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3-D numerical modelling of the influence of pre-existing faults and boundary conditions on the distribution of deformation: Example of North-Western Ghana

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ABSTRACT

High-strain zones bound and separate the high-grade tectono-metamorphic terranes from low-grade greenstone belts in the North-Western parts of Ghana. These belts are bounded by granitoid domains characterized by two main episodic pulses of magmatic intrusive events, which occurred between 2213 Ma and 2086 Ma. High-strain zones are thought to play a significant role in creating fluid pathways, particularly for partially molten material from lower crustal sources to the upper crust. In this study, a three-dimensional thermo-mechanical model has been used to explore the evolution of high-strain zones and relief under compressional and simple shear boundary conditions. Different orientations of a system of branched strike-slip faults were tested. The effects of the frictional angle and density contrast on the evolution of relief were also compared in this study. The resulting model indicates domains of tensile vs. compressional strain as well as shear zones. This shows that the internal fault zones as well as the host rock in between the faults behave as relatively weaker domains than the external regions. Under both applied compressive and simple shear boundary conditions, these weakened domains constitute preferential zones of tensile and shear strain accommodations in the upper crust, which may favour infilling by deeper partially molten rocks. This processes is suggested by the authors as the most likely processes to have occurred in pre-existing branched shear zones systems in North-Western Ghana during the Eburnean orogeny (around 2.20–2.10 Ga).

The orientations of faults in these models play an important role in controlling the evolution of relief and localized deformation. In particular, greatest the largest relief is obtained when faults dip parallel to each other and when they are inclined at depth, as they thus facilitate strain rotation and material transfer from depth. The host rock density does not play a primary role in producing relief compared to variations in friction angle at crustal scale of our model. Relief increases by 200–300 m when the host rock density is increased by 200 kg/m^3, whereas relief reduces by about 1200 m when decreasing the host rock friction from $\varphi = 20^\circ$ to 10°. This study suggests a model for interpreting the evolution and locus of exhumation of partially molten rocks in North-Western Ghana.

1. Introduction

It has been previously established that pre-existing shear zones in the crust may be reactivated and act as preferential loci for strain accommodation, when the principal stress field changes or rotates under external boundary conditions (D'Alessio and Martel, 2004; Fialko et al., 2005; Fialko, 2006; Gerbault et al., 2003; Middleton and Copley, 2013; Nieto-Samaniego, 1999; Scholz, 2007; Sibson, 1977; Tong et al., 2014; Walsh et al., 2002; Zhang et al., 2009). It has also been suggested that shear zones play a significant role in providing fluid pathways for partially molten materials from lower crustal levels to the upper crust (Neves et al., 2000; Pereira et al., 2013; Snoke et al., 1999; Vignerésse and Tikoff, 1999; Weinberg et al., 2006).

Even at constant obliquity of far-field motion, the development of high-strain shear zones results in highly variable structures and fabrics. Whereas numerical modelling studies of oblique tectonics in the crust (e.g. Braun and Beaumont, 1995; Braun and Yamato,

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2010; Gerbault et al., 2002; Le Pourhiet et al., 2012) are still constrained by computational limitations, a large number of analogue modelling studies have investigated aspects of localized deformation in three-dimensional strike-slip settings (e.g., see review by Dooley and Schreurs, 2012, and references therein; Leever et al., 2011). Such numerical and analogue studies reproduce quite well field observations such as evolving Riedel shears, connection with P shears and the building of positive or negative flower structures. All of these structures mentioned above depend on lateral and basal boundary conditions, the initial geometries and the mechanical properties of the modelled crustal material. The orientation, magnitude and shape (flattening vs constriction, etc.) of finite strain ellipsoids tend to change continually as a result of the increasing simple shear component with respect to the coaxial components of deformation (Fossen and Tikoff, 1998; Sanderson and Marchini, 1984; Leever et al., 2011; Dooley and Schreurs, 2012). Further complications arise with heterogeneous deformation, non-steady-state deformation and strain partitioning. Within a shear zone, strain may either increase in intensity towards the central part of the zone, or be preferentially partitioned as a localized simple shear component within the broader high strain zone. In such partitioned shear zones, parts of the terranes may actually move faster than the relative plate motion, while other sections may move slower than or even in an antithetical direction to plate motion (Fossen and Tikoff, 1998; Dooley and Schreurs, 2012). This highlights the difficulty in reconstructing initial geometries and boundary conditions that produce high-strain shear zones, and then in understanding the strain field allowing deeper fluids to flow throughout the solid upper crust.

The crustal dynamics of an interacting fault system represent a complex problem due to varying orientation (Peltzer et al., 2001) and strike-slip instability along fault (Xing et al., 2007) over geological time scales. The spatial and temporal pattern of deformation is controlled by the orientations of pre-existing fault zones with respect to far-field boundary conditions (e.g., Buck and Lavier, 2001; Sibson and Xie, 1998; Tranos, 2012). In particular, new shear zones and localized deformation may develop through time (Alberti, 2010; Avouac and Burov, 1996; Giger et al., 2008; Jessell et al., 2012; Rice, 1993). Two interacting faults can be mutually constrained over a time period, during which faults weaken and also impact on the surrounding host rocks (Imber et al., 2004), possibly initiating new failures (Buck and Lavier, 2001; Leever et al., 2011). Conversely, varying boundary conditions simulate how different paleostress fields affect strain localization of interacting faults over geological time (Naylor et al., 1986; Ueta et al., 2000).

