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Growth of lithosphere-scale fault system in NE Tibet: Numerical modeling constrained by high-resolution seismic reflection data

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ABSTRACT

The east Kunlun fault is an important strike-slip shear zone to understand continental deformation in NE Tibet. The recent high-resolution deep seismic reflection profiling across the Kunlun fault reveals a thrust fault system and two decollements in the crust, along with another thrust fault system which reaches to the depth of upper mantle and cuts off the Moho. The mechanism of the growth of these shear zones at lithosphere-scale, which reveals the type of deep deformation, is investigated using the finite-element method with an elastic-plastic constitutive relationship. The results show that the thrust fault system in the crust may be explained by the conjugated plastic deformation belts under compression from the Indian plate. The pre-existing fault in the depth may develop to cut the Moho toward two new directions rather than along the original direction. The vertical and lateral heterogeneity of material, frictional property and geometry of the models all affect the feature of the fault growth. The growth of the thrust fault system on both sides of the Kunlun fault is only located in the crust, it means that the Kunlun fault does not reach to the Moho depth.

1. Introduction

Genesis of faults is fundamental problems in geodynamics and geology, which has great significance in understanding the deformation pattern and tectonic evolution of the lithosphere (Mukherjee and Koyi, 2010a, 2010b; Mukherjee et al., 2012, 2013, 2015; Misra et al., 2014; Mukherjee, 2007, 2010a, 2010b, 2013a, 2015, 2017; Babar et al., 2017; Kaplay et al., 2017a, 2017b; Misra and Mukherjee, 2017). The Kunlun fault in NE Tibet is an important fault to affect the deformation of Tibetan Plateau and its surroundings. The recent high-resolution deep seismic reflection profiling across the Kunlun fault reveals a thrust fault system and two decollements in the crust (Wang et al., 2011). Moreover, the Moho is cut by another thrust fault system which extends through the upper mantle. What kind of dynamic background breeds the fault systems? How does the fault system develop to cut the Moho?

Obviously, the field investigations and experimental models (Ackermann et al., 2001; Bellahsen et al., 2003; Filbrandt et al., 2007) are difficult to give dynamic mechanism of these questions in details, which mainly provide some qualitative or conceptual explanations. Thus, a mechanical analysis is expected to interpret the growth and development of the faults at the lithosphere-scale constrained by the seismic data.

In the past decades, numerical simulation has been an important way to understand various geological process in mechanics (e.g. Apuani et al., 2007; Beer et al., 2012), such as providing the dynamic interpretation for seismic imaging of the underlying lithosphere (Pysklywec et al., 2002). The seismic image reveals the geometry of lithosphere and has been a valuable constraint on the numerical models in depth. With the development of technology, the new high-resolution seismic reflection profile provides more detailed structure than observed in earlier years and can not be explained by old deformation styles (Wang et al., 2011). In this paper we try to present a mechanical evidence of deformation based on simulation.

Numerical modeling is widely used to simulate the deformation caused by tectonic movements created by the plates or earthquakes, which can concentrate on the mechanism of faults evolution (Bellahsen et al., 2003; Filbrandt et al., 2007; Schopfer et al., 2007a, 2007b; Gerya, 2013). Typically, the growth of faults based on the numerical simulations of strain partitioning has been well

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discussed by Braun (1994) and Braun and Beaumont (1995). They investigate the distribution of deformation in a elastic-plastic crustal layer at obliquely convergent plate boundaries and wrenching boundaries, respectively. The modeling predict the growth of a pair of thrust shear zones arranged in a "V" structure and strike-slip zones arranged in a "flower" structure corresponding to convergent and transcurrent motion, respectively (Braun and Beaumont, 1995), which predicts the growth of new faults in intact crust. But for the development of pre-existing faults, the numerical analysis have not been involved in their study. It becomes more complicated due to the nonlinearity caused by the discontinuity and stress concentration in the tips.

In this study, we use finite element method to investigate the mechanism of fault growth aided by the high-resolution deep seismic reflection profiling across the Kunlun fault in NE Tibet (Wang et al., 2011). The modeling for the growth of new faults in a continuum model and the development of a pre-existing fault simulated by a contact model are both included in the study. It is not our intention to provide a complete history of lithospheric deformation and evolution related to the reflection profiling across the Kunlun fault, but instead to explain the mechanical deformation features of fault growth under the tectonic loading and to investigate how and why the fault growth is affected by the geometry and material property. Numerical models with elastic-plastic constitutive relationship are used to study the plastic deformation of faults caused by applied loads. The viscosity of lithosphere may provide the temporal evolution of deformation process but is not considered here for simplicity since we focus on the feature of fault growth instead of the accurate time of fault growth. Therefore the viscous deformation with a long time may be reflected equivalently by plastic deformation under imposed loading and it may be reasonable to the first order by ignoring viscous flow at greater depth.

