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Structure and kinematics of the Sumatran Fault System in North Sumatra (Indonesia)

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ABSTRACT

Lithospheric-scale faults related to oblique subduction are responsible for some of the most hazardous earthquakes reported worldwide. The mega-thrust in the Sunda sector of the Sumatran oblique subduction has been intensively studied, especially after the infamous 2004 Mw 9.1 earthquake, but its onshore kinematic complement within the Sumatran subduction, the transform Sumatran Fault System, has received considerably less attention. In this paper, we apply a combination of analysis of Digital Elevation Models (ASTER GDEM) and field evidence to resolve the kinematics of the leading edge of deformation of the northern sector of the Sumatran Fault System. To this end, we mapped the northernmost tip of Sumatra, including the islands to the northwest, between 4.5°N and 6°N. Here, major topographic highs are related to different faults. Using field evidence and our GDEM structural mapping, we can show that in the area where the fault bifurcates into two fault strands, two independent kinematic regimes evolve, both consistent with the large-scale framework of the Sumatran Fault System. Whereas the eastern branch is a classic Riedel system, the western branch features a fold-and-thrust belt. The latter contractional feature accommodated significant amounts (c. 20%) of shortening of the system in the study area. Our field observations of the tip of the NSFS match a strain pattern with a western contractional domain (Pulau Weh thrust splay) and an eastern extensional domain (Pulau Aceh Riedel system), which are together characteristic of the tip of a propagating strike-slip fault, from a mechanical viewpoint. For the first time, we describe the strain partitioning resulting from the propagation of the NSFS in Sumatra mainland. Our study helps understanding complex kinematics of an evolving strike-slip system, and stresses the importance of field studies in addition to remote sensing and geophysical studies.

1. Introduction

Lithospheric-scale strike-slip faults develop worldwide by slip partitioning during oblique convergence between two tectonic plates. These trench-parallel strike-slip faults accommodate margin-parallel slip while the corresponding slabs subduct with slip normal to the margin. As a result, individual slivers of lithosphere (sliver plates) develop in the upper plate between the trench and its associated strike-slip faults (e.g. Fitch, 1972; Karig, 1978) (Fig. 1, panel A and B). These faults, reaching hundreds of kilometers of cumulative displacements along thousands of kilometers, favor localization of magmatic intrusions and influence the position of the volcanic arc (Sieh, 1988). Sense and rate of motion along these faults can be quantified using geophysical data, and large-scale domains of compression and tension can be identified in relation to the degree of convergent and divergent slip resulting from fault geometry (Prescott, 1981; Sieh, 1988).

The Peru-Chile trench and the Atacama fault in the west coast of South America (e.g. Allen, 1965), the Nankai Trough and the Median tectonic line in Japan (e.g. Kaneko, 1966), and the Sunda trench and the Sumatran Fault System in Sumatra Island (e.g. Katili, 1970; Fitch, 1972) are prominent examples of this particular tectonic setting highly prone to large, hazardous earthquakes. The system associated with the Sumatran Fault System (SFS) (Fig. 1.A) has attracted researchers, especially after the infamous 2004 Mw 9.1 earthquake off the west coast of northern Sumatra (Subarya et al., 2006; Fu and Sun, 2006; Chlieh et al., 2007; Franke et al., 2008). Intensive geophysical studies provide a good understanding of seismic coupling and vertical motions along the forearc side of the sliver plate (Simoes et al., 2004; Natawidjaja et al., 2004, 2006; Sieh, 2007; Berglar et al., 2010; Collings et al., 2012; Cook et al., 2014; Martin et al., 2014; Frederik et al., 2015). However, structural and kinematic analyses in the SFS and derived structures need to be improved to help evaluate the seismic hazard potential, and thus mitigate the impact of the devastating earthquakes associated with this system (e.g. Ishii et al., 2005; Moreno et al., 2010).

Sieh and Natawidjaja (2000) studied different sectors of the SFS using photo-interpretation in an area ranging from 6.75°S to 4.4°N;

