Paleo-stress estimates on ancient seismogenic faults based on frictional heating of coal

By
Kieran O’Hara
Dept. Geological Sciences
University of Kentucky
Lexington
KY 40502

Email: geokoh@uky.edu
Tel: 859-257-6931
FAX: 859-323-1938
Abstract Faulted coals from eastern Kentucky and Montana (USA), and the south Wales coalfield (UK) show fault-related vitrinite reflectance anomalies interpreted as due to frictional heating during seismic slip. The vitrinite reflectance anomalies are converted to temperature using kinetic-based software (Easy%R) for temperature gradients consistent with modeling of a seismic source. Shear stresses are calculated using Lachenbruch’s (1986) piezometer, which depends only on the area under the thermal anomaly and fault displacement. For displacements of 1-3 meters, the shear stresses are 15-40 MPa, and are similar to seismological estimates of stress drops during modern earthquakes. The calculated local mean normal stress is 75 MPa, resulting in coefficients of friction of 0.2-0.5 (thrust) and 0.3-0.7 (normal faults), which are lower than laboratory-based values.

Index list: 7221- paleoseismology; 8130-heat generation; 8164- stresses, crust and lithosphere

Introduction
A major problem in structural geology and tectonics today is the so called “heat-flow paradox” on the San Andreas fault (SAF) where little agreement exists on whether this plate boundary is weak or strong [e.g. Zoback, 2000; Scholz, 2000 and references therein]. Simply stated, a conspicuous local heat flow anomaly should be observed on the SAF due to repeated earthquakes if standard laboratory-based frictional strengths are used to generate frictional heat; however, no such localized anomaly has been observed [e.g. Lachenbruch and Saas, 1980; d’Alessio et al., 2003].
A related observation to the question of the strength of faults, is that stress drops during moderate to large earthquakes are typically low [3-30 MPa; Kanamori, 1994; Scholz, 1990]. Do these stresses represent total stress drops on weak faults or partial stress drops on strong faults and do we understand the physical processes operative during rapid slip? This study places constraints on the thermal structure and the strength of smaller scale ancient faults using coal metamorphism as an indicator of frictional heating and thermal structure.

**Frictional heating on faults**

If all the work is converted to frictional heat during slip, and grain-size reduction, seismic radiation and work against gravity are neglected [e.g. Kanamori, 1994] the heat generated per unit area of the fault is given by $Q = \tau D$, where $\tau$ is shear stress and $D$ is slip displacement. The standard relationship $\tau = \mu \sigma_n$ is used here (but see Discussion), where $\mu$ is the coefficient of friction and $\sigma_n$ is normal stress. If heat is transferred by conduction only and the observation time is large compared to the time constant $\lambda (= a^2/4 \kappa)$, where $a$ is the fault half-width and $\kappa$ is thermal diffusivity ($10^{-6}$ m$^2$/s), then the fault can be treated as an instantaneous heat source of zero width [Lachenbruch, 1986]. For a fault zone 2 cm wide or less, typical of the faults described below, $\lambda$ is 25 seconds, which is short compared to the observation times considered here.

Figure 1 shows the temperature evolution as a function of distance from the fault for three different times [Carslaw and Jaeger, 1959, p. 259; Lachenbruch, 1986]. For post-seismic times between $10^2$ seconds (1.6 minutes) and $10^3$ seconds (17 minutes), temperatures between 1463 °C and 463 °C are reached, corresponding to a mean
temperature gradient of about $1 \, ^\circ\text{Cs}^{-1}$. For post-seismic times between $10^3$ seconds and $10^4$ seconds (2.7 hours), temperatures between 463 $^\circ\text{C}$ and 146 $^\circ$C are reached, corresponding to a mean temperature gradient of $0.035 \, ^\circ\text{Cs}^{-1}$. Because the density of coal is half that of typical rock, the temperature spikes are twice normal. It is shown below that subjecting coal to these temperatures and temperature gradients is sufficient to cause an increase in coal maturation as measured by vitrinite reflectance.

**Vitrinite reflectance**

The mechanism of coal metamorphism can be attributed to chemical reactions involving driving off of H, C and O in the form of CH$_n$, water, CO$_2$, resulting in an increase in the reflectance of vitrinite. When measured petrographically, vitrinite reflectance is annotated as $R_0\%$, $R_{\text{min}}\%$ or $R_{\text{max}}\%$, corresponding to mean, minimum and maximum values, respectively; $R\%$ is used here to indicate computer generated values. Vitrinite reflectance of coal does not undergo retrograde reactions (excepting weathering) and therefore records the peak temperature. The reactions can be described by a first order Arrhenius law where each reaction is assigned an activation energy and the overall extent of parallel reactions, $F$, is calculated [Sweeney and Burnham, 1990]. $R\%$ is related to $F$ by the relation $R\% = \exp(-1.6 + 3.7 F)$, which is calibrated using H/C and O/C atomic ratios of coals. Here I apply Sweeney and Burnham’s [1991] software (Easy%R), which is applicable over nine orders of magnitude of temperature gradient, to calculate vitrinite reflectance values that would be produced on a fault surface by a seismic heat source.

