Heat Flow across the San Andreas Fault

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Outline

- San Andreas Heat Flow Paradox
- Average Shear Stress vs. Earthquake Stress Drop
- Solving for Temperature and Surface Heat Flow
- Data Comparison
- Considering Hydrothermal Circulation
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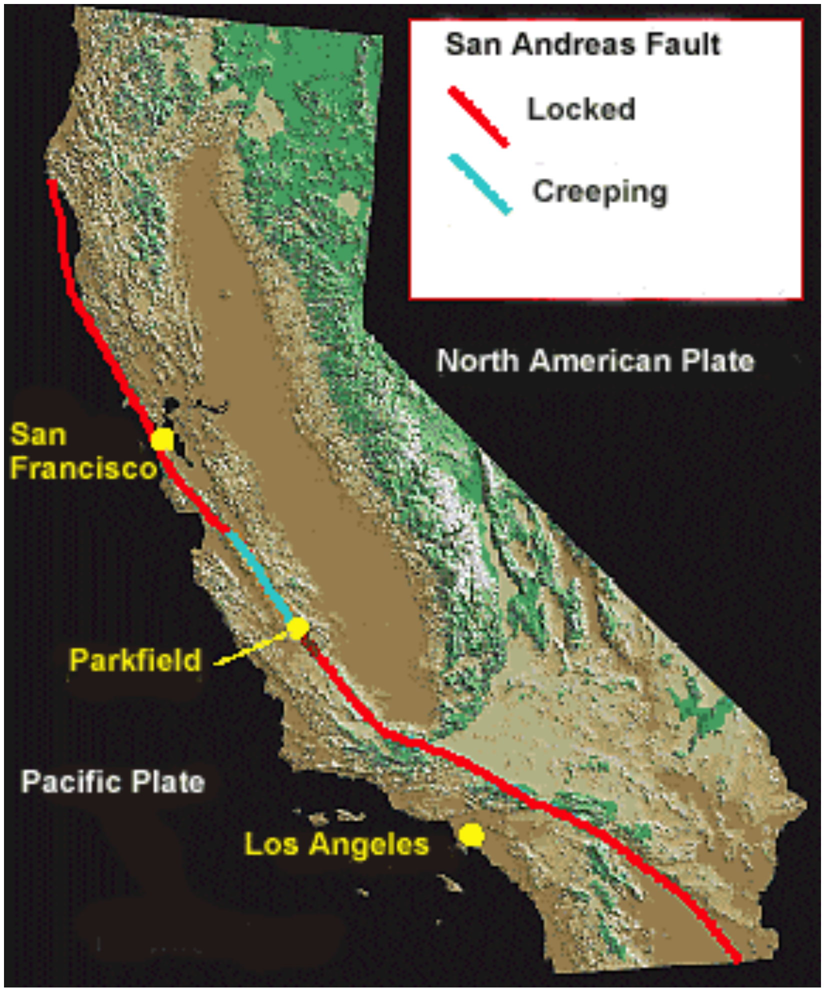
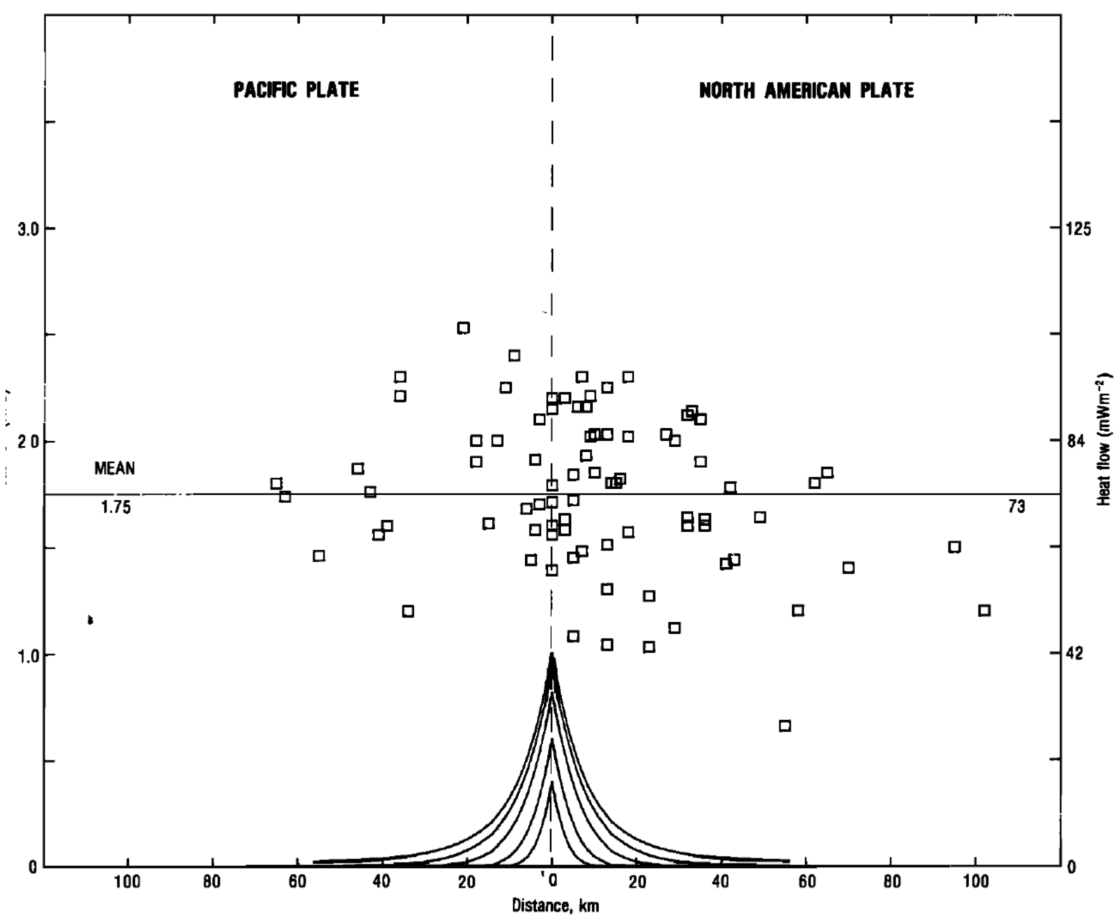
San Andreas Fault



