Surface Heat Flow Across the San Andreas Fault

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SIO 234: Geodynamics

October 28, 2013

Shear Stress on San Andreas Fault

$$\tau(z) = \mu \rho_c g z$$

Calculated shear stress for San Andreas Fault: ~100 MPa

For an earthquake:

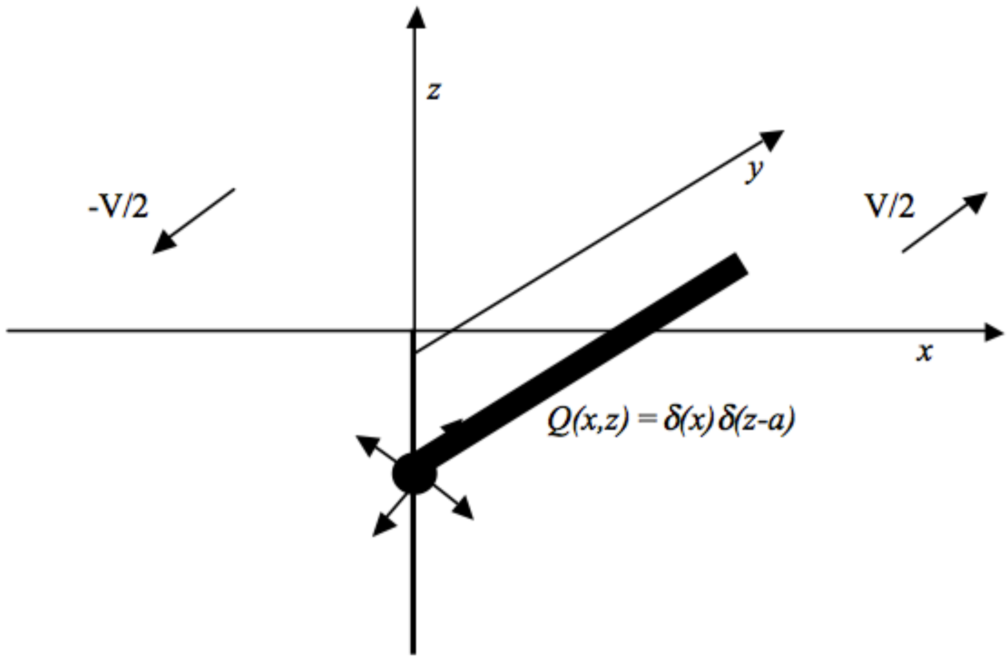
Average recorded stress drop ~ 0.1 – 1 MPa

Locally can be up to 20 Mpa

Derive an expression for heat flow anomaly at the surface due to frictional heating along the fault

Heat source across fault: $v*\tau(z)$

Derivation of Temperature Anomaly Over a Line Source of Heat



Differential Equation and Boundary Conditions:

$$\nabla^2 T = (1/k)Q(x,z) = \delta(x)\delta(z+a)$$

$$T(x,0) = 0, \lim_{|x|\to\infty} T(x,z) = 0, \lim_{z\to\infty} T(x,z) = 0$$

Derivation of Temperature Anomaly Over a Line Source of Heat

2-D Fourier Transform, followed by Inverse Transforms:

$$T(k_x, k_z) = \frac{e^{-i2\pi k_z a}}{-4\pi^2(k_x^2 + k_z^2)}$$

Inverse transform with respect to z:

$$T(k_x, z) = \frac{-1}{4\pi^2} \int_{\infty}^{\infty} \frac{e^{i2\pi k_z(z+a)}}{(k_z + ik_x)(k_z - ik_x)} dk_z$$

$$= \frac{-e^{-2\pi |k_x| (z+a)}}{4\pi \, |k_x|}$$

Derivation of Temperature Anomaly Over a Line Source of Heat

Inverse Transform with respect to x:

$$T(x,z) = \frac{-1}{4\pi}\int_{\infty}^{\infty} \frac{e^{-2\pi|k_x|(z+a)}}{|k_x|} e^{i2\pi|k_x|x} dk_x$$

Use derivative property of Fourier transforms to evaluate integral:

$$\frac{\partial T(x,z)}{\partial z} = \frac{1}{2}\int_{\infty}^{\infty} e^{-2\pi|k_x|(z+a)} e^{i2\pi k_x x} dk_x$$

Derivation of Temperature Anomaly Over a Line Source of Heat

Fortunately, we can look up this integral:

$$\frac{\partial T(x,z)}{\partial z} = \frac{-(z+a)}{4\pi[x^2+(z+a)^2]}$$

And analytically solve:

$$T(x,z) = \frac{-1}{4\pi}\ln[x^2+(z+a)^2]^{1/2}$$

Solving for boundary conditions...

