Assessing the impact of sedimentation on fault spacing at the Andaman Sea spreading center

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ABSTRACT

The stabilizing effect of surface processes on strain localization, albeit predicted by several decades of geodynamic modeling, remains difficult to document in real tectonic settings. Here we assess whether intense sedimentation can explain the longevity of the normal faults bounding the Andaman Sea spreading center (ASSC). The structure of the ASSC is analogous to a slow-spreading mid-ocean ridge (MOR), with symmetric, evenly spaced axis-facing faults. The average spacing of faults with throws ≥100 m (8.8 km) is however large compared to unsedimented MORs of commensurate spreading rate, suggesting that sedimentation helps focus tectonic strain onto a smaller number of longer-lived faults. We test this idea by simulating a MOR with a specified fraction of magmatic plate separation (M), subjected to a sedimentation rate (s) ranging from 0 to 1 mm/yr. We find that for a given M ≥ 0.7, increasing s increases fault lifespan by ~50%, and the effect plateaus for s > 0.5 mm/yr. Sedimentation prolongs slip on active faults by leveling seafloor relief and raising the threshold for breaking new faults. The effect is more pronounced for faults with a slower throw rate, which is favored by a greater M. These results suggest that sedimentation-enhanced fault lifespan is a viable explanation for the large spacing of ASSC faults if magmatic input is sufficiently robust. By contrast, longer-lived faults that form under low M are not strongly influenced by sedimentation.

INTRODUCTION

Tectonic models commonly predict that erosion and sedimentation enhance strain localization onto a few major faults at subaerial plate boundaries such as orogens (e.g., Masek and Duncan, 1998; Willett, 1999) and continental rifts (Olive et al., 2014; Andrés-Martínez et al., 2019; Theunissen and Huismans, 2019). By contrast, the influence of seafloor-shaping processes on the tectonic makeup of submarine boundaries has received far less attention, possibly because erosion is commonly considered highly inefficient in the deep ocean. Submarine plate boundaries are however subjected to a wide range of sedimentation rates and constitute excellent natural laboratories to investigate the influence of sediment deposition on seafloor-shaping tectonics (e.g., Bialas and Buck, 2009; Worthington et al., 2018). Here we assess the impact of heavy terrigenous sedimentation on fault development at the Andaman Sea spreading center (ASSC) by comparing it to unsedimented mid-ocean ridges (MORs) of commensurate spreading rate.

The ASSC is a divergent boundary marking a releasing step between the Sumatra and Sakaigawa strike-slip fault systems (Fig. 1A). It allows the opening of a 200-km-long, 120-km-wide pull-apart basin in the back-arc domain of the oblique Sumatra subduction (Curry et al., 1979; Sieh and Natawidjaja, 2000; Singh et al., 2013). While the onset and exact modes of pre-Quaternary extension in the region have been debated (Curry, 2015; Morley and Alvey, 2015), magnetic anomalies suggest accretion of oceanic crust at the ASSC since ca. 4 Ma, initially at 16 mm/yr and increasing to 38 mm/yr since 2 Ma (Kamesh Raju et al., 2004). Bathymetric and seismic reflection data show that the ASSC features the axial valley and shoulders commonly observed at slow MORs (Fig. 1B). Seafloor relief, however, lacks typical rugged abyssal hill morphology in the off-axis domain (Jourdain et al., 2016). Instead, fault-induced topography within ~30 km normal to the ASSC axis (≥2 Ma) is buried under a sedimentary layer as thick as 1.5–2 km. This massive sedimentary input is largely provided by the Irrawaddy River, 500 km to the north (Curry, 2005), and amounts to ~0.75–1 mm/yr of syntectonic deposition over the past 2 m.y.

