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Spacing and strength of active continental strike-slip faults

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ABSTRACT

Parallel and evenly-spaced active strike-slip faults occur widely in nature across diverse tectonic settings. Despite their common existence, the fundamental question of what controls fault spacing remains unanswered. Here we present a mechanical model for the generation of parallel strike-slip faults that relates fault spacing to the following parameters: (1) brittle-crust thickness, (2) fault strength, (3) crustal strength, and (4) crustal stress state. Scaled analogue experiments using dry sand, dry crushed walnut shells, and viscous putty were employed to test the key assumptions of our quantitative model. The physical models demonstrate that fault spacing (S) is linearly proportional to brittle-layer thickness (h), both in experiments with only brittle materials and in two-layer trials involving dry sand overlying viscous putty. The S/h slope in the two-layer sand–putty experiments may be controlled by the (1) rheological/geometric properties of the viscous layer, (2) effects of distributed basal loading caused by the viscous shear of the putty layer, and/or (3) frictional interaction at the sand–putty interface (i.e., coupling between the viscous and brittle layers). We tentatively suggest that this third effect exerts the strongest control on fault spacing in the analogue experiments. By applying our quantitative model to crustal-scale strike-slip faults using fault spacing and the seismogenic-zone thickness obtained from high-resolution earthquake-location data, we estimate absolute fault friction of active strike-slip faults in Asia and along the San Andreas fault system in California. We show that the average friction coefficient of strike-slip faults in the India–Asia collisional orogen is lower than that of faults in the San Andreas fault system. Weaker faults explain why deformation penetrates >3500 km into Asia from the Himalaya and why the interior of Asia is prone to large ($M > 7.0$) devastating earthquakes along major intra-continental strike-slip faults. Our new approach of estimating absolute fault strength may be useful in future studies of continental deformation and earthquake mechanics.

1. Introduction

Parallel strike-slip faults occur widely in nature, from a few meters to more than hundreds of km in length and spacing (e.g., Segall and Pollard, 1983; Davy and Cobbold, 1988; Swanson, 1988; Martel and Pollard, 1989; Dickinson, 1996; Yin, 2010). Regularly spaced strike-slip faults are observed along plate transform boundaries (e.g., the San Andreas fault system; Fig. 1a) (e.g., Nur et al., 1986; Dickinson, 1996), across collisional orogens (e.g., the Himalayan–Tibetan orogen; Fig. 1b) (Molnar and Tapponnier, 1975; Taylor and Yin, 2009; Yin, 2010; Zuza and Yin, 2016), in analogue experiments (e.g., Tchalenko, 1970; Freund, 1974; Naylor et al., 1986; Yin and Taylor, 2011), and on icy satellites in the outer solar system (e.g., Yin et al., 2016). Irregularly spaced parallel strike-slip systems have also been documented, including the seismically active right-slip fault systems across northern China where fault spacing varies from ~100 km to ~500 km (e.g., Yin et al., 2015). The characteristic spacing of strike-slip faults, or lack thereof, inevitably reflects how the faults interact with one another and with the fault-bounded crust. Thus, this readily observed geometric parameter may be used to estimate fault strength and stress state across diverse tectonic settings on Earth and other solar system bodies. Despite being such a common feature in zones of lithospheric deformation, the mechanics of evenly-spaced active continental strike-slip faults has never been satisfactorily explained nor quantified.

In this contribution, we develop a stress-shadow model (e.g., Lachenbruch, 1961; Yin et al., 2016) that relates strike-slip-fault spacing to the brittle-crust thickness of the fault-hosting lithosphere, fault and crustal strength, and the remote regional stress. Our model assumptions are tested and validated with scaled analogue experiments using dry sand, dry crushed walnut shells, and

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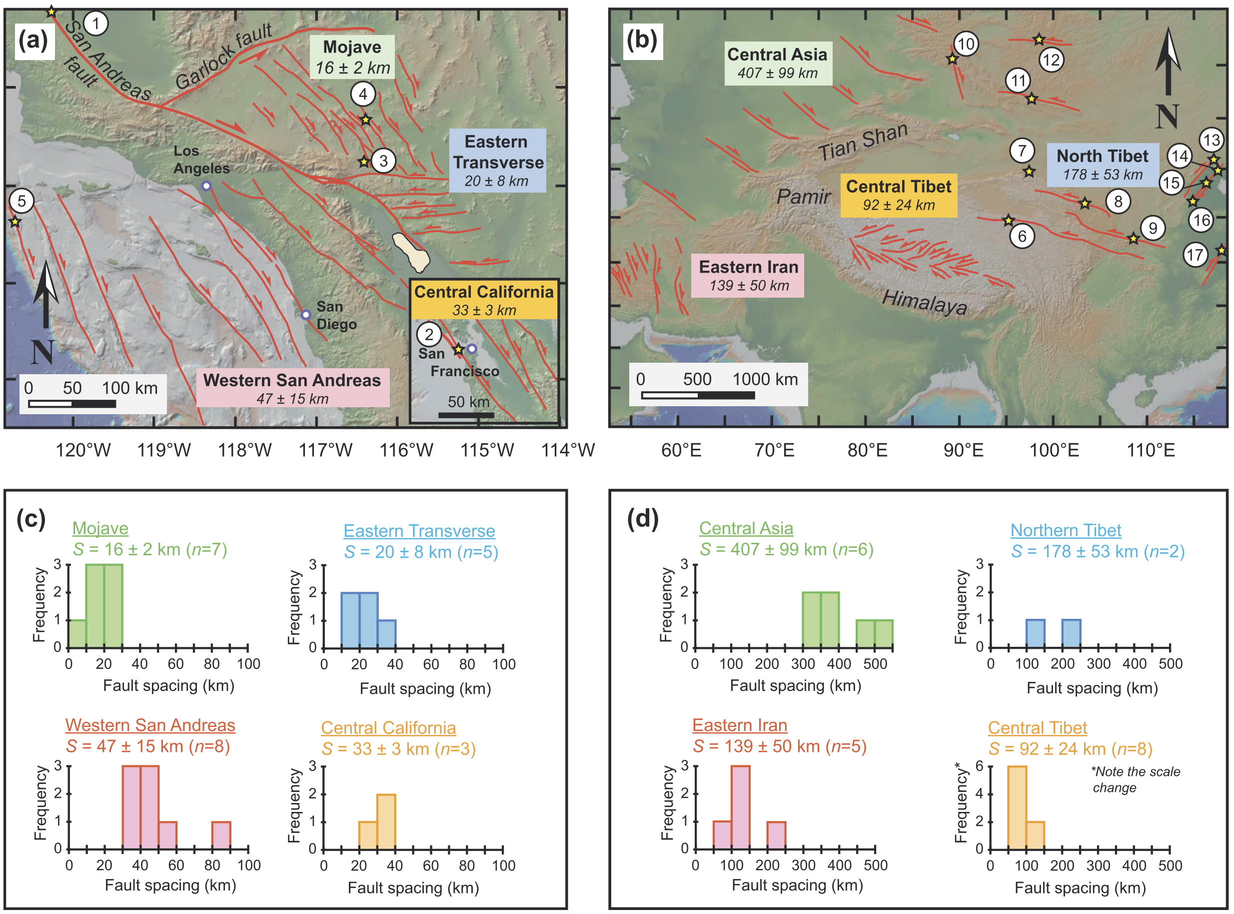