$$T(x,z) = \frac{-1}{4\pi}\ln\left(\frac{x^2+(z+a)^2}{x^2+(z-a)^2}\right)^{1/2}$$

Derivation of Surface Heat Anomaly Over a Line Source of Heat

We now want to look at heat flow in our area using this temperature anomaly:

$$q(x,z,a) = -k\frac{\partial T}{\partial z} = \frac{1}{4\pi}\left[\frac{z+a}{x^2+(z+a)^2} - \frac{z-a}{x^2+(z-a)^2}\right]$$

The surface heat anomaly is this evaluated at z = 0:

$$q(x,z,a)|_{z=0} = q(x,a) = \frac{1}{4\pi}\left[\frac{a}{x^2+a^2} - \frac{-a}{x^2+a^2}\right]$$

$$= \frac{1}{4\pi}\frac{2a}{x^2+a^2}$$

Derivation of Surface Heat Anomaly for a Frictionally Generated Heat Source

Use a Green's function, *q(x,a),* to evaluate the heat flow over an arbitrary source distribution, *f(a)*:

$$q(x) = \int q(x,a) f(a) da$$

We already solved for *q(x,a).*

For our system, *f(a)* is the heat generated due to frictional heating:

$$f(a) = v \cdot \tau = v \mu \rho_c g a$$

Derivation of Surface Heat Anomaly for a Frictionally Generated Heat Source

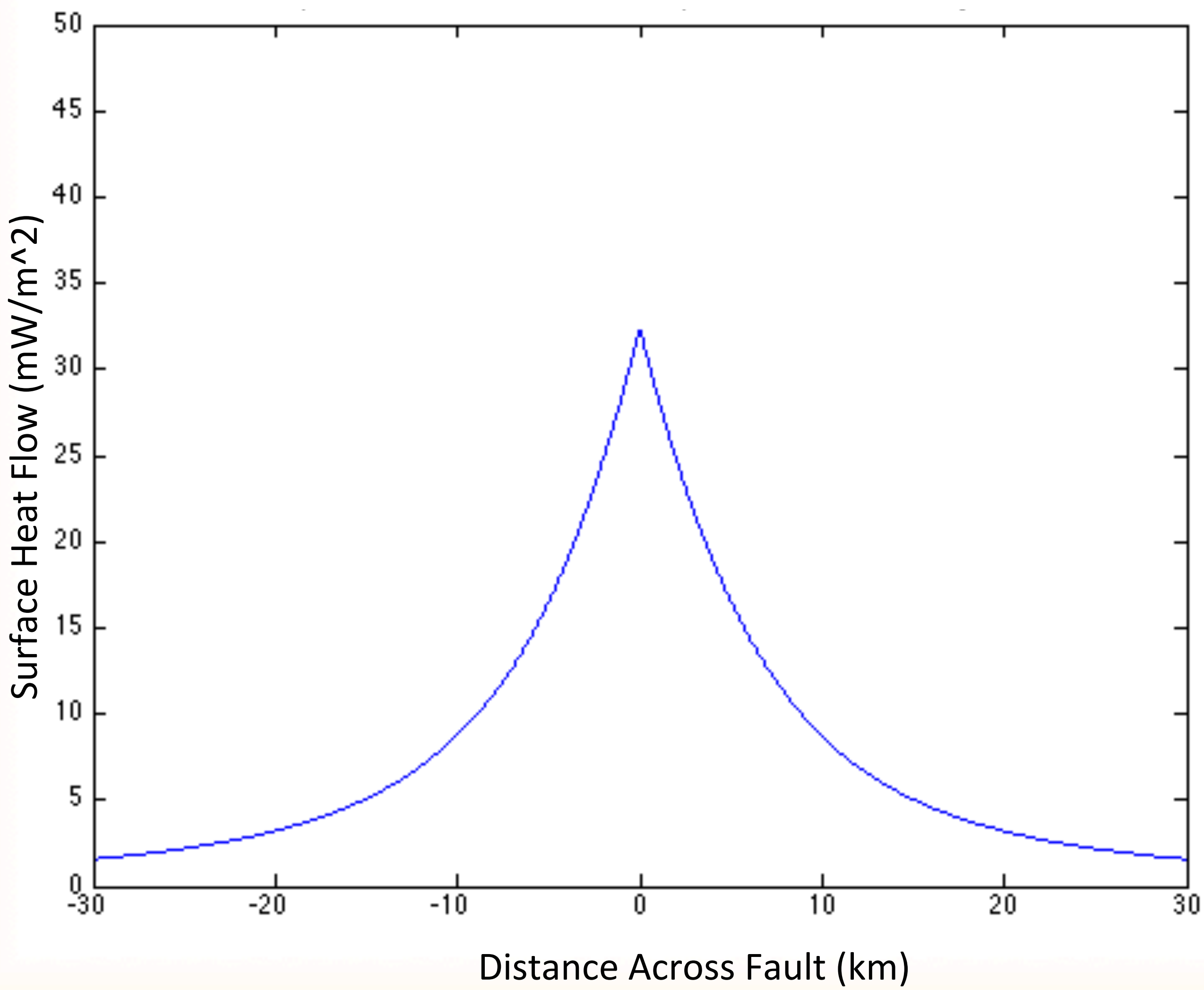
We can substitute *q(x,a)* and *f(a)* into the equation:

$$q(x) = \frac{2v\mu\rho_c g}{4\pi} \int_{a_1}^{a_2} \frac{a^2}{x^2 + a^2} da$$

The expected surface heat anomaly:

$$q(x) = \frac{2v\mu\rho_c g}{4\pi} \left[a - x \tan^{-1}\left(\frac{a}{x}\right)\right]\Big|_{a_1}^{a_2}$$

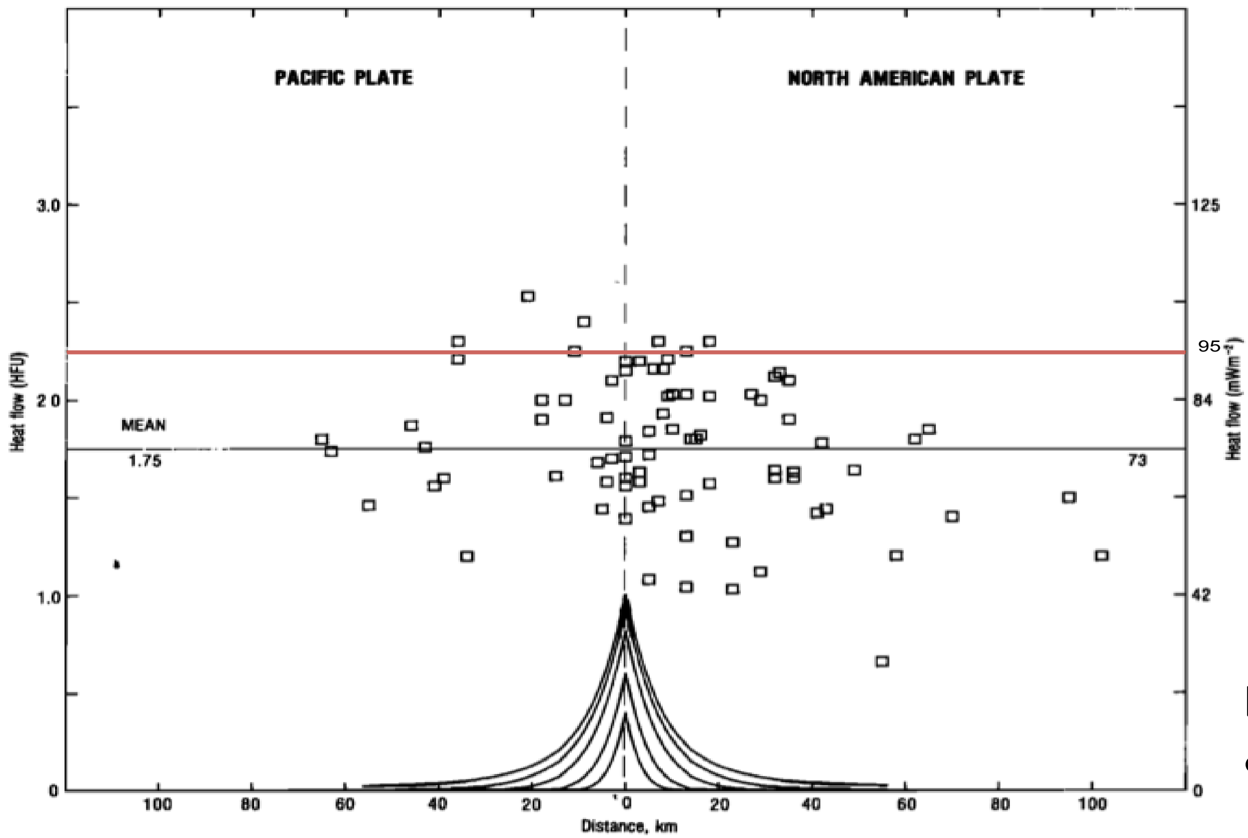
Expected Surface Heat Anomaly Across the San Andreas Fault