Jourdain et al. (2016) identified crustal-scale normal faults at the ASSC (Fig. 1B). By converting their reflection data to depth based on root-mean square (RMS) velocities, they proposed dips of 20°–40°, which is consistent with the seismic activity observed by Diehl et al. (2013) but unusually shallow compared to the typical MOR range of 45°–60° (Thatcher and Hill, 1995). The faults are inward facing and, to first order, symmetric about the spreading axis, as is common at magmatically robust sections of slow MORs (Escartín et al., 2008). However, we estimate the average spacing of faults with heaves >100 m at 8.8 ± 3 km, which falls on the high end of fault spacing at symmetric slow MOR segments (Fig. 2; see the Supplemental Material). A large body of theoretical work suggests that MOR fault spacing reflects the fraction of plate separation (M) accommodated by axial magmatic injection (Buck et al., 2005; Behn and Ito, 2008; Ito and Behn, 2008; Olive et al., 2015). Values of M between ~0.4 and ~0.6 promote widely spaced (>5–15 km), large-offset detachment faults. By contrast, increasing M to >0.6 leads to more closely spaced faults developing symmetrically about the spreading axis. Thus, one explanation for the large spacing of faults at the ASSC could be a weak magma supply. Seismic imaging, however, provides ample evidence for robust magmatic emplacement at the ASSC, such as multiple sills distributed through ~7-km-thick igneous crust (Fig. 1B).

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METHODS

We simulate a sedimented spreading center (Fig. 3) using Fast Lagrangian Analysis of Continua software (FLAC; Cundall, 1989), an explicit finite difference method solving momentum, heat, and mass conservation in a domain representing a 60-km-wide and 20-km-deep two-dimensional vertical cross section of an elastic-brittle lithosphere (material colder than ~600 °C) over a viscous asthenosphere (see the Supplemental Material for details and parameter values). Symmetric extension is applied on the sides at a full rate of 38 mm/yr. Strain localization by cohesion loss enables spontaneous fault development when the Mohr-Coulomb criterion is reached in the lithosphere (e.g., Poliakov and Buck, 1998; Lavier et al., 2000). A narrow axial dike widening at M times the total extension rate simulates continuous magma injection (Behn and Ito, 2008).

Sedimentation at rate $s$ is simulated by blanketing a low-density layer on top of the domain through uniformly raising the top nodes of the grid by $s \times \Delta t$ at every time increment and then allowing the resulting topography to diffuse (Fig. S2 in the Supplemental Material). With this compromise between infilling and uniform blanketing, we reproduce two key effects of sedimentation: mass addition and relief suppression.

RESULTS

We ran 5-m.y.-long simulations with $M$ varying between 0.6 and 0.8 and $s$ between 0 and 1 mm/yr. In agreement with previous studies, all runs produced sequences of normal faults commonly forming on alternating sides of the axis (Fig. 3). Without sedimentation, the simulation with $M = 0.6$ (Fig. 3A) produced a few large-offset (10+ km) faults that induce seafloor doming, while $M = 0.8$ (Fig. 3B) yielded multiple short-offset (~1 km) faults typically 5 km apart (Buck et al., 2005). The addition of sediments at $s = 0.5$ mm/yr led to longer-lived, more-widely spaced faults (~9 km) that undergo greater amounts of rotation, down to ~40° from an initial dip of ~60° (Fig. 3D). Interestingly, in the $M = 0.6$ case, the addition of sediments suppressed the formation of detachments, replacing them with symmetric faults of moderate offset and spacing (Fig. 3C).

To further quantify these effects, we measured the lifespan of each individual fault, as well as its heave at abandonment, in all simulations. We also measured the distance between successive hanging-wall cutoffs visible in seafloor or basement topography at the end of each run, except in the $s = 0$ and $M = 0.6$ case, which produced large-offset detachments with spacings in some cases exceeding the half-width of the domain (Fig. 3A); in this case, we estimated fault spacing at different times during the run and discarded the very short-lived faults formed at the beginning of the simulation prior to steady detachment faulting.

Figure 4A summarizes our measurements of fault lifespan as a function of $s$ for different values of $M$. We find that the trend of decreasing fault lifespan with increasing $M$ reported by Buck et al. (2005) and Behn and Ito (2008) holds true with sediment deposition. We also find that for a given $M \geq 0.7$, increasing $s$ increases fault lifespan by as much as ~50%, and the effect plateaus at $s \sim 0.5$ mm/yr. By contrast, we cannot resolve any significant effect of sedimentation on fault lifespan for $M \leq 0.65$. 