The San Andreas Fault is a continental transform fault that runs a length of roughly 810 miles (1,300 km) through California in the United States. The fault's motion is right-lateral strike-slip (horizontal motion). It forms the tectonic boundary between the Pacific Plate and the North American Plate.

It begins near the Salton Sea at the northern terminus of the East Pacific Rise and runs mainly northwest until terminating at the Mendocino Triple Junction.

San Andreas Heat Flow Paradox



It was recognized about 40 years ago that if the frictional strength of faults was as high as indicated by laboratory rock mechanics experiments (coefficient of friction 0.6 to 0.7), there should be an observable heat flow anomaly associated with high slip rate faults, such as the San Andreas.

However, the lack of an observed heat flow anomaly on the San Andreas has been termed the "San Andreas Heat Flow Paradox" [Lachenbruch and Sass, 1980].

Shear Stress on the Fault

The shear stress on the locked fault :

$$\tau(z) = f\rho_c gz$$

Assuming that water percolates to 12 km depths to lower friction on the fault, the average shear stress on the fault can be computed as:

$$\tau(z) = f(\rho_c - \rho_w)gz$$

where

f---static coefficient of friction (~0.60)

ρ_c---crustal density (2600kg/m^3)

ρ_w---water density (2600kg/m^3)

g---acceleration of gravity (9.8m/s^2)

D---depth of seismogenic zone (12km)