Figure 2 shows a plot of temperature versus $R\%$ for geologic (low) temperature gradients (curve A, Fig. 2) and for seismic (high) temperature gradients (curves B, C, Fig.
2) based on Easy%R. Curve A (1-100°C/Ma) is in good agreement with independent geologic data (dashed curve, Fig. 2) [Barker and Goldstein, 1990]. Curves B and C represent gradients of 0.035 and 1.0 °Cs⁻¹ respectively, consistent with a seismic heat source (Fig.1). As expected, higher temperature gradients require higher temperatures to produce a given R% value and these temperatures are consistent with Bustin's [1983] experimental data on coals (shaded region, Fig. 2).

Observations on natural coals

South Wales coalfield

Pennsylvanian coals and associated sandstones and siltstones in the coalfield of South Wales were involved in extensive brittle (rather than ductile) failure (Fig. 3a), including detachments, duplexes and small-scale thrusts related to the Variscan orogeny (~300 Ma) [Frodsham and Gayer, 1999; Gayer and Fowler, 1997]. Many faulted coals show highly localized excursions from regional coal rank trends that correspond to thrusts [Gayer et al., 1997] and the excursions are strongly correlated with the intensity of brittle deformation (Fig. 3b). Reflectance spikes (Rₚ,%) typically have a magnitude of 0.1-0.2 % and range from 0.8% to 1.07% with a standard error of less that 0.04% [Gayer and Fowler, 1997]. The deformation index (D.I., Fig, 3b) is based on the state of preservation of coal fractures, the coherence of the coal, the presence of folds and faults and tectonic fabric. Outcrop-scale faulted coals are characterized by meter-scale displacements (Fig. 3a) and cm-scale widths [Frodsham and Gayer, 1999].

The strong correlation between deformation and vitrinite reflectance (Fig. 3b) may be due to 1) shear strain, 2) hydrothermal fluid flow along deformed (and more
permeable) coals seams and 3) frictional heating during seismic slip. Several studies have shown that while shear strain can cause the anisotropy of vitrinite reflectance ($R_{\text{\%} \text{max}} - R_{\text{\%} \text{min}}$) to increase, although the absolute value of the mean reflectance ($R_{\text{\%}}$) does not change [e.g. Levine and Davis, 1989; Stone and Cook, 1979], ruling out shear strain as a cause of the reflectance excursions. Long-lived basin wide hydrothermal fluid flow would homogenize the entire coal seam on a short time scale rather than preserve the highly variable values observed (Fig. 3b). For example, heat from hydrothermal fluids will homogenize the coal on a time scale of $t = x^2/k$, where $x$ is distance, $t$ is time, and $k$ is thermal diffusivity of coal ($2 \times 10^{-7} \text{ m}^2\text{s}^{-1}$). For a 2 meter thick seam the time scale of homogenization, by conduction alone, is less than 1 year. If heat transport is by fluid advection in permeable coals, the homogenization will be even faster. On the other hand, repeated rapid pulsing of fluid along faults (e.g. by seismic pumping), would require temperatures of about $450^\circ\text{C}$ to produce the observed coal $R_{\text{\%}}$ values (curves B, C, Fig. 2), which seems excessive based on fluid inclusion studies and basin modeling [Hover and Gayer, 2000]. While basin-wide hydrothermal fluid flow can explain mineralized coal fractures, it cannot explain the anomalous excursions in $R_{\text{\%}}$ values on faults observed in figure 3b. The reflectance anomalies are best explained by frictionally generated temperature spikes of $425-475^\circ\text{C}$ (curves B, C, Fig. 2).

**Rocky Mountains, Montana**

Figure 3 shows vitrinite reflectance ($R_{\text{\%}}$) data from the Lewis thrust, Montana, plotted as a function of log distance from the fault [Bustin, 1983, Table 1]. The fault places Precambrian strata over Cretaceous clastic sedimentary rock and shales, and shearing is
restricted to a zone 1-3 cm thick. \(R_o\%\) values on individual shears immediately at the fault range from 0.7 to 3.1%. Bustin [1983, p. 316; pers. comm, 2003] attributes the anomalous values to frictional heating within 5 cm of the fault. Assuming a seismic heat source, \(R_o\%\) values of 3.0 can be produced by temperature spikes of 580-680°C (curves B, C, Fig. 2).