Parameters:

- v = 35 mm/yr
- g = 9.8 m/s^2
- ρ = 2600 kg/m^3
- **D = 0 - 12 km**
- **μ = 0.6**

Surface Heat Flow Measurements Across the San Andreas Fault



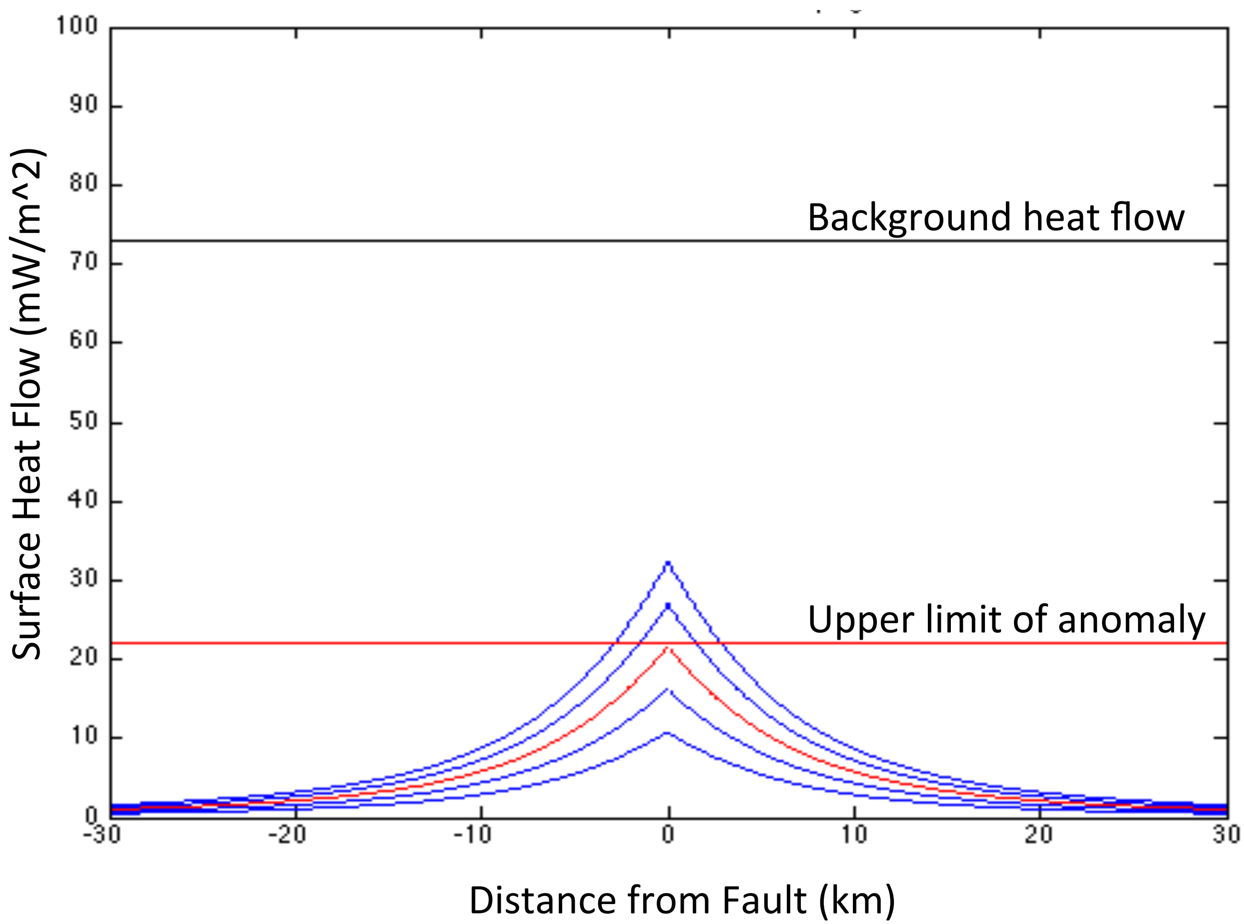
Lachenbruch & Sass (1980)

No observed heat flow anomaly

Background surface heat = 73 mW/m^2

What is the upper limit on μ in order for the anomaly to fit within the data?