Average Shear Stress vs Stress Drop

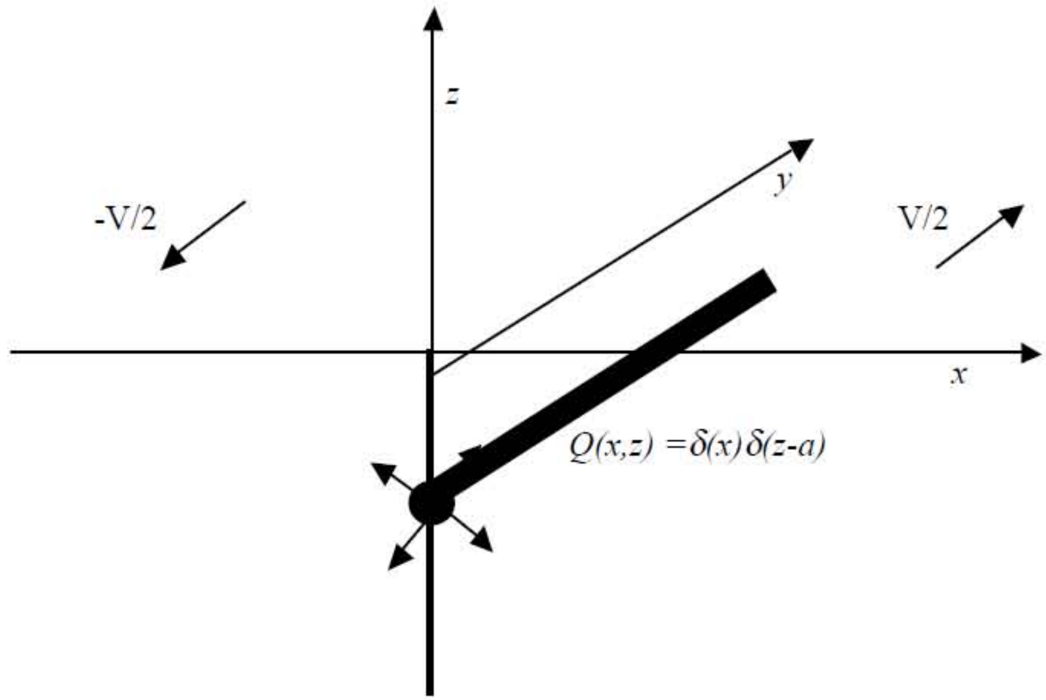
The seismogenic zone extends from the surface to a depth of about 12 km. The average shear stress on the fault could be computed as:

$$\bar{\tau} = \frac{1}{D}\int_0^D f\rho_c gzdz = \frac{1}{2}f\rho_c gD = 91.7\ MPa$$

$$\bar{\tau} = \frac{1}{D}\int_0^D f(\rho_c - \rho_w)gzdz = \frac{1}{2}f\ (\rho_c - \rho_w)gD = 56.4\ MPa$$

The observed stress drop during an earthquake ranges from 0.1 to 10 MPa with a typical value of 5 MPa which is about 18 times smaller than the average stress from above. This implies that only a fraction of the total stress is released during an earthquake.

Line Source Model of Hear Flow



Assumptions:

- Thermal conductivity is the only mode of heat transfer.
- There is infinite extension in the y-direction.
- This considers a narrow zone of seismicity.

Differential Equation and Boundary Conditions

The differential equation for a unit amplitude, line source at depth a

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

Boundary conditions

$$T(x,0)$$

which implies that no temperature anomaly at the ground surface, and

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

which indicates that temperature anomaly vanishes when the distance and the depth are large enough from the source.

Solution for Temperature Anomaly

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{k}\delta(x)\delta(z+a)$$

Fourier Transform in both Side

$$-(2\pi)^2(k_x^2 + k_z^2)T(\vec{k}) = \frac{1}{k}e^{i2\pi k_z a}$$

Solve for T

$$T(\vec{k}) = -\frac{1}{k}\frac{e^{i2\pi k_z a}}{(2\pi)^2(k_x^2 + k_z^2)}$$

Solution for Temperature Anomaly

Inverse Fourier Transform of T

$$T(k_x, z) = -\frac{1}{(k2\pi)^2} \int_{-\infty}^{\infty} \frac{e^{i2\pi k_z (z+a)}}{(k_x^2 + k_z^2)} dk_z$$

$$T(k_x, z) = -\frac{1}{(k2\pi)^2} \int_{-\infty}^{\infty} \frac{e^{i2\pi k_z (z+a)}}{(k_x + ik_z)(k_x - ik_z)} dk_z$$