**Appalachian mountains, Eastern Kentucky**

Pennsylvanian coal (~310 Ma) in easternmost Kentucky is sheared and faulted along normal faults in the hanging wall of the major Pine Mountain thrust that formed during the Late Paleozoic Alleghanian orogeny (~300 Ma.). Figure 4 shows \(R_o\) values for non-sheared and sheared coals on faults from the Cumberland pilot tunnel at the western end of the Pine Mt. thrust sheet [O’Hara et al., 1990]. The coals occur in thick (1 m) horizontal interbedded sandstones and thin (cm) shales. The displacement on these faults, as indicated by displaced strata, is approximately 1-2 m. The \(R_o\%\) values of un-sheared samples are 0.72% and 0.69%, whereas sheared samples from 3 different faults have values of 0.85%, 0.80%, and 0.87%. The standard error on these analyses is 0.04% [O’Hara et al., 1990]. The enhanced maturation on the faults is again interpreted as due to frictional heating, and can be explained by a temperature spike of 425-475 °C (curves B, C, Fig. 2).

**Estimate of shear stress**

The area under the curves in Figure 1 for different times are equal because they represent a single event involving a constant amount of energy. This area A is given by \(\tau D/\rho c\)
where \( \rho \) is rock density, \( c \) is specific heat capacity, \( D \) is displacement and \( \tau \) is shear stress [Lachenbruch, 1986], which, re-arranging, gives a shear stress paleopiezometer:

\[
\tau = \frac{\rho c A}{D} \quad \text{[Eqn. 1]}
\]

In the case of the Lewis thrust Montana (Fig. 4) the area under the curve can be approximated as a triangle with a half-width at the base of 5 cm and a height of 580-680 \( ^\circ \text{C} \) (Fig. 2), giving an area of 29-34 degree-meters. Assuming the thermal anomaly was produced by a single earthquake, for a displacement of between 1 and 3 meters (corresponding to moderate and large earthquakes, respectively), and a constant value for \( \rho c (1.35 \times 10^6 \text{ Jm}^{-3} \text{ K}^{-1}) \) the calculated shear stress on the thrust is 13-39 MPa (Table 1). Using the same approach for the anomalous coal rank in the Pennsylvanian coals of eastern Kentucky, and assuming the mean fault rank anomaly (\( R_o = 0.9\% \)) was produced by a temperature spike of 425-475 \( ^\circ \text{C} \) (Fig. 2) with a 5 cm half-width, and a displacement of 1-2 m, shear stresses of 15-32 MPa are calculated (Table 1).

In the South Wales coalfield, sampling was on the 10 cm scale (Fig. 3b), so that the anomalies occur on this scale or smaller, similar to that on the Lewis thrust, Montana, and also consistent with figure 1 for \( t = 100 \text{ s} \). Temperature spikes of 425-475 \( ^\circ \text{C} \) can explain the anomalies at the four seams (Fig. 2), resulting in areas under the anomaly of 21-24 degree-meters. For displacements of 1 to 2 meters, this corresponds to stresses of 15–32 MPa (Table 1). The total range in estimated stresses for the three locations is 15-40 MPa, which is similar to stress drops during modern earthquakes [e.g. Kanamori, 1994]

The background vitrinite reflectance in the areas referred to above is typically 0.7-0.8\%, which corresponds to a maximum burial temperature of about 125\( ^\circ \text{C} \) (curve A, Fig.
Using a high geothermal gradient of 45°C/km, typical of coal and shale-bearing sequences [Cercone et al., 1996], and a pressure gradient of 26MPa/km, a normal stress of approximately 75 MPa for these areas is indicated. The coefficient of friction (μ = shear stress/normal stress) on these faults would then span the range 0.2–0.5 (assuming normal stress = vertical stress), which is substantially below the laboratory value of 0.85 for normal stresses up to 200 MPa [Byerlee, 1978].

**DISCUSSION**

Assuming a lower geothermal gradient than 45°C/km, the estimated range of μ above would decrease. Conversely, removal of the overburden by erosion prior to faulting would increase the estimated value of μ. However, uplift and erosion of the Pennsylvanian strata (~310 Ma) is unlikely to have occurred until after thrust emplacement during the Alleghanian-Variscan orogeny (~300 Ma) in both the eastern Kentucky and South Wales coalfields. For a low angle (20°) thrust fault, a Mohr circle analysis indicates the assumption above, that normal stress = vertical stress, is reasonable (80 vs. 75 MPa, assuming a differential stress of 60 MPa). For a steeply dipping (60°) normal fault, the normal stress will be somewhat less than the vertical stress (60 vs. 75 MPa), resulting in a higher calculated range in the coefficient of friction (0.3–0.7). The value of μ, as estimated here, is actually an apparent or “effective” coefficient of friction, μ’, which enfolds several variables including the effects of fluid pressure and fault zone material properties, which are poorly known [e.g. Harris, 1998].