In this study we have investigated the role NE-SW trending crustal scale shear zone architecture plays in controlling the loci of exhumation during the Eburnean Orogeny in the Birimian of North-Western Ghana. According to Block et al. (2015), the high grade Bole-Bulenga terrane in North-Western Ghana, is composed mostly of gneisses, metabasites and monzogranites and located between the craton scale N-S Jirapa and the NE-SW Bole-Nangodi shear zones (Fig. 1). These high strain shear zones separate the high grade tectono-metamorphic Bole-Bulenga terrane from adjacent low grade greenstone belts (i.e. Wa-Lawra and Julie belts) which is mostly characterized by early thrust and late stage kinematic shear deformation. The minimum pressure difference between high grade amphibolite–migmatite facies Bole-Bulenga terrane (lower crust) and the adjacent greenschist facies belts (upper crustal materials) is about 3 kbar, corresponding to over 10 km in thickness.

Although Block et al. (2015) highlighted the significance of extension for exhumation in the Bole-Bulenga terrane; they also indicated that extension is certainly not the only process accounting for the exhumation of lower crust. In addition, Sakyi et al. (2014) concluded that the oldest pulses of granitic emplacement in the Wa-Lawra belt are around 2212 ± 1 Ma. This indicates that the emplacement of Birimian granitoids in the study area should have commenced much earlier than previous studies have mentioned. All these uncertainties show that insights into the exhumation mechanisms for high grade rocks along and in between these two faults are of interest in this region. Generally, the spatial–temporal evolution of high-strain zones relating to pre-existing branched faults systems is still not completely understood. Simultaneously, fault zones in this area of Ghana are generally treated as vertical or sub-vertical (Adjei, 1992; Harcouët-Menou et al., 2009; Lompo, 2010). These uncertainties associated with the interpretation and geometry of the fault zones provided the motivation to test the influence of fault orientations on the distribution of high-strain zones reactivated in a specific kinematic setting.

The aim of this paper is not to re-produce the exact evolutionary history of geological structures in North-Western Ghana, but rather to use this geology as a basic example for assessing how the orientations of a paired fault zone system influences the distribution of high-strain zones and relief. In this study, we assume that the pre-existing faults interact with hard linkage (Gupta and Scholz, 2000), rather than interacting only through their stress fields (soft linkage), and the choice of soft linkages would significantly alter the results, but were not studied here. We use a three-dimensional thermo-mechanical model to explore the distribution of high-strain zones and relief associated with pre-existing weak domains, by testing various orientations of a system of two strike-slip faults under pure shear as well as simple shear boundary conditions. We also test the relative effects of friction angle and density contrast on the evolution of relief. These tests may shed light on exhumation process of high grade rocks associated with strain, as well as the topographic evolution in North-Western Ghana. According to tomographic models and velocity group dispersion analysis, in the Kaapvaal, Congo, Cameroon and West African/(WAC) cratons, the depth of the Moho has been estimated as 40 km and even deeper towards the south-west margin of the WAC or at about 43–48 km in the Congo Basin (Fishwick and Bastow, 2011; Lebedev et al., 2009; Pasyanos and Nyblade, 2007; Seber et al., 2001; Tokam et al., 2010) while it can reach as high as 30 km in northern Africa (Marone et al., 2003). Similar or complementary data of the Precambrian lithosphere structure has also been detailed in Lebedev et al. (2009). A compilation of Moho depths for the West African Craton (Jessell et al., 2015) reveals considerable uncertainty, and we have taken a thinner crust depth around 30 km in the present 3D modelling studies assuming that this was more or less the Proterozoic Moho depth.

2. Geological setting

2.1. Summary of the Birimian in the West African Craton

Most modern orogenic belts, such as the Alpine or Himalayan chains, display greenschist and blueschist facies metamorphism (Avé Lallemant and Guth, 1990; Maruyama et al., 1996; Ota and Kaneko, 2010), whereas the existence of modern-style plate subduction in ancient orogenic belts remains the subject of debate (Ganne et al., 2011; Stern, 2007, 2008; Condie and Kröner, 2008). Precambrian terranes also display widespread greenschist rocks, characterized by the development of a subvertical foliation, which is also axial-planar to elongated synforms and antiforms in greenstone lithologies (Cagnard et al., 2006a,b, 2007; Rey and Houseman, 2006). Such tectonic features are exemplified by the upper crustal portions of the Archaean crust in India (Chardon et al., 2009; Hansen et al., 1995; Jagadeesh and Rai, 2008; Mall et al., 2012). These Precambrian deformation events are proposed to have occurred in a regime of moderate regional convergence, which involved dominantly horizontal and locally vertical motions of material in the