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Inter-book normal fault-related shear heating in brittle bookshelf faults

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ABSTRACT

This work models shear heat-related temperature rise due to inter-book dip-slip normal faults by a bookshelf mechanism. Such faults are characterized by temporally changing the dip of the inter-book fault planes. Considerable temperature can be produced by such faulting, although the effects of high temperature have not yet been reported around such fault planes. This may mean that fluids flowing through such planes do not allow shear heating to accumulate.

1. Introduction

Book-shelf sliding, either strike slip or dip slip, involves brittle slip by simple shear between crustal-blocks of the order of several km in length and width (Green et al., 2014) along pre-existing planes (Fig. 1), which is ideally restricted within the brittle domain (Cobbold et al., 1989) and are rather frequent in the deltaic shelves (Mandl, 1987, 2000). Crustal blocks rotate as rigid-bodies, so that each part of the blocks should undergo the same amount of rotation (Rouby et al., 1996). Inter-block antithetic normal fault planes achieve progressively gentler dip. This deformation mechanism is importance in applied geosciences since these normal faults can transport fluids (e.g., hydrocarbons). Besides, the open spaces developed in between the "books" at top and bottom can work as hydrocarbon reservoirs. Bookshelf rotation of a part of lithosphere can produce depressions that can act as new basins (McQueen and Beaumont, 1989). Either the dip slip or the strike slip bookshelf gliding mechanism is presented in detail by de Figueiredo et al. (2004), Savage et al. (2004), Zuza and Yin (2016) and Mukherjee (in press). Under an optical microcope, book-shelf glided mineral grains, most notably micas and feldspar, have also been reported (e.g., Mukherjee, 2013a). This article, on the other hand deals with km-scale dip slip book-shelf gliding. Few authors have described domino mode of deformation also as book-shelf faulting (e.g., Triantafyllidis et al., 2011). This article avoids such faults.

Bookshelf slide is an important mechanism in ocean floor that affects the seafloor fabric, especially the abyssal hills, and the oceanic shear zones (Morgan and Kleinrock, 1991 and references therein). Constraining bookshelf mechanism-related parameters may not be easy since paleomagnetic rotation may not always estimate accurately the bookshelf-related rotation (Payne et al., 2013). Likewise, geodetic studies may not succeed to detect such faults (Platt and Becker, 2013). Nevertheless, as much as 30^0 rotation has been reported from the bookshelf faults at the Sovanco fracture zone, located offshore of Vancouver Island, Canada (Cowan et al., 1986). Fossen (2016) refers a higher amount of 45^0 for such bookshelf faults or his "hard domino models". A few low rotation rates and slip rates of bookshelf glided faults are available (Table 1). Out of these, the highest and the lowest rates of rotation are 1.8 and 57^0 Ma^{-1}, and that for the associated inter-block slip rates are 1.7 and 10.8 mm yr^{-1}.

Brittle faulting-induced shear/frictional heating is relevant in petroleum geosciences, tectonics and seismicity (e.g., Rupakhety and Sigbjornsson, 2014). Heating along fault plane can mature hydrocarbons (Keym et al., 2006). Shear heating also can modify the thermal structure of rocks and that can in turn affect seismicity (e.g., van Kenen et al., 2012). Several works in this front are available for translational- (Cardwell et al., 1978; Mukherjee, 2017), and very few for rotational faults (Mukherjee and Khonsari, 2017). If not flushed by fluids, frictional heating due to reverse faulting elevates temperature adiabatically proportional to the *(i)* frictional coefficient, and *(ii)* the thickness of the hangingwall block (Mukherjee, 2017). Additionally *(iii)* after time 't', the temperature rise is proportional to the specific heat at constant pressure (C_p). The first two constraints (i and ii above) also hold true for rotational and roto-translational faults. Note here the presence of the parameter of constant pressure (C_p) does not connote to the shear pressure/stress and normal pressure/stress that act between the hangingwall and the footwall blocks. Here C_p can be linked at best with the confining pressure in the geological context. For a purely scissors fault having only rotational and no translational slip, such a