Figure 1. (A) Tectonic context of the Andaman Sea. ASSC—Andaman Sea spreading center; ANF—Andaman-Nicobar fault; SFS—Sumatra fault system. Green lines: profiles PG508-21 (east) and PG508-23 (west) of Jourdain et al. (2016). (B) Interpreted crustal structure of the ASSC, from Jourdain et al. (2016). Seismic wave velocities at key depths are indicated on the left, in km/s. U-AML and L-AML—upper and lower axial melt lens, respectively; OB—to outer bounding fault; VE—vertical exaggeration.
The impact of sedimentation is more visible on fault spacing (e.g., Figs. 3B versus 3D). Figure 4B shows that even slow sedimentation rates strongly attenuate the decrease in fault spacing with increasing $M$ that is commonly observed without sediments (Buck et al., 2005; Behn and Ito, 2008). In fact, sedimentation rates as fast as 1 mm/yr nearly suppress the effect of $M$ on fault spacing.

**DISCUSSION**

Erosion and sedimentation have been shown to enhance the lifespan of individual normal faults in numerical simulations (Olive et al., 2014; Andrés-Martínez et al., 2019; Theunissen and Huismans, 2019). Olive et al. (2014) attributed this effect to surficial mass redistribution alleviating the energy cost of topography buildup. More specifically, sustaining slip on a normal fault requires an ever-increasing amount of energy (i.e., the work of far-field tractions), which is partly stored and dissipated through elasto-plastic flexure of the fault-bounded blocks, and partly stored as gravitational potential energy (GPE; Buck, 1993; Masek and Duncan, 1998; Olive et al., 2014). In this framework, breaking a new fault in undeformed lithosphere can rapidly become more energetically efficient than continuing slipping on an existing fault. Surface processes reduce the GPE associated with topographic highs and lows (Bialas and Buck, 2009) and thus slow down the increase in energy demand associated with increasing fault offset, ultimately delaying the moment when breaking a new fault becomes favorable.

We postulate that a similar mechanism is at play in our simulations, with the primary effect of sedimentation being topographic leveling. Because net mass is added to the system, sedimentation does not suppress the GPE cost of fault growth. However, in the extreme case where sediments completely bury all fault-induced relief beneath a flat seafloor, the GPE associated with basement topography is lessened because it scales with the lower density contrast between basement and sediment, as opposed to that between basement and water. Sedimentation also raises the average normal stress in axial lithosphere, and thus the force threshold to break a new fault.

An important outcome of our simulations, albeit specific to spreading centers, is that $M$ modulates the impact of sedimentation on fault lifespan and spacing. On the one hand, the relative enhancement in fault spacing due to sedimentation seems greater for greater values of $M$ (Fig. 4B). This is straightforwardly explained by the kinematic fault model of Buck et al. (2005), which relates fault lifespan $\tau$ and fault spacing $\Delta S$ according to

$$\Delta S = 2MU_s \tau,$$  \tag{1}

where $U_s$ is the spreading half-rate. Equation 1 constitutes a good first-order approximation of our results (see the Supplemental Material). On the other hand, $M$ seems to modulate the effect of sedimentation on fault lifespan, with values $> 0.7$ allowing the greatest lifespan enhancement. A likely explanation is that the effective throw rate on each normal fault scales as $2 \times U_s(1 - M)$ and is thus slower when $M$ is greater. Topography that grows more slowly can be buried more efficiently by sedimentation acting at a given $s$. Conversely, reduced magma supply leads to faster-growing tectonic relief, more difficult to suppress with sediments. This could explain why we do not see any significant impact of $s$ on fault lifespans at $M \leq 0.65$ (Fig. 4A).