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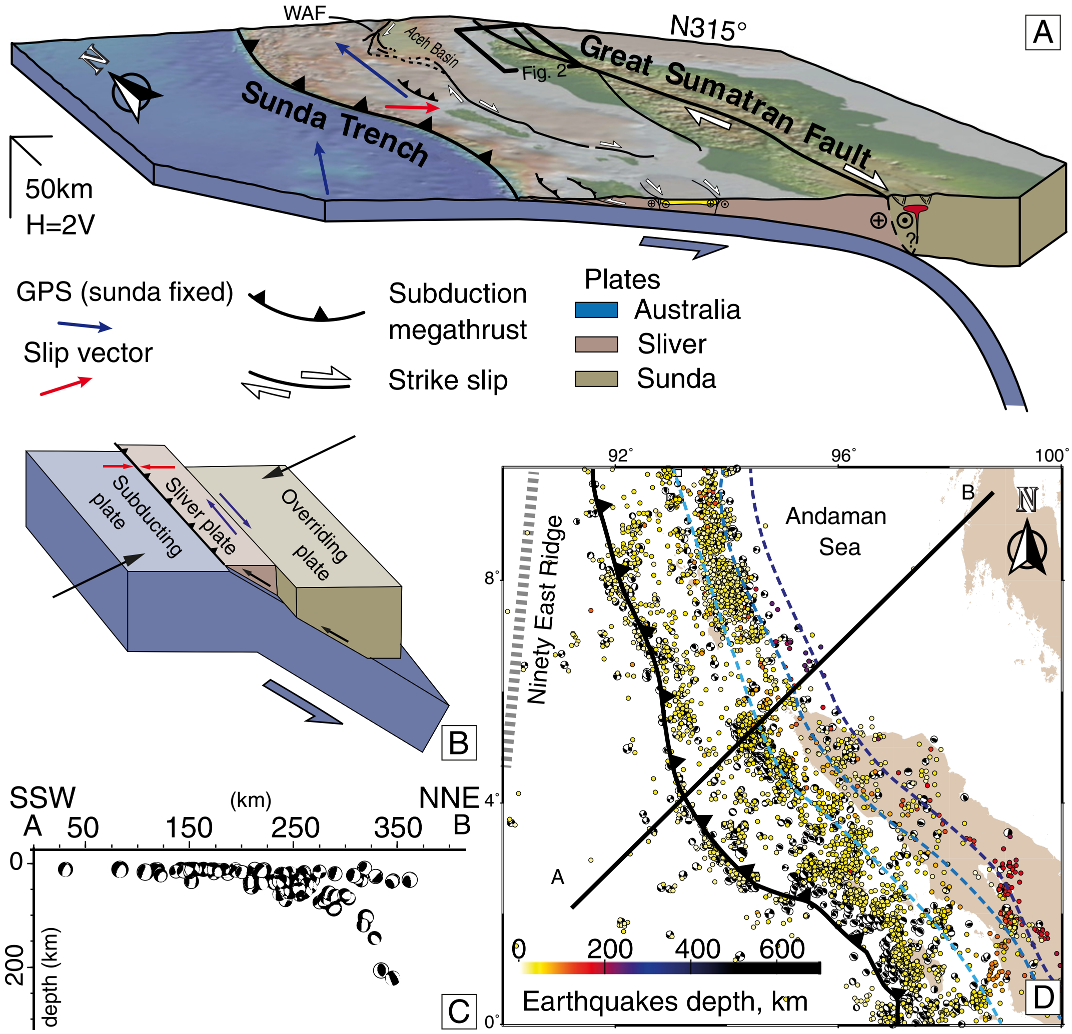

Fig. 1. General tectonic context in the Sumatran section of the Sunda forearc. A: Real-scale 3D view of the tectonic configuration of the northern sector of the Sumatran section of the Sunda arc, showing the main regional and tectonic-scale features, as well as GPS and slip vectors. The frontal cross-section transects the Nias island and the Toba caldera in a direction roughly perpendicular to the Sunda Trench and the Sumatran Fault System. Location of the study area (frame of Fig. 2) is also shown. Northern Sumatra off-shore structures are from Martin et al. (2014); WAF stands for West Andaman Fault. B: Idealized block diagram showing the geometry of the sliver plate and overall motions under oblique subduction (modified from McCaffrey (2009) to emphasize correlations with panel A). Cross-section (C) and map view (D) showing the location and depth of earthquakes and their focal mechanisms in the study area and surroundings, after Heuret and Lallemand, (2005). Blue dotted lines represents the slab 50 km-isocontours with a color gradient from light to dark with increasing depth (Gudmundsson and Sambridge, 1998).

we study the geometry of the northern sector of Sumatra including the islands in northwest offshore Sumatra, which have not been described in detail in previous studies. Here, we investigate whether the structural framework of the northern sector of the Sumatran Fault System (NSFS) is variable, and how this variability might reflect strain partitioning. To this end, we analyze new detailed structural data from the NSFS, with special attention to the aforementioned islands. These islands exhibit the youngest deformation in relation to oblique convergence, located at the leading edge of northwestwardly propagating continental sliver deformation exposed on land (Jarrard, 1986; McCaffrey, 1991, 1992).

2. Present day geodynamic context

2.1. Geometry, kinematics, volcanism and seismicity

The strike-slip SFS accommodates the high-angle oblique subduction of the Australian Plate below the Sunda Plate. The right-lateral transpressional SFS runs parallel to the trench with an overall linear, slightly sinusoidal geometry (e.g. Natawidjaja, 2002), and cuts the Sumatran lithosphere vertically down to the asthenosphere (Bellier and Sébrier, 1994). The SFS defines the eastern boundary of the Sumatran sliver plate; its western limit is the NNW–SSE curved Sunda Trench (Fitch, 1972; Karig, 1978; McCaffrey, 2009) (Fig. 1.A). This sliver plate thus represents an individualized sector of the Sunda Plate forearc (more than 1650 km long and 250–300 km wide), which moves northwestwards along the trench, driven by basal shear (McCaffrey et al., 2000; McCaffrey, 2009) (Fig. 1.B).

The Australian Plate moves northwards at a rate of 59 ± 3 mm $year^{-1}$ at the latitude of Sumatra Island, east of the Ninety East ridge; west of the ridge, the Indian Plate moves at a lower rate of 39 ± 3 mm $year^{-1}$ (Martin et al., 2014). Both, the Australian and Indian plates move almost parallel to the N-S trending Sunda Trench. The Sunda Trench shows pure dip slip motion at a mean rate of 45 mm $year^{-1}$, accommodating the normal-to-trench motion of Australia (Jarrard, 1986; McCaffrey, 1991, 1992; Bock et al., 2003). The movement parallel to the trench is partly (~2/3) accommodated by strike-slip along the SFS at rate of 24.5 ± 4.5 mm $year^{-1}$ (Chlieh et al., 2008), and partly (~1/3) by full margin parallel motion probably between the forearc islands and the trench (McCaffrey et al., 2000) (Fig. 1.A). Slip rates increase towards the northwest along the SFS, as indicated by the arcuate shape of the subduction trench, a distant pole of rotation, and earthquake slip vectors from the subduction mega-thrust, as well as GPS data (Huchon