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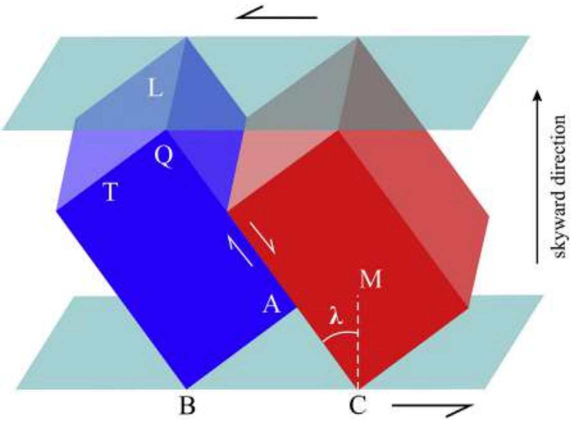

Fig. 1. Book-shelf faulting. Top-to-right (down) slip between blocks. CM: orientation of line CQ before shear. ∠QCM = λ. In Δ ABC: AC = T.tan λ. Area ΔABC = 0.5.AB.AC = 0.5.T^2.tan λ.

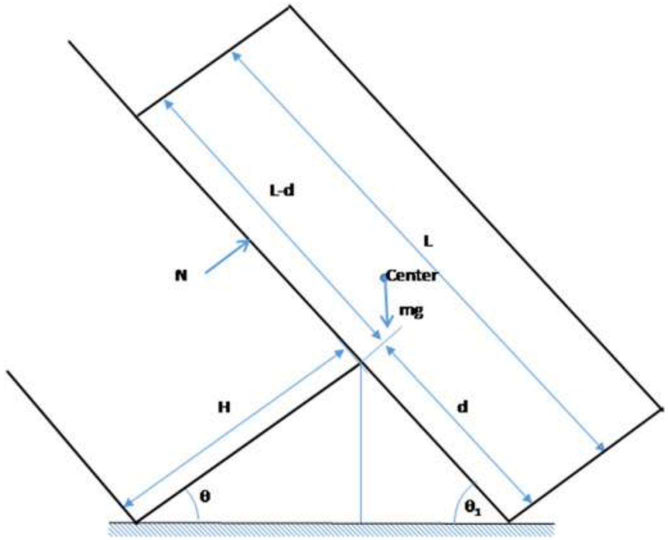

Fig. 2. Construction for frictional temperature rise calculation. Meaning of symbols in Section 2: Model.

temperature rise per unit time is proportional to the relative angular velocity between the hangingwall and the footwall block, which does not work for roto-translational faults (Mukherjee and Khonsari, 2017).

Previous models of shear heat assumed fault planes possess fixed temporal orientation (e.g. Hamada et al., 2009). However, different types of faults have been recognized by geoscientists, such as the bookshelf faults, where the fault plane itself rotates during the faulting process (review in Mukherjee, 2014; also see Freund, 1970, 1974). In this paper, a simple model is developed to estimate shear heat related temperature rise by dip-slip bookshelf faulting.

2. A model in 2D

Referring to Fig. 2, let the thickness of the book defining the footwall block be '*H*', the length of the book defining the hanging wall block "*L*", and the length of the hangingwall and the footwall block books in contact "*L-d*". The dip amount of the hangingwall block and the footwall block books under consideration are'(90^0-θ_1)' and 'θ', respectively. These two blocks dip towards the right hand side, the same direction as that of the fault plane dipping at 'θ_1'. Let '*N*' be the normal reaction (normal force) acting perpendicular to the fault plane, '*g*' the acceleration due to gravity, 'μ'the coefficient of friction, 'C_p' the specific heat of the rock at constant pressure, and '*V*' the relative slip rate of the fault blocks/books.

The angular velocity, defined as $\Omega = \dot{\theta}$, is generally not constant since the moment increases with θ. Note

$$\theta = \Omega t \tag{1}$$

The power is

$$P = \mu N V \tag{2}$$

Using eqn (1) and

$$d = H\tan\theta \tag{3}$$

$$V = -\frac{d(L-d)}{dt} = \dot{d} = H\frac{d(\tan\theta)}{dt} = H\Omega\sec^2\theta \rightarrow P = \mu N H\Omega\sec^2\theta \tag{4}$$

$$\frac{\Delta T}{\Delta t} = \frac{P}{mc_p} = \frac{\mu N H\Omega\sec^2\theta}{mc_p} \tag{5}$$

Note that both the normal force $N = N(t)$ and the angular velocity, $\Omega = \Omega(t)$ are both a function of time.

