Earth and Planetary Science Letters 502 (2018) 253–261

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Biomarker thermal maturity experiments at earthquake slip rates

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ARTICLE INFO

Article history:
Received 7 March 2018
Received in revised form 14 August 2018
Accepted 20 August 2018
Available online xxxx
Editor: J.-P. Avouac

Keywords:
fault mechanics
paleoseismic indicators
high-velocity friction experiments

ABSTRACT

Evidence of temperature rise is useful for identifying where within a fault zone earthquake slip has occurred, as well as some attributes of the earthquake such as energy output. Biomarker thermal maturity can elucidate structures within a fault zone that were hotter than surrounding rock, and therefore likely to have hosted earthquakes. We performed a series of friction experiments on thin gouge layers of Woodford shale at slip rates of 1 m/s. Our results show that biomarker thermal maturity can clearly delineate zones of slip that are as thin as 150 μm. We establish that the kinetics of methylphenanthrene reaction previously determined at longer durations and lower temperatures are applicable at seismic slip rates and timescales. Temperature estimates show that once the slipping zone reached ∼500 °C, biomarker reaction was significant, as predicted by the reaction kinetics. Our results demonstrate that temperature rise in fault zones is a function of both the work density and power density during the earthquake. Biomarker reactions, along with other Arrhenius-style reactions such as those that lead to dynamic shear weakening, are both a function of slip speed and frictional work.

1. Introduction

The active slipping zone of a fault during an earthquake can control fault strength, energy dissipation, and rupture propagation (Kanamori and Heaton, 2000; Sibson, 2003). For example, slipping zone thickness directly affects temperature rise, and therefore the kinetics and thermodynamics of chemical reactions that may reduce frictional strength and enhance propagation (Di Toro et al., 2011). Although seismological constraints can be made on total fault zone thickness (e.g. Savage et al., 2017), we cannot image the active slipping zone during an earthquake through seismological techniques. Field exposures of faults contain discrete structures with large offsets. However, as fault slip can occur from earthquake speeds to plate rates, we need independent methods to identify structures that participated in earthquake slip, as opposed to slower deformation (Cowan, 1999; Rowe and Griffith, 2015). Without this link between earthquakes and fault structure, the mechanics and geometry of earthquake slip will remain elusive.

Earthquake slip is thought to localize deformation onto thin structures (on the order of micrometers in some cases) within the overall fault zone based on field observation (e.g. Boullier et al., 2009, Chester and Logan, 1986; Otsuki et al., 2003; Sagy and Brodsky, 2009; Shipton and Cowie, 2001; Sibson, 2003; Smith et al., 2011) and theory (Platt et al., 2014; Rice, 2006; Rice et al., 2014). However, in laboratory work, localization can occur both at fast (Boutareaud et al., 2010; Fondriest et al., 2012; French et al., 2014; Kitajima et al., 2010; Mizoguchi et al., 2009; Proctor et al., 2014; Rempe et al., 2017; Smith et al., 2015; Ujiie et al., 2013) and slow speeds (Ikari et al., 2015; Mair and Marone, 1999), indicating that localization alone is not a sufficient diagnostic for earthquake slip. One way to identify earthquake slip in faults is through proxies of temperature rise. The actively slipping areas of faults heat up during earthquakes because frictional slip generates heat faster than it dissipates into the host rock (Lachenbruch and Sass, 1980). Differential temperature rise between localized zones and the surrounding fault provide independent verification that localized slip structures were seismic (Savage et al., 2014).

Temperature rise in fault zones is a useful metric in other respects as well. Theoretical analyses of heat generation during earthquakes suggest that if faults are strong, with coefficient of friction ∼0.6, even small earthquakes should generate temperatures that would cause frictional melt (pseudotachylyte) (Rice, 2006). However, the relative dearth of pseudotachylyte in the rock record suggests that faults do not achieve these temperatures very

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https://doi.org/10.1016/j.epsl.2018.08.038

often, although in some cases the absence of pseudotachylyte is due to retrograde reactions (Kirkpatrick and Rowe, 2013). Instead, dynamic weakening mechanisms could significantly reduce shear strength and lower the overall temperature rise during slip so that melting is not pervasive (Rice, 2006). Other thermal weakening processes may occur as revealed by high slip velocity experiments that invoke thermal pressurization of pore fluids, graphitization, decarbonation, dehydration, flash heating, nanoparticle lubrication, and gel lubrication (Brantut et al., 2008; Ferri et al., 2010; Goldsby and Tullis, 2002, 2011; Han et al., 2007). Unfortunately, evidence of dynamic weakening or its chemical byproducts in the field is limited to a few cases (Collettini et al., 2013; Kirkpatrick et al., 2013; Rowe et al., 2012), partly due to lack of preservation in the rock record and/or our current limitations in identification. Dynamic weakening mechanisms themselves, however, require some temperature rise to occur. As we will describe more fully in the next section, temperature rise is a function of the magnitude and rate of heat generation (work and work rate, i.e. power) tempered by thermal diffusivity of the material. Without subsolidus temperature proxies for fault zones, it is impossible to reconcile whether faults achieved temperatures that would allow for various dynamic weakening mechanisms to occur.

Estimates of earthquake temperature rise also allow for understanding how energy is dissipated during earthquakes. Fracture energy and radiated energy (in the form of seismic waves) are related to stress drop and can be determined through seismic analysis (Kanamori and Rivera, 2006). Frictional work on the other hand, involves the absolute stress rather than stress drop, and therefore its quantification requires different methodology. Because frictional work is dissipated as heat, temperature rise can be used to constrain frictional work if other fault parameters and material properties are known or reasonably estimated (Lachenbruch and Sass, 1980). Calculation of frictional work during earthquakes is the only way to approximate the shear stress during slip (Fulton et al., 2013).