A comparison between Easy%R (curve A, Fig. 2) and geologic data (dashed curve, Fig. 2) indicates an error of ± 50°C for R% in the range 0.3-3.0%. For steep
temperature gradients, the conversion of R% to temperature also has an error of ± 50°C associated with the choice of temperature gradient, so that the overall uncertainty is ± 100°C. This uncertainty leads to a relatively small error in the area under the thermal anomaly (± 5 degree-meters) and also the estimated shear stress (± 20%). The major source of uncertainty in equation 1 is, therefore, fault displacement D (Table 1). The range of shear stresses calculated, however, is independent of $\sigma_n$ or $\mu$, and is similar to modern earthquake stress drops, consistent with the assumption of a seismic origin for the coal rank anomalies.
References

Bustin, R. M., Heating during thrust faulting in the Rocky Mountains: Friction or fiction. 

Barker, C., and R. H. Goldstein, Fluid-inclusion technique for determining maximum 
temperature in calcite and its comparison to the vitrinite reflectance 


Cercone, K. R., D. Deming, H. N. Pollack, Insulating effect of coals and black shales in 

Levine, J. R., A. Davis, Relation of coal optical fabrics to Alleghanian tectonic 
deformation in the central Appalachian fold-and-thrust-belt, Pennsylvania, USA,  

d'Alessio, M. A., A. E. Blythe, and R Burgmann, No frictional heat along the San 
Gabriel fault, California: Evidence from fission-track thermochronology, 

Frodsham, K. and R. Gayer, The impact of tectonic deformation upon coal seams in the 
South Wales coalfield, UK. *International Journal of Coal Geology*, 38, 297-332, 
1999.

Gayer, R., R. Fowler, and G. Davies, Coal rank variations related to major thrust 
detachments in South Wales coalfield: implications for fluid flow and 
mineralization, in European Coal Geology and Technology, *Geological Society of*


Figure captions

**Figure 1.** Plot of temperature versus distance from fault for three different post-seismic times, assuming an instantaneous frictional heat source on a fault of zero width [eqn.5, *Lachenbruch*, 1986]. Displacement = 1 meter, coefficient of friction =0.7, normal stress $\sigma_n = 100$ MPa.

**Figure 2.** Plot of vitrinite reflectance (R%) versus temperature for different temperature gradients using EasyR% (*Sweeney and Burnham*, 1990). Curve A- geologic heating rates (1-100°C/Ma). For comparison, the dashed curve represents the best fit to geologic data after *Barker and Goldstein* [1990]. Curves B and C- seismic temperature gradients of 0.035°C/s and 1.0 °C/s, respectively, corresponding to the average rates in figure 1. The shaded region corresponds to experimental data (heating for minutes to hours) of *Bustin* [1983].

**Figure 3a.** Geologic cross section through four coal seams from South Wales coalfield showing meter-scale fault offsets of coals, after *Fowler and Gayer* [1999].

**Figure 3b.** Plot of mean vitrinite reflectance ($R_o$%; solid diamonds) and Deformation Index (DI, open diamonds) for the same four coal seams as figure 3a (after *Gayer and Fowler*, 1997, Table 2). Deformation Index and vitrinite reflectance are highly correlated. Sample interval 10 cm.

**Figure 4.** Plot of random vitrinite reflectance ($R_o$%) versus log distance for the Lewis thrust, Montana [after *Bustin*, 1983, Table 1]. Immediately adjacent to the fault values range from 0.7 to 3.1%. Error bars represent sample resolution (5 cm) at the fault (*M.*
Bustin, pers comm. 2003). Background values are 0.78-0.97%. Shaded triangle represents area under the anomaly.

**Figure 5.** Data from horizontal coal-bearing Pennsylvanian strata in the Cumberland pilot tunnel, eastern Kentucky, showing elevated $R_o$% values on northwest dipping normal faults, after O’Hara et al. [1990].
Figure 3b

Figure 4

Figure 5
<table>
<thead>
<tr>
<th>Location</th>
<th>Temp. (°C)</th>
<th>D(m)</th>
<th>Area (deg.m)</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montana</td>
<td>580-680</td>
<td>1-3</td>
<td>29-34</td>
<td>13–39</td>
</tr>
<tr>
<td>E. Kentucky</td>
<td>425-475</td>
<td>1-2</td>
<td>21-24</td>
<td>15-32</td>
</tr>
<tr>
<td>S. Wales</td>
<td>425-475</td>
<td>1-2</td>
<td>21-24</td>
<td>15-32</td>
</tr>
</tbody>
</table>