If Ω is constant, then, as per symbols additionally defined in Fig. 2,

$$mg\frac{L}{2}\cos\theta_1 = N\left[d + \frac{1}{2}(L-d)\right] \tag{6}$$

$$mg\frac{L}{2}\cos\theta_1 = \frac{1}{2}N(L+d) \rightarrow mg\cos\theta_1 = N\left(1 + \frac{H}{L}\tan\theta\right) \tag{7}$$

$$\rightarrow N = \frac{mg\sin\theta}{1+(H/L)\tan\theta} \quad \text{with } \sin\theta = \cos\theta_1 \tag{8}$$

$$\begin{aligned}\frac{\Delta T}{\Delta t} &= \frac{\mu N H\Omega\sec^2\theta}{mc_p} = \frac{\mu H\Omega\sec^2\theta}{mc_p}\frac{mg\sin\theta}{1+(H/L)\tan\theta}\\ &= \frac{\mu g\Omega L}{c_p}\left[\frac{(H/L)\tan\theta}{1+(H/L)\tan\theta}\right]\sec\theta\end{aligned} \tag{9}$$

Eliminating θ from eqns (8) and (9),

$$\Delta T/\Delta t = \mu g\Omega L C_p{}^{-1}[\{HL^{-1}\mathrm{Cot}\theta_1\}\ \{1+HL^{-1}\mathrm{Cot}\theta_1\}^{-1}]\mathrm{Cosec}\theta_1 \tag{10}$$

Table 1
Review of rotation- and slip rate related to book-shelf glided fault blocks.

Reference	Type of bookshelf fault	Rotation rate (degree per million year)	Slip rate (km per Ma; same as mm per yr)	Location
Sigmundsson et al. (1995)	Dip slip	28.9 to 57	–	South Iceland
Savage et al. (2004)	Strike slip	4.1	–	Mojave domain, eastern California
Szeliga (2010)	Dip slip	38.96 ± 4.6	9.7 ± 1.1	Pakistan Himalayan syntaxis
Platt and Becker (2013)	ip slip	5 (in long term) 1.8 (in short term)	1.7	Western Transverse range, San Andreas System
Green et al. (2014)	Strike slip	20 to 40	0.9–1.8	North Iceland volcanic rift zone
Zuza and Yin (2016)	Strike slip	0.65	–	North Tibet
Zuza (2016)	Dip slip	4.4 ± 0.7	6	Garlock Fault, near San Andreas Transform Plate Boundary

3. Discussions & conclusions

To capture the essence of the problem, we develop a very simple model with minimum and most useful physical parameters the temperature rise by frictional heating in normal faults under bookshelf mechanism. Eqn (10) shows, as in case of rotational, translational and roto-translational faults, the temperature rise at any instant by shear heating for bookshelf faulting is proportional to the coefficient of friction μ, and is inversely proportional to C_p. In addition, the equation states that the temperature rise (ΔT) is proportional to the angular velocity (Ω) of the blocks. No such simple (inversely) proportional relation exists between temperature rise (ΔT) and *(i)* the dimension of the faulted blocks (such as L and H), *(ii)* the dip (θ_1) of the fault plane, and *(iii)* total angular rotation (θ) of the faulted blocks at any instant. Note that while the thickness (H) of the footwall block is a part of the temperature rise eqn (10), and that of the hanging wall block does not appear in the expression. For all other parameters (μ, g, Ω, L, C_p, θ_1) remaining the same, temperature rise is proportional to the time duration of book-shelf gliding.

Since brittle faulting usually restricts at shallow depth ($< \sim 8$ km), shear heat estimation to consider C_p at some low temperature. C_p of gneiss at 20 °C is 770 J kg^{-1} K^{-1} (Waples and Waples, 2004). The frictional coefficient (‘μ’) of rocks is ~0.3 (Byerlee, 1978). Except seismic slip cases (e.g., stick and slip mechanism), tectonic aseismic slip takes place for thousands of years (review in Mukherjee, 2013b). Choosing few realistic parameters (Table 2a,b), change in temperature ΔT in two instances, for faulting within gneiss as the continental crust, are calculated as ~ 21.2 °C and 671 °C, for 1.8^0 Ma^{-1} and 57^0 Ma^{-1}, respectively. Parameters for dip slip faults as in Table 1 were used in this calculation, and those for strike slip faults were not used.