Cauchy Residue Theorem

$$\oint \frac{f(x)}{x - x_0} = i2\pi f(x)$$

Solution for Temperature Anomaly

Taking the absolute value of k_x

$$T(k_x, z) = -\frac{1}{2k}\frac{e^{-i2\pi|k_x|(z+a)}}{(2\pi \mid k_x \mid)}$$

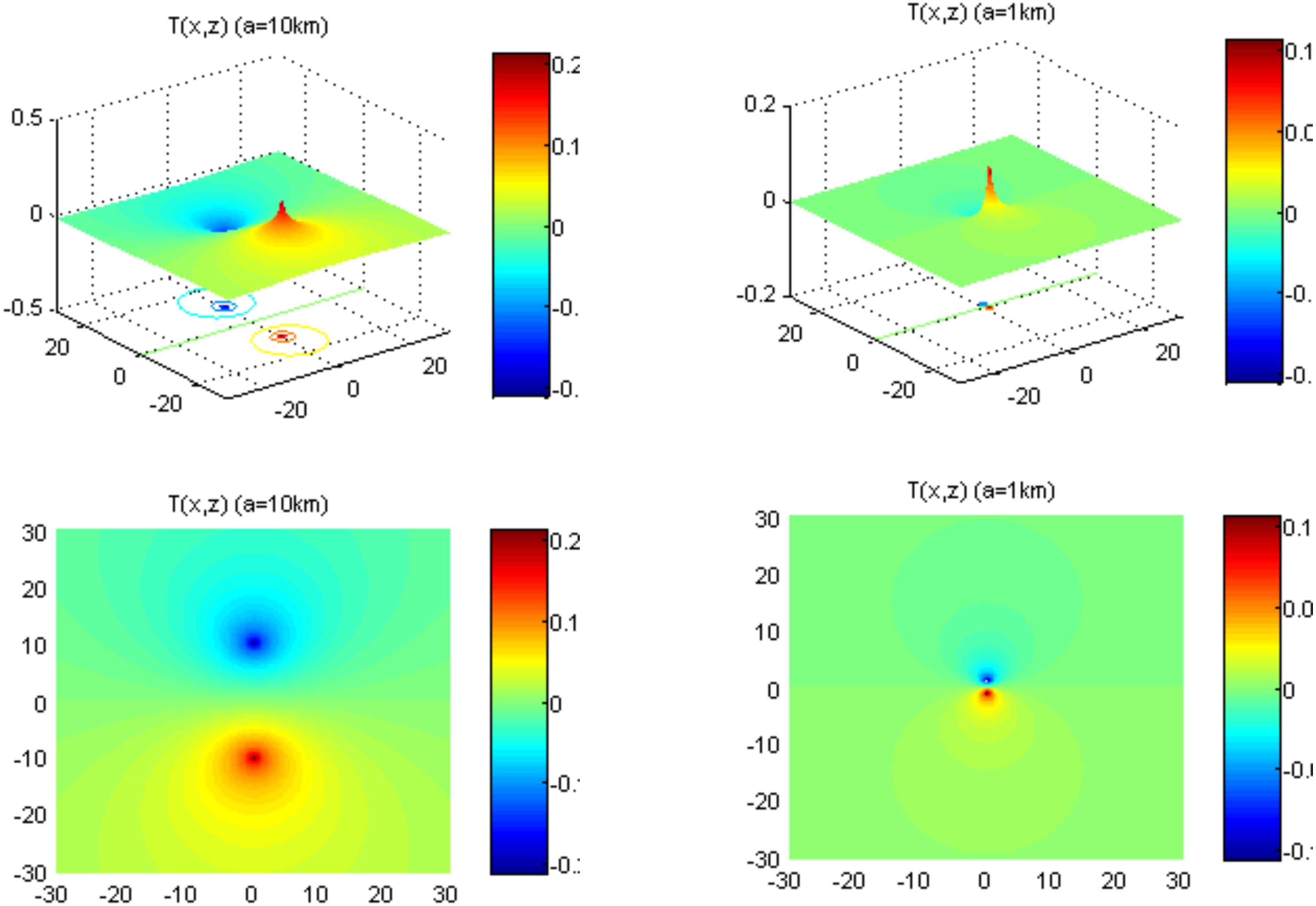
The Green's Function of Inverse Cosine Transform

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

Including the Image Source

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

T(x,z) Plots



T(x,z) (a=10km)
0.5
0
-0.5
20
0
-20
-20
0
20
0.2
0.1
0
T(x,z) (a=1km)
0.2
0
-0.2
20
0
-20
-20
0
20
0.1
0
T(x,z) (a=10km)
30
20
10
0
-10
-20
-30
-30 -20 -10 0 10 20 30
0.2
0.1
0
T(x,z) (a=1km)
30
20
10
0
-10
-20
-30
-30 -20 -10 0 10 20 30
0.1
0