Fig. 1. Evenly-spaced strike-slip fault domains in (a) California and (b) Asia and their average fault spacing. Inset in (a) shows parallel faults in central California. Histograms show fault spacing for each domain of strike-slip faulting in (c) California and (d) Asia. Locations (shown as yellow stars) and magnitudes of major strike-slip fault earthquakes in California and Asia: (1) 1857 M = 7.9 Fort Tejon earthquake, (2) 1906 M = 7.8 San Francisco earthquake, (3) 1992 M = 7.3 Landers earthquake, (4) 1999 M = 7.1 Hector Mine earthquake, (5) 1927 M = 7.3 Lompoc earthquake, (6) 2001 M = 8.1 Kunlun Pass earthquake, (7) 1932 M = 7.6 Changma earthquake, (8) 1920 M = 7.8 Haiyuan earthquake, (9) 1556 M = 8.0 Shaanxi earthquake, (10) 1931 M = 8.0 Fuyun earthquake, (11) 1957 M = 8.1 Gobi Altai earthquake, (12) 1905 M = 8.4 Bulnay earthquake, (13) 1679 M = 8.0 Sanhe-Pinggu earthquake, (14) 1976 M = 7.8 Tanshan earthquake, (15) 1966 M = 7.2 Xingtai earthquake, (16) 1830 M = 7.5 Cixian earthquake, and (17) 1668 M = 8.0 Tancheng earthquake. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

viscous putty. These models use a basal shear device to generate Riedel shears in the dry granular materials. By experimenting with various thicknesses and viscosities of a putty layer beneath a brittle layer, we also explore the effects of distributed versus localized basal shear on strike-slip fault spacing.

In this study we show that strike-slip fault spacing is linearly proportional to brittle-layer thickness in both our analogue experiments and for naturally occurring crustal-scale faults. The application of our theoretical model using observed seismogenic zone thickness and fault spacing allows us to estimate the effective coefficient of fault friction ($\overline{\mu_f}$) of strike-slip faults in actively deforming regions on Earth. This method leads to the finding that the faults in the India–Asia collisional orogen are weaker ($\overline{\mu_f} = \sim$0.10–0.20) than faults in the San Andreas transform system ($\overline{\mu_f} = \sim$0.15–0.22) in California, which has implications for the mode and extent of continental tectonics away from plate boundaries.

2. Generating parallel strike-slip faults

2.1. Existing models

The following models have been proposed to account for the generation of parallel strike-slip faults: (1) reactivation of preexisting extensional joints in crystalline and/or other low-porosity rock (e.g., Segall and Pollard, 1983; Martel and Pollard, 1989), (2) deformation band formation in high-porosity rocks (e.g., Aydin and Johnson, 1978; Fossen et al., 2007), and (3) viscoelastic models that predict strike-slip fault spacing based on the rheological contrasts of the upper and lower crust (Roy and Royden, 2000a, 2000b).

The first two groups of models explain faulting by a specific sequence of pre- and syn-faulting stress state acting on a particular rock type (e.g., previously normal-faulted rocks or deformation-band generation in porous sandstone) at small spatial scales (i.e., $< \sim 1$ km). Therefore, they ultimately lack generality for crustal-scale strike-slip faulting in diverse tectonic settings. For example, it is unlikely that strike-slip faulting at a range of scales from <1 mm to >1000s km across diverse lithologies (e.g., Fig. 1) is universally derived from the reactivation of preexisting and regularly-spaced structures. We note that strike-slip faulting in northern Tibet and certain regions of California may be respectively exploiting suture zones and older normal faults (e.g., Taylor and Yin, 2009; Dokka, 1989), but the majority of the faults in both settings actually crosscut preexisting fabrics (Fig. 1) (Dickinson, 1996; Yin and Taylor, 2011). The deformation band mechanism (Aydin and Johnson, 1978) leads to strain localization and strain hardening, which in turn can produce through-going faults. This process predicts sequential initiation and deactivation of individual faults, but does not explain coeval motion of parallel strike-slip faults that occur independent of the fault-hosting lithology.

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