraulically diffusive crust. Differentiating once more leads to a solution for the delay of the peak in pore-fluid pressure with respect to the start of recharge. This expression is used to estimate hydraulic diffusivity with the assumption that an earthquake is triggered when the pore-fluid pressure reaches a maximum.



$$\rho\, S\frac{\partial p}{\partial t} - \nabla\cdot\left(\rho\,\frac{k}{\mu}\,\nabla p\right) = 0$$

$$\rho\, S_f\, d_f\frac{\partial p}{\partial t} - \nabla_T\cdot\left(\rho\,\frac{k_f}{\mu}\,d_f\,\nabla_T\, p\right) = 0$$

(Fully coupled COMSOL poroelastic model)

Output pore-fluid pressure from FEM calculations at 8 km depth within fracture zone for a hydraulic Diffusivity of 2 m2/sec

(versus observed 162 days for my choice of a recharge period that was obtained from the hydrograph separation)

Figure 5. Diffusion of groundwater recharge from the surface down along the fault zone triggers the earthquake when the pore-fluid pressure reaches a peak after a delay of about 160 days after the start of recharge. The fault shown in the FEM was defined by the thousands of aftershocks associated with the magnitude 5.7 Virginia earthquake of August 23, 2011

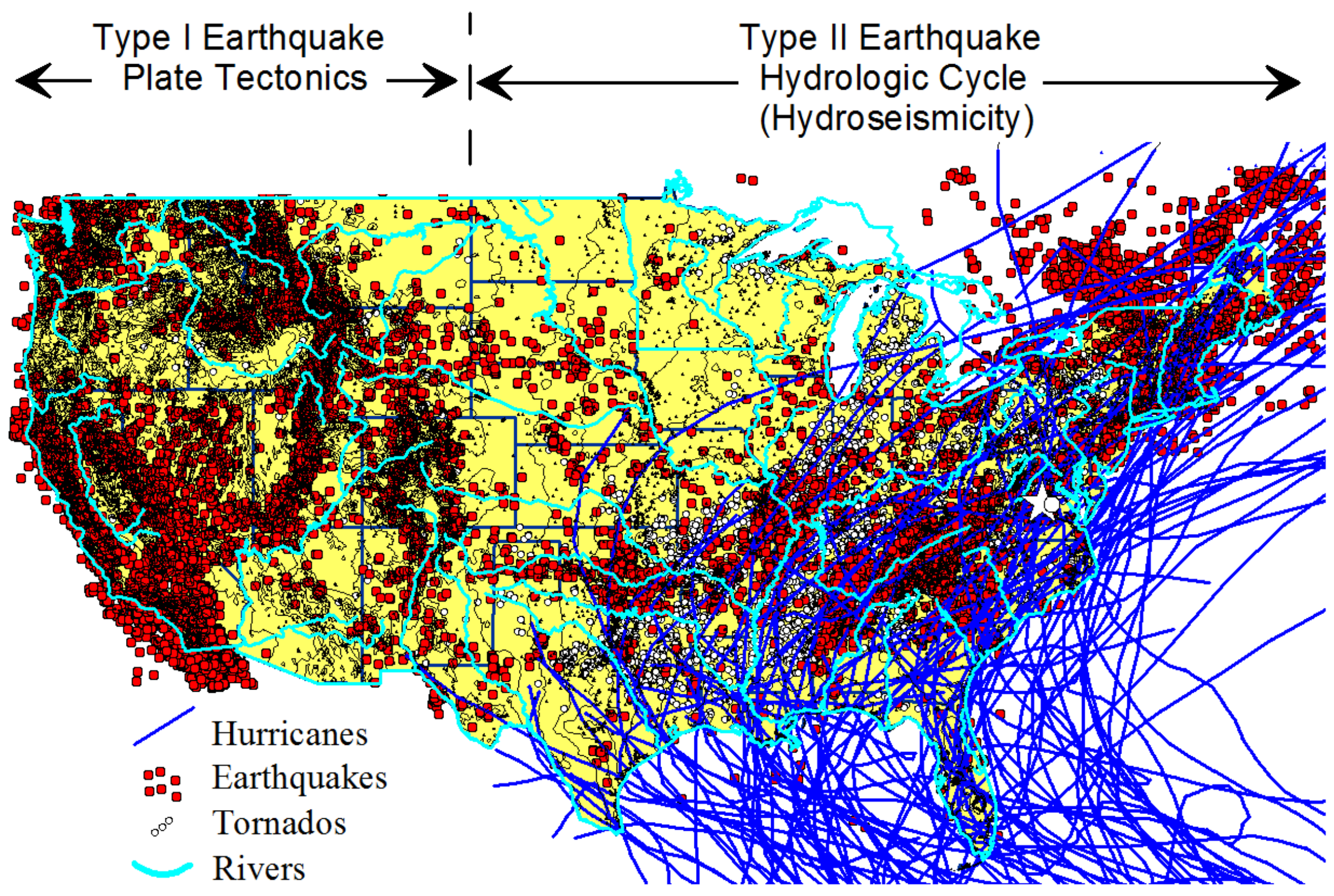
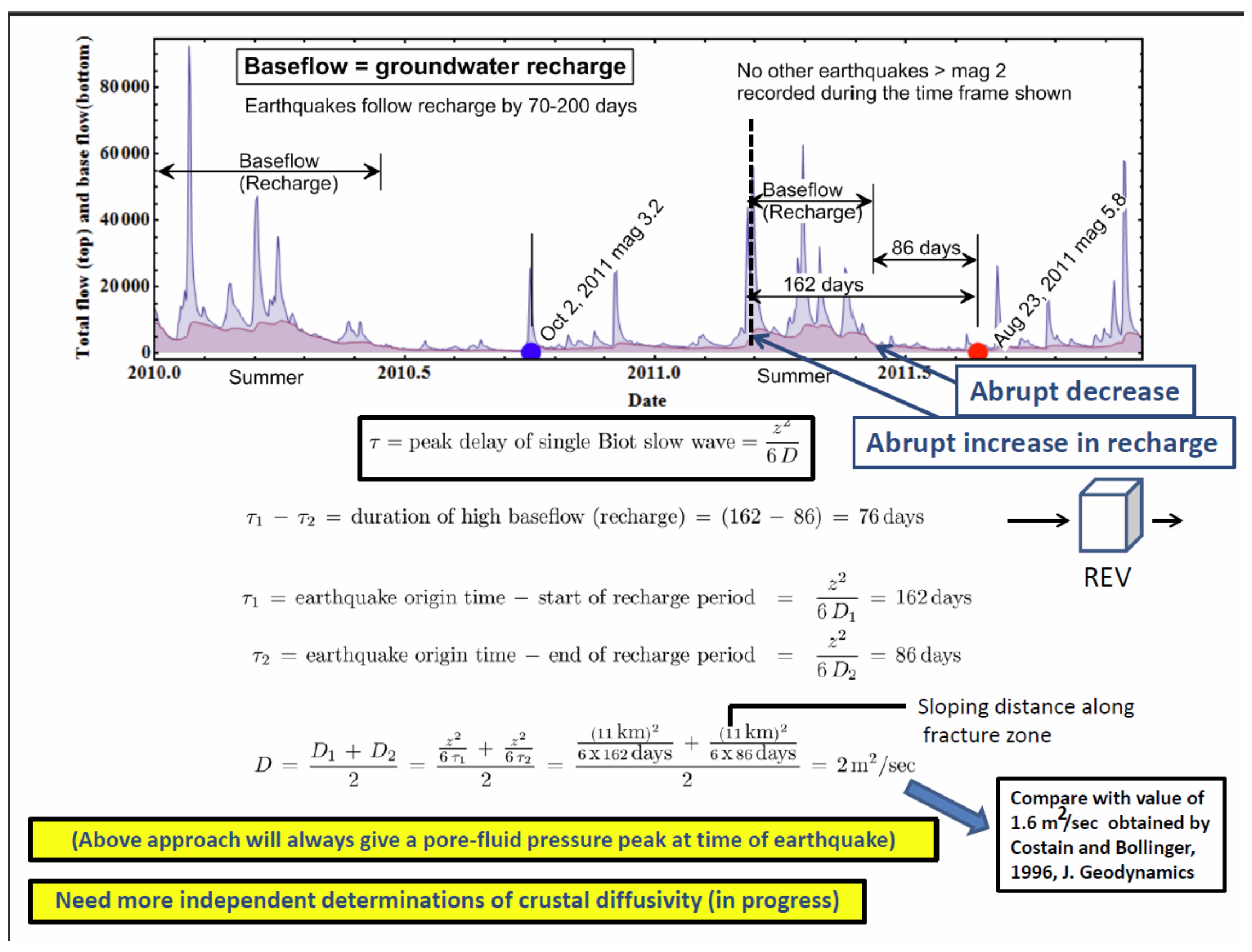


