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Strain heating in process zones; implications for metamorphism and partial melting in the lithosphere

Maud H. Devès *, Stephen R. Tait, Geoffrey C.P. King, Raphaël Grandin

Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ. Paris Diderot, UMR 7154 CNRS, F-75005 Paris, France

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ABSTRACT

Since the late 1970s, most earth scientists have discounted the plausibility of melting by shear–strain heating because temperature-dependent creep rheology leads to negative feedback and self-regulation. This paper presents a new model of distributed shear-strain heating that can account for the genesis of large volumes of magmas in both the crust and the mantle of the lithosphere. The kinematic (geometry and rates) frustration associated with incompatible fault junctions (e.g. triple-junction) prevents localisation of all strain on the major faults. Instead, deformation distributes off the main faults forming a large process zone that deforms still at high rates under both brittle and ductile conditions. The increased size of the shear-heated region minimises conductive heat loss, compared with that commonly associated with narrow shear zones, thus promoting strong heating and melting under reasonable rheological assumptions. Given the large volume of the heated zone, large volumes of melt can be generated even at small melt fractions.

There are clear examples of volcanism correlated with fault complexities that remain enigmatic and that could be related to that mechanism of "process zone heating". We propose here a simple dislocation model to define the process zones, determine off-fault strain rates and quantify how much plastic work can be dissipated as heat. To provide an example, we examine the case of the junction between the East and North Anatolian shear zones in eastern Turkey. This is chosen because the composition and age of emplacement of the quite extensive volcanics are well known, as are the rates of motion on the associated strike-slip faults. The geometry of the system also allows the dislocation method to be easily adopted. We conclude that melting of the crust and the lithospheric mantle could start only a few Myrs after the onset of deformation. Conservative assumptions for rheological parameters and melting points can explain both the timing and the bimodal nature of the volcanism. Predictions of melt volume are within the rheological uncertainties. While the current paper is focused on strike-slip faults, the approach can be applied to kinematic complexities associated with thrust faults as well, and, maybe more generally, to regions in the lithosphere where oblique boundary conditions force deformation to occur partly in a distributed manner, while still at high rates.

1. The efficiency of strain heating in the lithosphere: a controversy

The spatio-temporal correlation between the emplacement of metamorphic or magmatic bodies and continental deformation suggest an intimate relationship between the thermal and mechanical processes taking place in the lithosphere (e.g. Zhang and Schärer, 1999; Leloup et al., 1999; Jolivet et al., 2003; Rosenberg, 2004; Weinberg et al., 2004; Nabelek and Liu, 2004; Devès, 2010). However, whether lithospheric deformation can of itself produce enough heat to cause high heat flow, high-temperature metamorphism or partial melting in continents is a long-standing debate (e.g. Brune et al., 1969; Yuen et al., 1978; Lachenbruch and Sass, 1980; Ricard et al., 1983; So and Yuen, 2013).

The rate of heat production by dissipation of mechanical work during irreversible deformation (called strain heating) depends on the product of lithospheric strength and strain rate. Whilst enough laboratory data are now available to have a reasonable idea of rock strength, evaluation of the magnitude of strain rate, and of its distribution, is less straightforward. Finite strains within continents do not take place in a homogeneous and steady manner, nor are

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* Corresponding author.
E-mail address: deves@ipgp.fr (M.H. Devès).

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they perfectly concentrated on a finite number of large faults. No model formulation of the relationship between strain and heat has been so far successful in convincingly linking observables of lithospheric deformation with volumes and distributions of magmas produced.

It is common in the literature to distinguish between *frictional heating*, i.e. heat produced during friction on a fault plane in the brittle domain, and *viscous heating*, i.e. heat associated with ductile shearing either on a narrow ductile shear zone or by larger-scale distributed deformation of a viscous lithosphere. Two "end member" approaches have been adopted to model the deformation. One extreme is to assume that the lithosphere can be represented as a viscous fluid subject to the far-field relative plate motion (e.g. England and McKenzie, 1982; Houseman and England, 1986; Kincaid and Silver, 1996). Doing so downplays the heterogeneity of the deformation that is observed at various scales in the field, and notably the occurrence of well-documented tectonic structures, which represent discontinuities in the deformation field that can occur up to the lithospheric scale (e.g. Wittlinger et al., 1998; Armijo et al., 1999; Tapponnier et al., 2001). Another extreme is to assume that continental deformation is characterised by relative motion of a number of rigid blocks along major tectonic boundaries (e.g. Leloup et al., 1999; Rolandone and Jaupart, 2002). In that case, strain heating is focused along well-localised faults or shear zones. In both cases, the strain rate is still fundamentally equal to the velocity applied on the shear zone, or in the far field, divided by the width of the deforming zone. High strain rates are thus predicted for narrow shear zones. For wider zones of deformation, strain rates are lower and predicted heating rates become insignificant (e.g. Kincaid and Silver, 1996; Hartz and Podladchikov, 2008). This has led to the view that narrow shear zones are the most likely places where significant strain heating should occur, and hence where partial melting could take place.