Heat Flow for a Line Source

The heat flow for a unit amplitude, line source at depth a

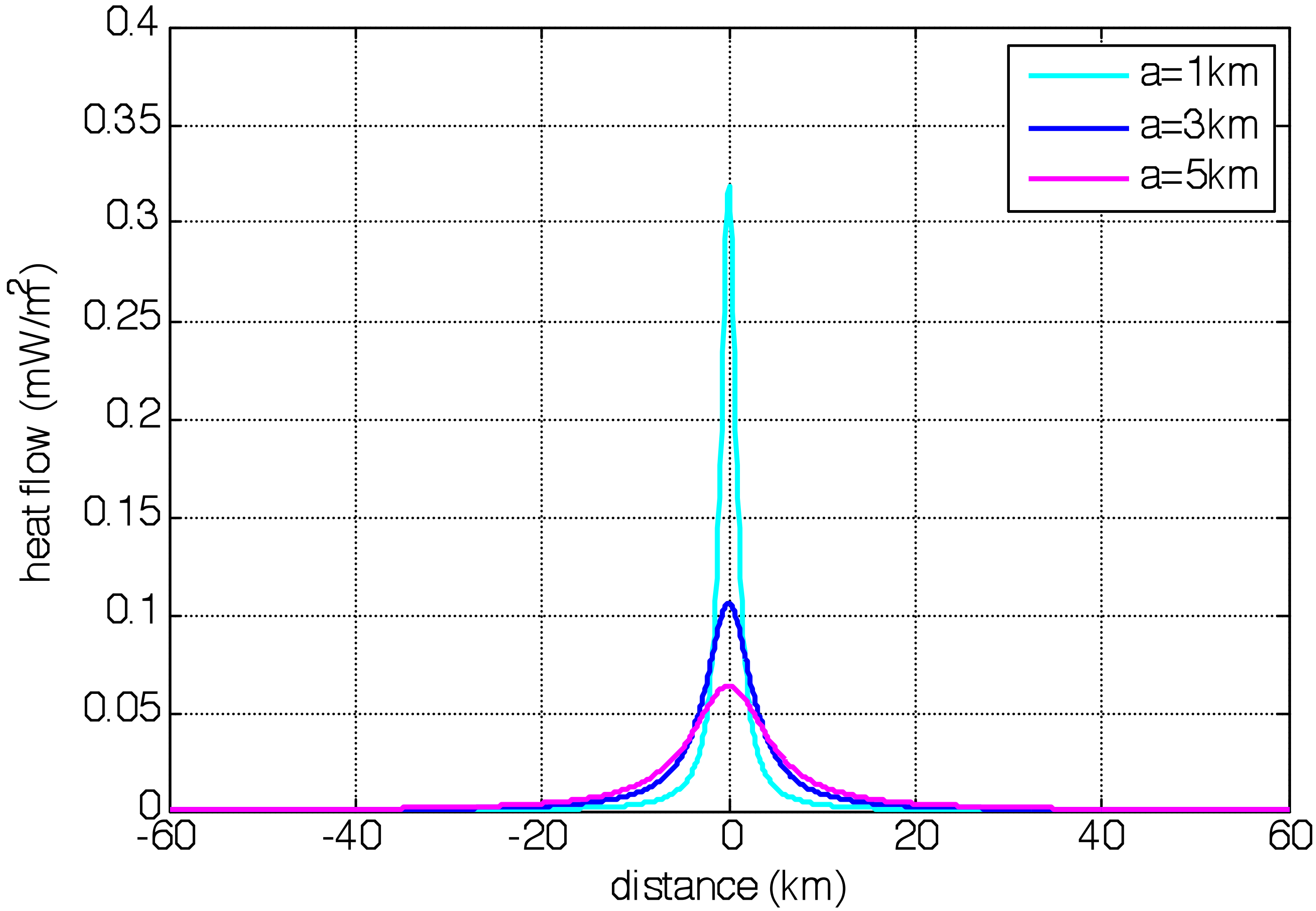
$$q(x,z) = -k\frac{dT}{dz}$$

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

The surface heat flow for a unit amplitude, line source at depth a

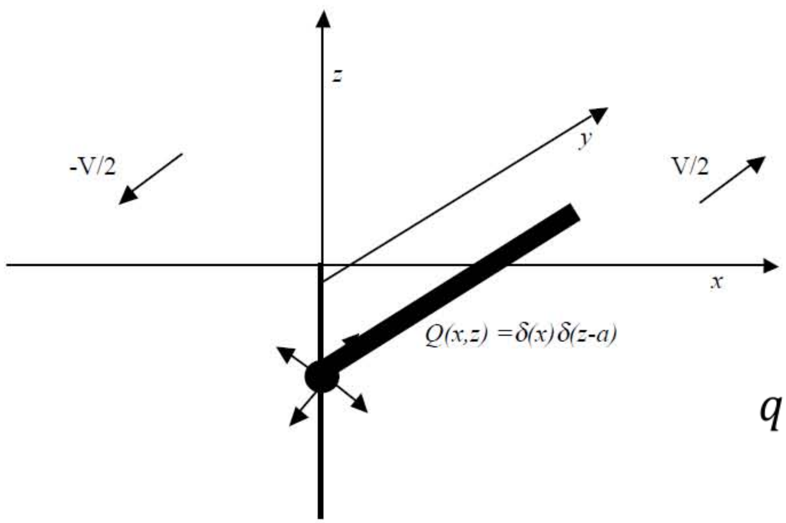
$$q(x) = \frac{1}{\pi}\,\frac{a}{x^2+a^2}$$

