The molecular record of thermal history: using organic molecules in faults to measure frictional heating

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Introduction
The heating signature recorded in a fault after an earthquake is a reliable indicator of the shear stress during slip. To determine how much a fault has been heated, we examined the thermal alteration of organic material, a new method that can be applied even when there are no other indicators of heating, such as pseudotachylyte (frictional melt in rock). Due to differences in thermal stability, if a rock is heated the refractory molecules become more concentrated relative to those that are less thermally stable. We calculated these concentrations in samples from two different faults: the methylphenanthrene index MPI-1 in samples from the Muddy Mountain Fault, Nevada, and the ratio of highly stable diamondoids to less stable alkanes in the Pasagshak Point Fault, Alaska.

Background
Diamondoids are hydrocarbons with a rigid diamond-like ring structure that makes them highly stable, even at the high temperatures that break down the surrounding petroleum molecules into natural gas. As the temperature of the rock rises, diamondoids become more concentrated within this diminishing petroleum. If this concentration ratio is high, the rock has experienced more heating. We used the diamondoid diamantane (C_{20}H_{30}) for these calculations.

Diamondoid to alkane ratio: $\frac{D + 3MD + 4HD}{alkanes}$

Molecular structures of the three simplest diamondoids: adamantane, diamantane, and triamantane

Methylphenanthrenes are aromatic molecules whose pattern of methylation changes with thermal maturity. The second ratio used to evaluate our samples was the maturity index MPI-1. This ratio measures the amount of methylphenanthrene’s refractory isomers 2 and 3 relative to the less stable isomers 9 and 1. Similar to the diamondoid ratio, the methylphenanthrene index of a fault increases with increasing temperature.

Methylphenanthrene index:

$\text{MPI-1} = \frac{15(MP + 3MP) + 1(MP + 3MP + 5MP)}{F + 1(MP + 3MP)}$

Molecular structure of phenanthrene and the methylphenanthrenes

Methods
We analyzed 9 Muddy Mountain samples and 7 Pasagshak Point samples with the following steps:
1. Outside of the sample cleaned with dichloromethane.
2. Sample ground into a fine powder.
3. Organic molecules extracted using an Accelerated Solvent Extractor (ASE) or through sonication extraction.
4. Total lipid extract eluted through a silica-gel column to separate aliphatic, aromatic, and polar fractions.
5. Fractions analyzed on a combined gas chromatograph-mass spectrometer, then identified and quantified.

Results and discussion
In the Pasagshak Point fault, there is a visible line of pseudotachylyte (Figures 3 and 5). The diamondoid concentrations are much higher within and immediately adjacent to the pseudotachylyte, and decrease rapidly even millimeters away from it. Higher concentrations of diamondoids in pseudotachylyte-bearing rocks suggest that the thermal maturity of organic material is a reliable indicator of the fault’s thermal history. This result demonstrates that the molecular indicators of thermal alteration are sensitive to the rapid heating that occurs on a fault during an earthquake.

Our preliminary analysis of the Muddy Mountain samples found no difference in MPI-1 between the on-fault and off-fault samples. While this may suggest that the fault did not experience heating during slip, we are currently measuring additional samples to verify this result.

Conclusions
1. The Pasagshak Point Fault samples have diamondoid concentrations that increase nearer to the visible pseudotachylyte, demonstrating that these thermal indicators are sensitive to the rapid heating that occurs on a fault during an earthquake.
2. The ratios of refractory organic molecules to less thermally stable molecules can be used to measure the thermal maturity of fault rocks. This thermal signature contains valuable information on the temperature and shear stress a fault has experienced over its lifetime.
3. The Muddy Mountain Fault samples may not have experienced heating during slip, possibly indicating low shear stress. However, more analysis is needed.

References

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