The efficiency of strain heating depends on the competition between the rate of heat production and of weakening of the rocks due to thermal softening. While the exact position of the brittle–ductile transition is quantitatively important, the process is self-limiting overall because the strength of the lithosphere ultimately decreases with increasing temperature. Furthermore, thermal conduction evacuates heat, and is particularly efficient on heat sources like narrow planar shear zones. Models of shear zone heating have incorporated the influence of temperature-dependent thermal diffusivity and heat capacity to increase the efficiency of strain heating by decreasing the ability of the heated lithosphere to conduct heat away; and/or used rheological laws that tend to be less temperature-sensitive, thereby reducing the magnitude of thermal softening (Whittington et al., 2009; Nabelek et al., 2010). However, these advances have not fully closed the gap between model predictions and observations. Models predict relatively moderate temperature increases under geologically reasonable conditions, barely resulting in the generation of very small volumes of magmas (e.g. Leloup et al., 1999). Strain heating is not, therefore, usually considered as a key mechanism in producing the major thermal events that occur coevally with episodes of active deformation.

In this paper, we adopt a new approach by exploring a model in which localised and distributed deformation coexist. We focus on regions where deformation is demonstrably heterogeneous and irreversible while still occurring at high strain rates (Devès et al., 2011). These places are called accommodation zones in structural geology or process zones in material mechanics. In the following we use the term of process zone.

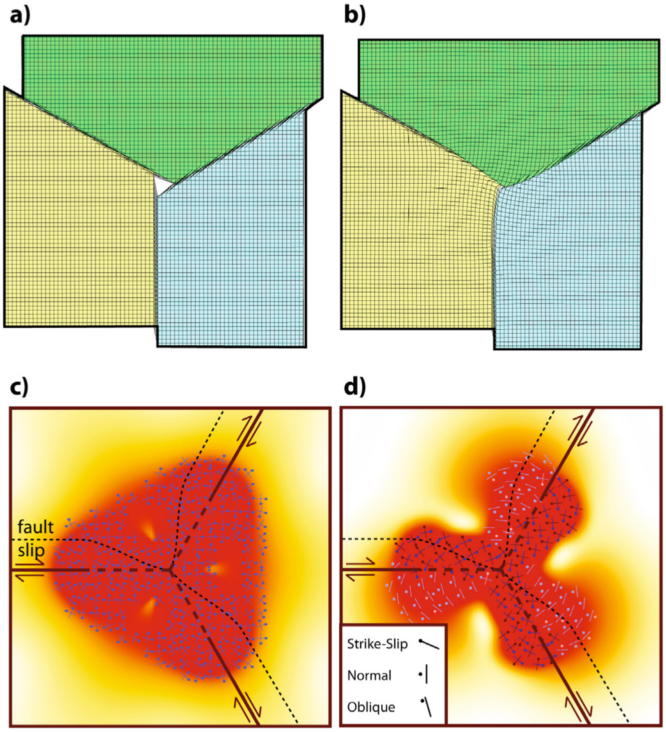

Fig. 1. Process zone of distributed deformation resulting from kinematic incompatibility. The deformation associated with finite motion at a junction between three strike-slip faults can be accommodated in two ways: (a) by opening of a void, or (b) by off-fault deformation when confining pressure prevents large volume changes. Significant shear strains are induced off-faults (reddish colours) (c) under plane strain conditions as (d) under plane stress conditions (for a compressional out of plane principle strain). The short lines shown in (c) and (d) represent the directions of shear predicted within what can be called a process zone. The insert gives the corresponding slip mechanisms. Shear occurs following directions that vary from place to place preventing the development of localised faults or shear zones on long distances. The strain distribution changes between plane strain and plane stress but in both cases, deformation remains distributed with respect to the length-scale of the main faults. The models shown in (c) and (d) have been obtained using a distribution of dislocations in an elastic medium. The figure has been modified from Devès et al. (2011) (see the original paper for more details).

2. A new hypothesis for strain heating

2.1. From kinematic incompatibility to process zones of distributed deformation

Even in the perfectly localised world of plate tectonics, important restrictions on the orientation of plate boundaries or on the relative velocity vectors are imposed by kinematics. Triple junctions are stable only if they allow continuous plate evolution, such as that between three ridges (Fig. 10-3 A, McKenzie and Morgan, 1969). All other possible triple junctions are kinematically unstable and are hence expected to evolve. The question is whether they can always do so whilst respecting their kinematic environment. The Mendocino triple junction for instance has migrated northward in response to the PA-AM-FA plate kinematics, but translation has not accommodated one hundred per cent of the strain. Sliding between the three, allegedly rigid, blocks has been associated with significant distributed deformation (up to about 35%, Field et al., 2013, Table 4). The present paper focuses on that fraction of the strain that cannot be accommodated by translation and localised sliding because of kinematic incompatibility.

An example of an unstable and strongly incompatible triple junction is the point at which three strike-slip faults meet (Fig. 1). The junction cannot evolve stably by translation and localised sliding only. The accumulation of finite motion on the faults requires