Heat Flow from a Line Source at Different Depth

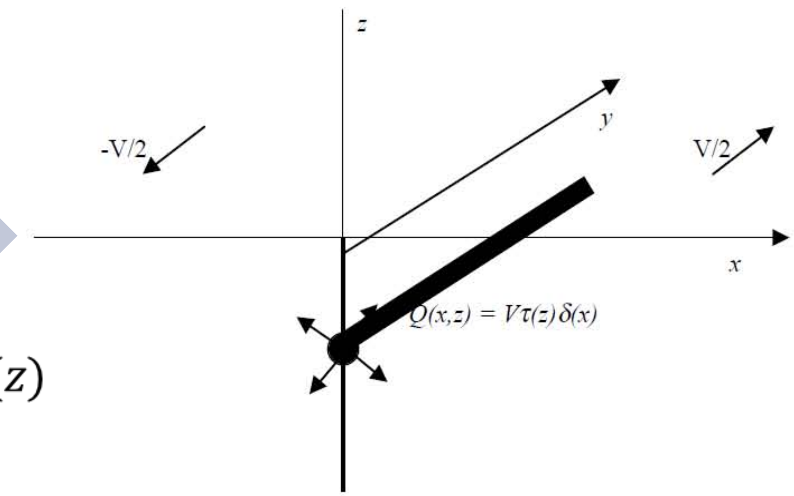


Line Source vs. Arbitrary Stress Distribution

a unit amplitude, line source at depth a



$$q = V\tau(z)$$



$$q(x) = \frac{1}{\pi} \frac{a}{x^2 + a^2}$$

$$q(x) = \frac{V}{\pi} \int_0^\infty \frac{z\tau(z)}{x^2 + z^2} dz$$

Heat Flow for Arbitrary Stress Distribution

The heat flow for an arbitrary shear stress distribution

$$q(x) = \frac{V}{\pi} \int_{0}^{\infty} \frac{z\tau(z)}{x^2 + z^2} dz$$

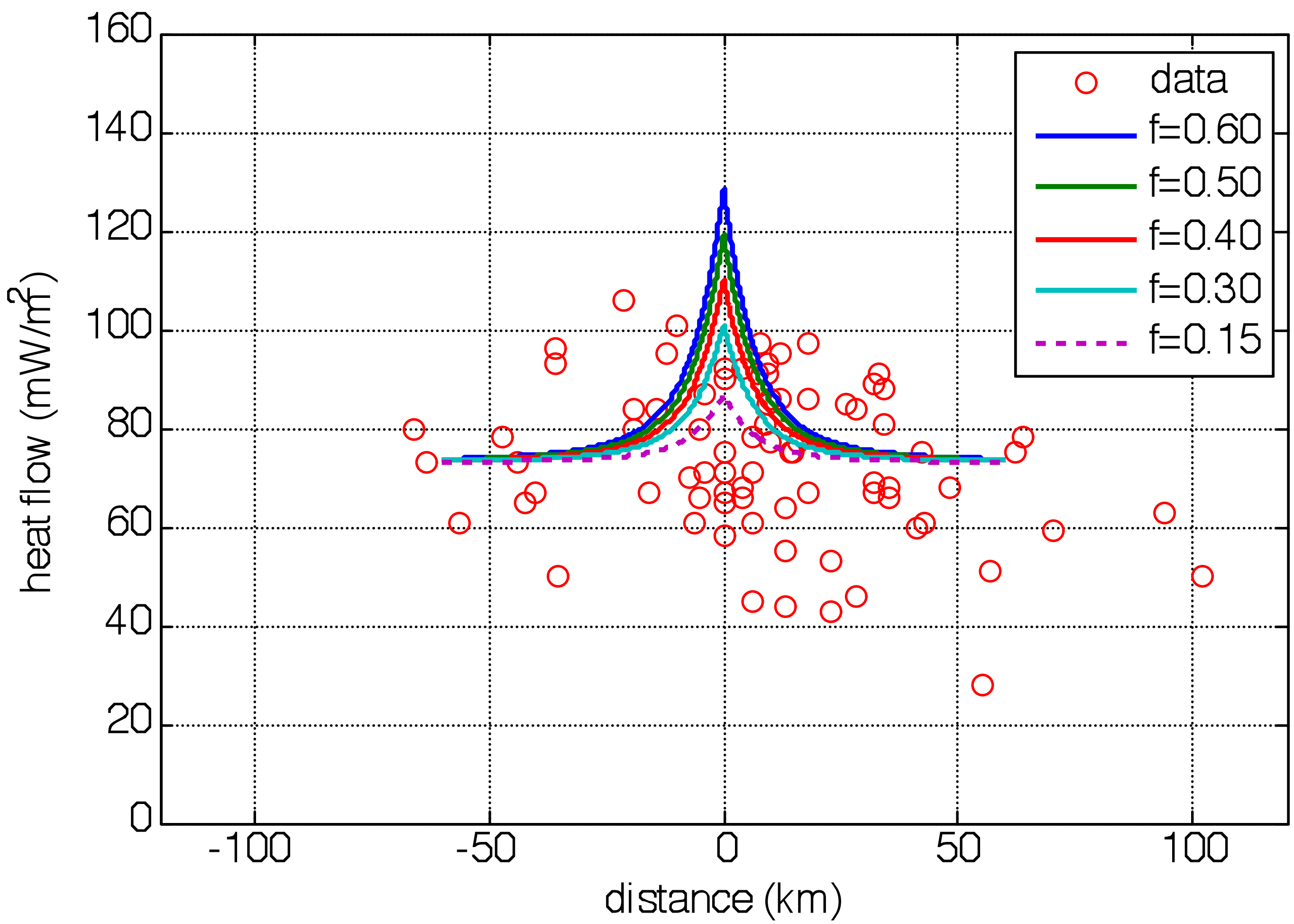
Plug the shear stress with the equation $\tau(z) = f\rho_c gz$