Further, one can write the eqn $Q = m\, C_P\, \Delta T$ (11)

as $Q/(t\rho v) = C_p\, (\Delta T/t)$ (12)

where Q is the heat produced, m the mass, and ΔT the temperature increase, v the volume and ρ the density of the rock, and t is the time duration. Taking $\rho = 2.7$ gm cm^{-3} (average density of the continental crust), and $t = 10$ yrs (as in Table 2a,b), the heat production rate per unit volume per second for those two cases come out to be 0.002 J m^{-3} s^{-1} and 62.2 J m^{-3} s^{-1}, respectively. Comparing these magnitudes with the average crustal heat production rate per unit volume of the rock, i.e., 4.6 ± 2.4 μW m^{-3} (Lewis et al., 2003), we can comment that the shear heating can substantially increase the heat budget of the crust locally. When the crustal radiogenic heat alone is compared (e.g., 6.68 ± 0.61 μW m^{-3}: Pasquale et al., 1997), a similar profound disparity is noted. As per eqns (10) and (12), a much higher heat production rate by shear heating related to inter-book faulting would take place if the coefficient of friction (μ) is much higher, such as 0.8 (Turcotte and Schubert, 2014). Also note that the effective frictional coefficient can get down to as low as 0.1 (Provost and Chery, 2006) for continental faults with or without the influence of pore pressure. The calculations presented above does not hold true for any specific geographic locations, but are just representative values. Bookshelf faulting has been reported from several places worldwide, e.g., the dip slip variety from the North Sea (Williams, 1993), and the strike slip variety from the north Iceland volcanic rift zone (Green et al., 2013). From no such single terrains so far all the parameters needed to calculate shear heat is available.

Pseudotachylite, local metamorphism, or (partial) melts along the inter-book faults in book-shelf faults have not yet been reported. This means either *(i)* the shear heating related temperature rise probably do not reach a very high magnitude by possibly fluid flow along the fault plane that flush out the frictional heat; or *(ii)* the rate of book shelf sliding is slow enough so that higher temperatures are not attained at all; or *(iii)* the rocks that underwent bookshelf glide has a higher thermal conductivity and heat could not store but dissipated rather quickly. Fluid flow would also obviously modify the magnitude of the frictional coefficient (μ; e.g. Sibson, 1974; Mitsui, 2012). Since μ is temperature-dependent (e.g., Ince and Guden, 2013), one can expect realistically that μ for fault planes would vary with depth.

However note that C_p increases with temperature, and therefore with depth (Waples and Waples, 2004). Therefore, eqns (9) and (10) apply better in terrains with a low geothermal gradient. We also considered fault blocks are of a single monominearlic rock type with uniform physical properties and the fault plane at the interface of such blocks are devoid of gouge, breccias and secondary faulting. The presented model of shear heat would come close to for rocks with low thermal conductivity (λ) such as basalt with $\lambda = 1.7$ W m^{-1} K^{-1} (Henderson and Henderson, 2009), or even better with clay ($\lambda_{\text{minimum}} = 0.6$ W m^{-1} K^{-1}: Schon, 2011). Rocks with high λ values such as quartzite ($\lambda = 5.0$: Henderson and Henderson, 2009) would deviate from the modeled shear heat. Further, even a single rock can vary in density in different directions, and in such cases expressions of representative densities (e.g., Mukherjee, 2017b; 2018a,b, in press)

Table 2
Parameters chosen for frictional temperature rise calculation in Section 3: “Discussions & Conclusions”. **a.** with rotation rate (Ω) 1.8^0 Ma^{-1}. **b.** Ω = 57^0 Ma^{-1}.

Parameter (unit)	Magnitude
θ (degree)	30
g (cm s^{-2})	980
μ (no unit)	0.3
Ω (degree Ma^{-1})	*1.8*
C_p (J kg^{-1} K^{-1})	770
H (km)	3
L (km)	10
Δt (Yr)	10^4
Calculated magnitude of temperature rise: ΔT (⁰C)	21.2

Parameter (unit)	Magnitude
θ (degree)	30
g (cm s^{-2})	980
μ (no unit)	0.3
Ω (degree Ma^{-1})	*57*
C_p (J kg^{-1} K^{-1})	770
H (km)	3
L (km)	10
Δt (Yr)	10^4
Calculated magnitude of temperature rise: ΔT (⁰C)	671

should be used in eqn (12).

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