Due to the interest in determining fault temperature during earthquakes, there have been a number of temperature proxies developed for fault zones in recent years. While pseudotachylyte (solidified frictional melt) was long the sole accepted indicator of temperature rise during earthquake slip in the rock record (Cowan, 1999; Di Toro et al., 2005; Rowe et al., 2005; Sibson, 1977), other proxies such as clay alteration, metal transition, and thermal maturity of organic matter are now used regularly (Evans et al., 2014; Furuichi et al., 2015; Polissar et al., 2011; Rowe and Griffith, 2015; Schleicher et al., 2015). Here we focus on biomarker thermal maturity as a measure of earthquake slip in faults.

Recent work shows that biomarker thermal maturity can be used as an earthquake indicator on natural faults that are hosted within sedimentary rocks (Polissar et al., 2011; Rabinowitz et al., 2017; Savage et al., 2014). Several faults studied to date (e.g. Punchbowl Fault, California; Muddy Mountain Thrust, Nevada; proto-megathrust at Sitkanak Island, Alaska) contain methylphenanthrenes, a common hydrocarbon in sedimentary rocks that have experienced burial heating (Coffey et al., 2016; Polissar et al., 2011; Savage et al., 2014). The distribution of methylphenanthrenes during burial heating and petroleum generation is well established (Radke et al., 1982; Szczerba and Rospondek, 2010). More recently, short-duration hydrous pyrolysis experiments demonstrated that methylphenanthrene thermal maturation follows first-order reaction kinetics, as the reaction rate depends linearly on the concentration of the reactant (Sheppard et al., 2015). However, these experiments were conducted at time scales of minutes to hours, and earthquakes occur on the order of seconds to minutes. In this paper, we run high-velocity friction experiments on an organic-rich shale in order to extend the analysis of reaction kinetics of the methylphenanthrene biomarker to include earthquake slip rates (seconds) while the sample is being sheared. Our results show that methylphenanthrenes are a faithful recorder of earthquake temperature, and indicate that differences in temperature on localized slip zones can be detected down to the sub-millimeter scale with this method. Furthermore, we explore the role that both work and power play in achieving temperature rise, and caution against neglecting the full kinetics of temperature proxies.

2. Background

2.1. Temperature rise during earthquakes

Following Cardwell et al. (1978) and Lachenbruch (1986), during earthquake slip, the frictional work per unit area done during sliding is the product of total slip, D, and shear stress, τ, which is in turn a function of normal stress (due to overburden less pore pressure) and frictional resistance, which can evolve with time (t):

$$W_f = \tau(t)D \quad \left[\mathrm{J\,m^{-2}}\right] \tag{1}$$

The temperature rise during an earthquake is a function of the frictional work term modulated by the heat capacity c_p, density ρ, and thickness $2a$ of the active slipping zone:

$$\Delta T \propto \frac{\tau V(t)t}{c_p\rho 2a} \tag{2}$$

where t is slip duration and $V(t)$ is slip velocity ($Vt = D$ at the end of the earthquake). Equation (2) can describe adiabatic temperature rise during earthquakes, and is applicable if the slipping zone is much thicker than the diffusion length scale, such that:

$$a > \sqrt{4\alpha t^*} \tag{3}$$

where α is thermal diffusivity, and t^* is the slip duration. However, in most fault zones, it is assumed that the diffusion length scale is larger than the active slipping zone thickness, and temperature rise is also a function of thermal diffusion (Carslaw and Jaeger, 1959) as:

$$\begin{aligned}\Delta T(x,t) = \frac{\tau V}{\rho c_p 2a}\Bigg\{&t\left[1 - 2i^2 erfc\frac{a-x}{\sqrt{4\alpha(t)}} - 2i^2 erfc\frac{a+x}{\sqrt{4\alpha(t)}}\right]\\ &- \left(t-t^*\right)\left[1 - 2i^2 erfc\frac{a-x}{\sqrt{4\alpha(t-t^*)}}\right.\\ &\left.- 2i^* erfc\frac{a+x}{\sqrt{4\alpha(t-t^*)}}\right]\Bigg\}, \quad x<a\end{aligned} \tag{4a}$$

$$\begin{aligned}\Delta T(x,t) = \frac{\tau V}{\rho c_p 2a}\Bigg\{&t\left[i^2 erfc\frac{x-a}{\sqrt{4\alpha(t)}} - i^2 erfc\frac{a+x}{\sqrt{4\alpha(t)}}\right]\\ &- \left(t-t^*\right)\left[i^2 erfc\frac{x-a}{\sqrt{4\alpha(t-t^*)}}\right.\\ &\left.- i^* erfc\frac{a+x}{\sqrt{4\alpha(t-t^*)}}\right]\Bigg\}, \quad x>a\end{aligned} \tag{4b}$$

where x is position perpendicular to the fault, and $i^2 erfc$ is the second derivative of the complementary error function. Equation (4a) describes temperature rise within a fault zone ($x < a$) and (4b) describes the adjacent rock ($x > a$).

2.2. Methylphenanthrenes

Methylphenanthrenes and other polycylic aromatic hydrocarbons are produced during thermal maturation of organic matter. They do not have any biosynthetic source, rather they are the molecular expression of the thermal alteration of bulk organic