$$q(x) = \frac{f\rho_c gV}{\pi} \int_{0}^{D} \frac{z^2}{x^2 + z^2} dz$$

Solve for surface heat flow

$$q(x) = \frac{f\rho_c gV}{\pi} [D - xtan^{-1}\left(\frac{D}{x}\right)]$$

Data Comparison



Surface Heat Flow w/ Hydrothermal Circulation

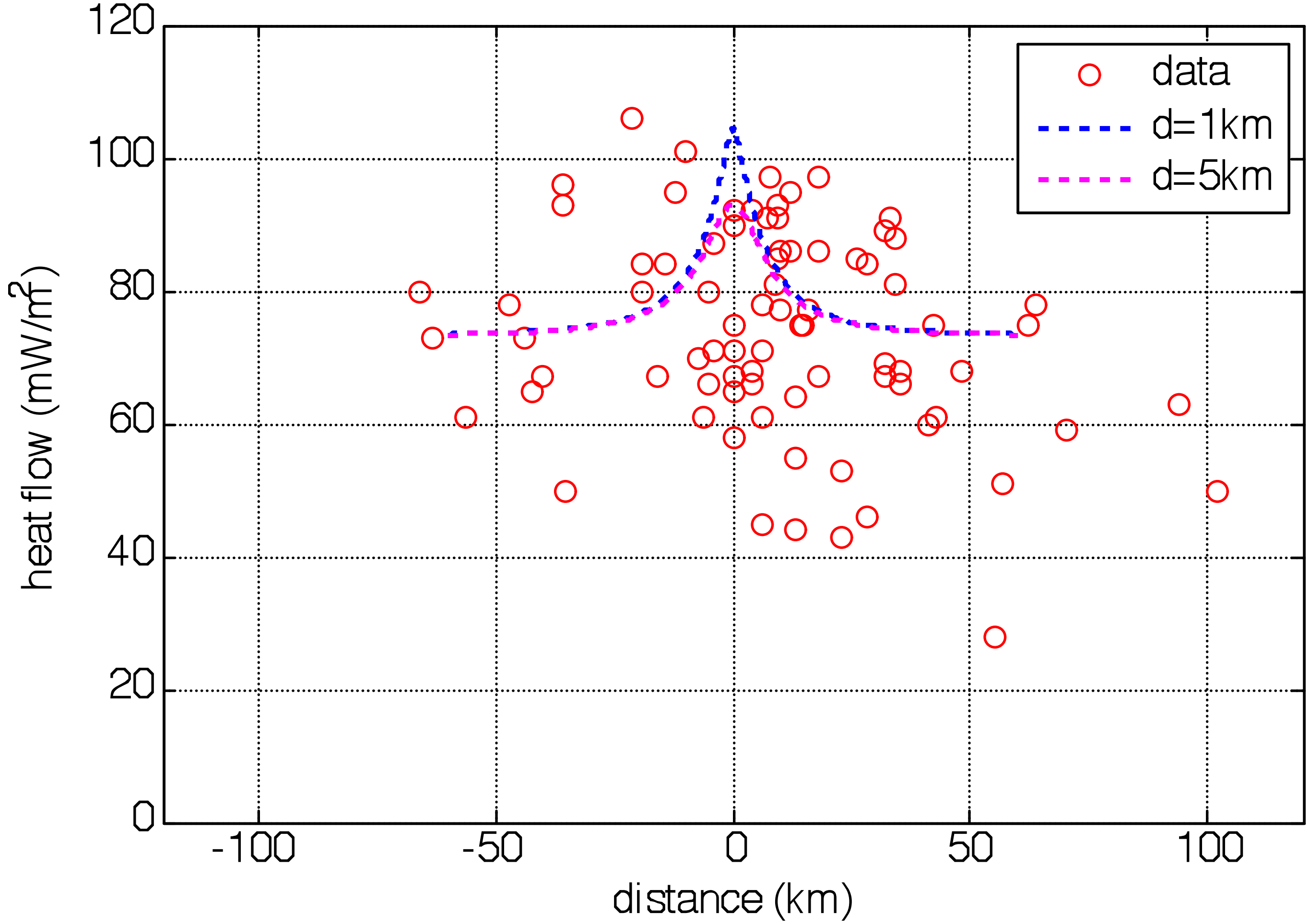
Considering a hydrothermal circulation penetrates the crust to a depth d and removes all the heat generated on the fault between 0 and d. The heat flow for an arbitrary shear stress distribution. Plug the shear stress with the equation $\tau(z) = f(\rho_c - \rho_w)gz$

$$q(x) = \frac{f(\rho_c - \rho_w)gV}{\pi} \int_d^D \frac{z^2}{x^2 + z^2} dz$$

Solve for surface heat flow

$$q(x) = \frac{f(\rho_c - \rho_w)gV}{\pi} \left\{ (D-d) + \left(x \tan^{-1}\frac{d}{x} - x \tan^{-1}\frac{D}{x} \right) \right\}$$

Data Comparison



Ways to Understand Heat Flow Paradox

1. "Low Strength" Fault: the friction strength of the fault is much lower than laboratory values
   - The friction coefficient could be low as 0.05 and the average stress on the fault is 10-20 times smaller than predicted by Byerlee's law.

2. "High Strength" Fault: the friction strength of the fault is as strong as the predicted values, but there are other factors
   - the coefficient of friction drops from 0.6 to 0.05 to temporarily disable the heat generation during an earthquake;
   - Heat is generated, but a large fraction of the heat is advected to the surface by circulation of water in the upper crust.

Summary

The observed typical stress drop during an earthquake is about 18 times smaller than the average stress from above. This implies that only a fraction of the total stress is released during an earthquake.

The temperature and heat flow from a fault can be derived analytically given the shear stress distribution of along the depth.

The heat flow obtained analytically is highly dependent on the frictional coefficient. Compared with measured data, the friction coefficient of 0.6 obviously overestimates the measured heat flow. None of the value agrees well with the measurements at SAF, since there is lack of observed heat flow anomaly at SAF.

Considering the hydrothermal circulation, the results somewhat improved in terms of peak values compared with the measured data. However, the results depends much on the value of depth d. Therefore, the friction coefficient of 0.6 obviously is acceptable if a reasonable valud depth d is chosen.

References

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