Varying the Coefficient of Friction



Upper limit of coefficient of friction: **μ ≈ 0.4**

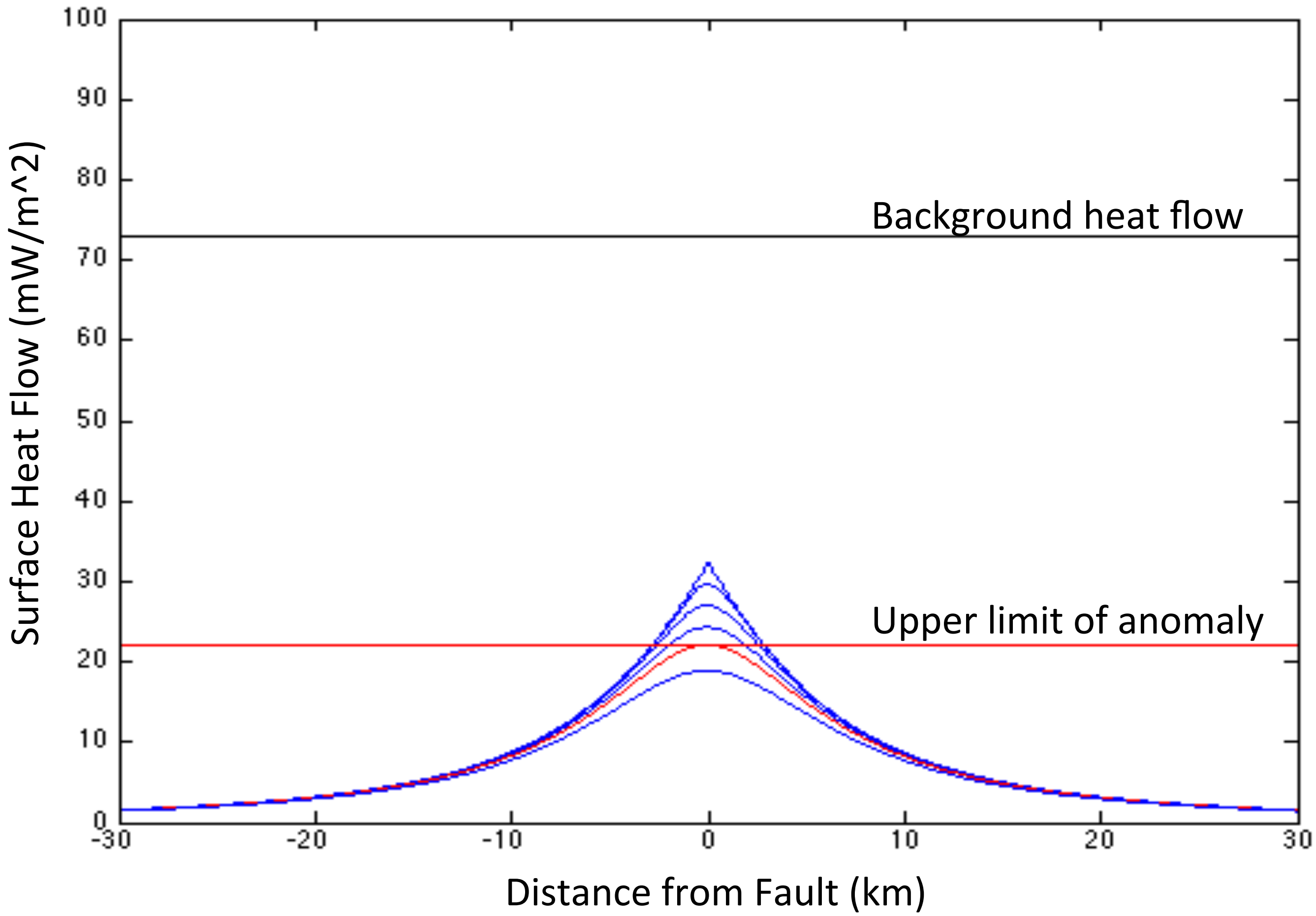
Could there be another reason why we don't see a heat flow anomaly?

Groundwater flow can redistribute the frictional heat generated from a strong fault

Effectively lowers the upper limit of the seismogenic zone

How deep would the groundwater have to penetrate in order for $\mu = 0.6$?

Varying Depth of Water Table



Groundwater must penetrate at least **3.8 km** in order for $\mu = 0.6$

The movement of groundwater alone cannot account for the missing anomaly

Is the San Andreas Fault a weak fault in a strong crust?

- Hot springs account for <1% of expected heat (Lachenbruch & Sass, 1980)
- Talc found in serpentinite could explain low μ value for creeping sections (Moore & Rymer, 2007)

However:

- Stress measurements either inconclusive or indicate strong fault (Scholz, 2000)

Summary

Expect surface heat flow anomaly to spike at the fault

Heat measurements indicate no such anomaly

Much debate over whether the San Andreas Fault is weak or if the heat flow model is wrong

References

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