2. Geologic setting

Northward converging Indian plate since ~55Ma significantly contracted the lithosphere of the Tibetan plateau (Jain et al., 2005; Mukherjee, 2005; Mukherjee et al., 2013, 2015). Crustal thickening was partly absorbed by the strike slip of large shear zones in the north, resulting in escaping of rocks to the east (Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993; Tapponnier et al., 1982, 2001). Typically, the active left-slip east Kunlun fault is an important strike-slip shear zone in NE Tibet, which absorbs 30–50% of the eastern motion of Tibetan Plateau relative to Alashan block (Peltzer and Saucier, 1996; Van der Woerd et al., 1998, 2000). The fault is more than 1300 km long and moved at a long-term slip rate of ~12 mm/year since ~40kyr BP (Van der Woerd et al., 1998, 2000). The earliest left slip motion of the fault can be traced back to the middle and late Triassic. After a long geological period of transformation from ductile shear zones to brittle ones, the fault was finally formed until Middle Pleistocene (Xu et al., 2007).

The Kunlun fault follows the Triassic Anyemaqen-Kunlun suture zone, which is the boundary between the east Kunlun-Qaidam terrane in the north and the Songpan-Ganze terrane in the south (Fig. 1a) (Yin and Harrison, 2000; Pan et al., 2004; Fu and Awata, 2007). The former is dominated by the Early- and Late Paleozoic, and Triassic strata, whereas the latter is characterized by thick Triassic flysch (Xu et al., 2007). They are distinctly different in the composition, tectonic deformation, evolution history and morphology (Xu et al., 2007). The difference of material property between the two terranes can also be recognized from the seismic velocity structures (Karplus et al., 2011; Mechie et al., 2012; Wang et al., 2013). The deep seismic reflection profile (Fig. 1) of Wang et al. (2011) along line AA' in Fig. 1a is selected to build the numerical models in this study.

The result of deep reflection profile in Fig. 1b shows two thrust fault systems and two decollements as interpreted by Wang et al. (2011). The upper thrust fault system is a duplex one (northern duplex and southern duplex) locating at both sides of the Kunlun fault. The other thrust fault system extends through the upper mantle and cuts the Moho. The two thrust systems are separated by an upper and a lower decollement in the middle, which indicate the decoupling of the deformation of upper crust and lithosphere mantle. The Moho offset and overlap imply that this profile has been strongly compressed. Consequently, predicting fault growth in this region may be simplified to a two-dimensional model considering pure contraction/pure shear, which matches with the geologic model of Wang et al. (2011). Being a compressional domain, normal faults are less likely. Therefore normal faults are not considered in this interpretation (Mukherjee, 2016).

The widespread plutons in the region across the Kunlun fault zone suggest that the Triassic suture, where the Kunlun fault is located, may have been healed by the later thermal event (Latest Triassic and early Jurassic) (Pan et al., 2004; Yuan et al., 2010). This may lead to the smooth and sub-horizontal Moho due to the thermally viscous flow in the lower crust and the upper mantle (as in Mukherjee et al., 2010; Mukherjee, 2000, 2012; Mukherjee and Mulchrone, 2012), though the initial Moho was created by Triassic closure of the Paleo-Tethys ocean and may be discontinuous (Wang et al., 2011). This is an important constraint for our simulation in model setting.

3. Model calculations

The finite element code ANSYS® was employed in this study for its versatility in solving complex structural problems. It is suitable to nonlinear analysis of mechanical system, such as nonlinear geometric, nonlinear material issues and contact of faults. All of this complexity can be handled efficiently by advanced solver techniques that reliably capture all subtleties. The model material follows elastic-plastic constitutive relationships with the Drucker-Prager yield criterion (Drucker and Prager, 1952) in calculations, which is widely used in plastic analysis and consists of the following yield function (f):

$$f = \alpha I_1 + \sqrt{J_2} - k = 0, \tag{1}$$

where

$$\alpha = \frac{2\sin\phi}{\sqrt{3}(3-\sin\phi)}, \tag{2}$$

$$k = \frac{6C\cos\phi}{\sqrt{3}(3-\sin\phi)}, \tag{3}$$

in which, I_1 is the first invariant of the stress tensor, J_2 is the second invariant of the deviatoric stress tensor, C is the cohesion, and ϕ is the friction angle. When the stress state satisfies Eq. (1), plastic behavior occurs. To be simple, we employ the associated flow rule. It means the rule has the same equation form as the yield law except the friction angle displaced by the dilation angle. The yield criterion is linear like the Mohr-Coulomb failure criterion, so fault growth based on the plastic analysis somewhat resembles Andersonian case.

The linear elastic portion of the material model requires specification of two elastic constants to relate stress (σ) and strain (ε), that is Young's modulus and Poisson's ratio, which can be obtained from the seismic velocity structure in the region (Karplus et al.,

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