Figure 1. Hurricane tracks, tornados, and major rivers of the conterminous U.S. These and rainy periods are elements of the hydrologic cycle that are the sources of pore-fluid pressure diffusion into a fractured and permeable SOC crust where they are hypothesized to trigger intraplate earthquakes. White star denotes the location of the Virginia earthquake of August 23, 2011 with a focal depth of 8 km. Smaller adjacent dot is the epicenter of a magnitude 3.2 event on October 2, 2010. The areal distribution of naturally-occurring earthquakes in the central and eastern U.S. is coincident with the dynamics of elements of the hydrologic cycle. Type I and Type II designations refer to the global division of naturally-occurring earthquakes proposed by Costain and Bollinger (2010).



$$\boxed{\tau = \text{peak delay of single Biot slow wave} = \frac{z^2}{6\,D}}$$

$$\tau_1 - \tau_2 = \text{duration of high baseflow (recharge)} = (162 - 86) = 76\,\text{days}$$

$$\tau_1 = \text{earthquake origin time} - \text{start of recharge period} = \frac{z^2}{6\,D_1} = 162\,\text{days}$$

$$\tau_2 = \text{earthquake origin time} - \text{end of recharge period} = \frac{z^2}{6\,D_2} = 86\,\text{days}$$

$$D = \frac{D_1 + D_2}{2} = \frac{\frac{z^2}{6\,\tau_1} + \frac{z^2}{6\,\tau_2}}{2} = \frac{\frac{(11\,\text{km})^2}{6\,\text{x}\,162\,\text{days}} + \frac{(11\,\text{km})^2}{6\,\text{x}\,86\,\text{days}}}{2} = 2\,\text{m}^2/\text{sec}$$

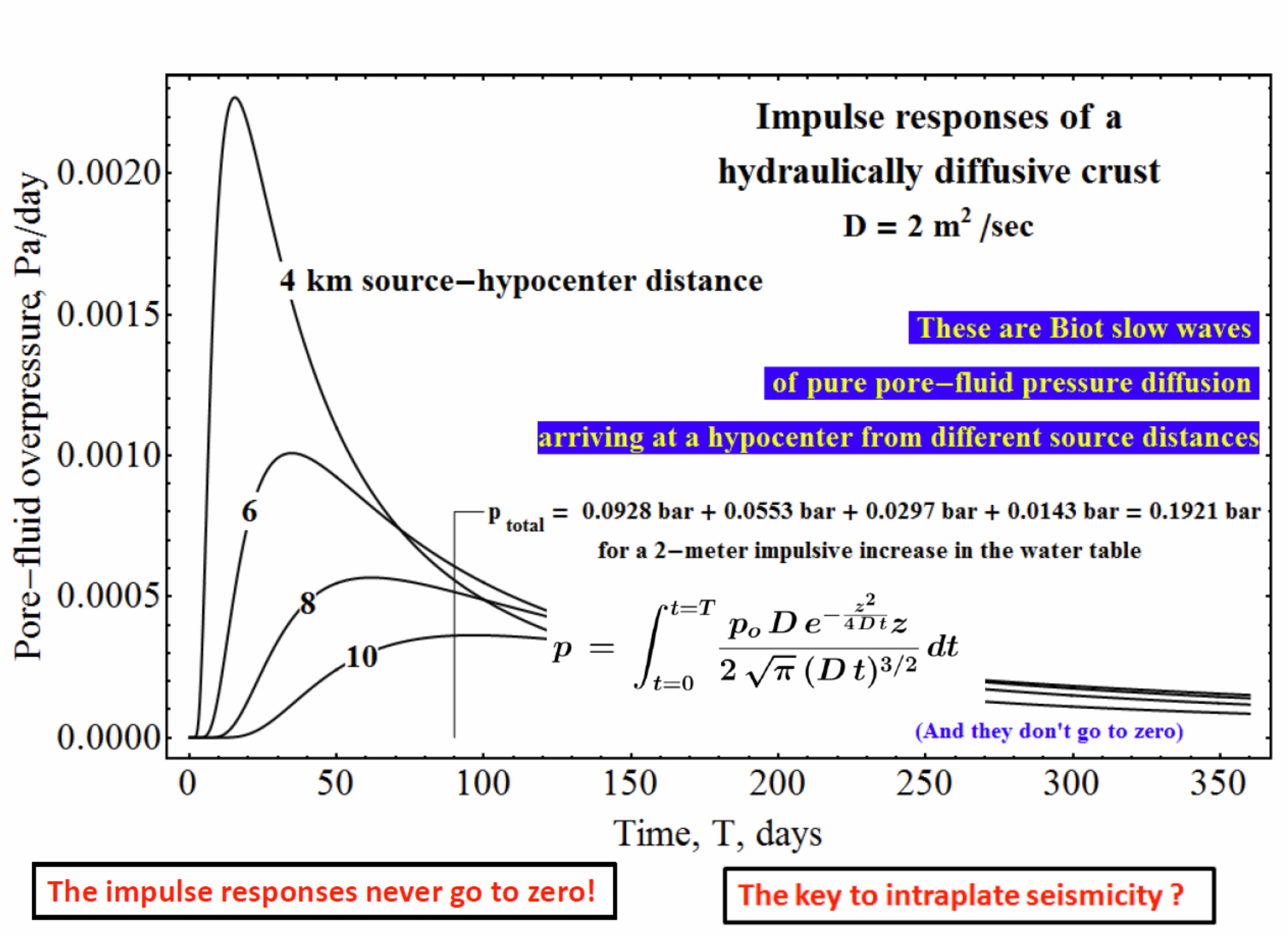
Compare with value of 1.6 m^2/sec obtained by Costain and Bollinger, 1996, J. Geodynamics

(Above approach will always give a pore-fluid pressure peak at time of earthquake)

Need more independent determinations of crustal diffusivity (in progress)

Figure 2. A hydrograph separation (purple) used to separate groundwater recharge (base flow) from total streamflow (lighter purple). The duration of base flow of 76 days (162-86) shown on the figure is the source function for the **COMSOL FEM** calculations. This groundwater recharge is believed to have triggered the magnitude 5.7 earthquake near Mineral, VA, on August 23, 2011 at a depth of 8 km.

The key characteristic of the hydraulic impulse response is that it never (theoretically) goes to zero for long times (Figure 4). Thus, the Earth's crust retains a memory of earlier pressure transients. Each recharge-day contributes to the pore-fluid pressure at depth. It is assumed that an earthquake is triggered when the pore-fluid pressure reaches a peak. Successive groundwater recharge elements send down impulses that always constructively interfere (a convolution), shifting the peak in pore-fluid pressure toward later times and gradually building up the peak until an earthquake is triggered by a reduction in effective stress. The physical significance of the convolution is best viewed from the standpoint of superposition, another name for the convolution integral.



p_{total} = 0.0928 bar + 0.0553 bar + 0.0297 bar + 0.0143 bar = 0.1921 bar for a 2–meter impulsive increase in the water table

$$p = \int_{t=0}^{t=T}\frac{p_o\,D\,e^{-\frac{z^2}{4Dt}}z}{2\sqrt{\pi}\,(D\,t)^{3/2}}\,dt$$

Figure 4. Biot slow waves of pure pore-fluid pressure diffusion in a poroelastic crust showing severe attenuation and dispersion. The pore-fluid pressure at the depth of the earthquake can be thought of as the convolution of functions like these with the surface recharge source function obtained from the hydrograph separation. Each recharge-day (an impulse) contributes a Biot slow wave.

Conclusion: Finite element models (FEMs) are useful as a way to examine the buildup of pore-fluid pressure in fracture zones due to groundwater recharge from the surface of the Earth. Results of FEM modeling using **COMSOL MultiPhysics** are consistent with the assumptions of "hydroseismicity", which attributes intraplate seismicity to the dynamics of the hydrologic cycle, and supports the suggestion of Costain and Bollinger (2010) that naturally-occurring earthquakes fall into just one of two categories: 1) those associated with the dynamics of plate tectonics, or 2) those associated with the dynamics of the hydrologic cycle. The triggered intraplate earthquakes typically follow surface disturbances in pore-fluid pressure by 60-90 days.

Reference: Costain, J.K. and G.A. Bollinger, Review: Research Results in Hydroseismicity from 1987 to 2009, Bulletin Seismological Society America, v. 100, No. 5A, p. 1841-1858 (2010).

Excerpt from the Proceedings of the 2013 COMSOL Conference in Boston