We further test this hypothesis by introducing a nondimensional number $\Psi$, representing the efficiency of topography burial, defined as sedimentation divided by throw rate for $45^\circ$ faults:

$$\Psi = \frac{s}{2 \times U_s(1 - M)},$$ \tag{2}

In Figure 4C, we plot fault lifespan enhancement (lifespan normalized by the lifespan from a corresponding run without sedimentation) as a function of $\Psi$. To first order, for $M > 0.6$, our results fall within a broad trend of increasing lifespan enhancement with increasing $\Psi$, plateauing at $\sim 50\%$ for $\Psi \geq 0.1$. This suggests that (1) our nondimensionalization appropriately corrects for the modulation of $M$ on the efficiency of sediment blanketing, and (2) infinitely efficient relief suppression would not suffice to promote infinitely long-lived faults, as observed.

**Figure 3.** Representative snapshots of plastic strain in our simulations ($s$—sedimentation rate; $M$—fraction of magmatic plate separation). Red line is Moho; orange rectangle is magma injection zone; yellow line is sediment-basement interface; solid white lines are isotherms (in °C); dotted white lines are inactivated faults. $U_s$—spreading half-rate.
in simulations with strong brittle layers (Olive et al., 2014). We, however, note that points in Figure 4C still cluster by $M$, suggesting that second-order effects of magmatic injection rates remain to be identified.

Applying our results to the ASSC requires estimates of both $s$ ($\sim 0.75 - 1$ mm/yr) and $M$ at the spreading axis. Diehl et al. (2013) used seismic moment budgets to estimate $M = 0.9$, but moment release at MORs is known to greatly underestimate the tectonic fraction of plate separation, and therefore overestimate $M$ (Cowie et al., 1993; Olive and Escartín, 2016). Measurable fault heaves ($\geq 100$ m) along seismic profiles PGS08-21 and PGS08-23 of Jourdain et al. (2016) can, however, be summed following the method of Escartín et al. (1999) to yield estimates of $M$ between 0.75 and 0.85 (see the Supplemental Material), on the high end of typical estimates for slow ridges. This may also represent an upper bound if a number of small faults below the resolution of the seismic data were missed in the summation.

If we have estimated $M$ correctly, then fault spacing at the ASSC exceeds those observed at unsedimented MORs (Fig. 4B, Ito and Behn [2008] data). Our model shows that sedimentation can account for the $\sim 4$ km difference in spacing. However, as noted above, $M$ may actually be $< 0.75$, in which case the large spacing of ASSC faults could primarily result from subdued magmatic input enabling faults to remain active longer at the axis. Interestingly, in this configuration, the faults would exhibit little sensitivity to sedimentation because their throw rates would be fast relative to the deposition rate ($\Psi < 1$). Simulations with $M = 0.65$, for example, predict fault spacings of 9–12 km regardless of $s$ (Fig. 4B). The back-arc setting of the ASSC (Fig. 1A) may account for a lower magmatic input compared to a MOR of similar spreading rate. Jourdain et al. (2016), however, identified multiple reflectors that they interpreted as sills and melt lenses, as well as a thick igneous crust (Fig. 1B), suggesting sizeable magmatic contribution to plate separation at the ASSC, plausibly accounting for $M \sim 0.8$.

Other parameters, such as the thermally controlled geometry of the lithosphere, could also influence tectonic styles in the ASSC. For example, slower off-axis lithosphere thickening could increase fault spacing at constant $M$ and $s$ (Behn and Ito, 2008). While we have little constraints over these parameters at the ASSC, the thermal structure of our simulations is self-evolved and not imposed. It is thus consistent with the prescribed $U_s$, $M$, and efficiency of on-axis hydrothermal cooling, the latter being chosen such that faults would root $\sim 5$ km below seafloor, as in the interpreted profiles of Jourdain et al. (2016) (Fig. 1B). We note that this develops an $\sim 15^\circ$ slope at the base of the lithosphere (Fig. 3), which could explain why simulations
with $s = 0$ slightly overpredict the spacing of faults at MORs (Fig. 4B). MOR faults are indeed better modeled with lithospheric slopes closer to $\sim 30^\circ$ (e.g., Behn and Ito, 2008, their figure 14). In any case, Behn and Ito (2008) reported that decreasing the lithospheric slope from $30^\circ$ to $10^\circ$ only increases fault spacing from $\sim 3 \text{ km}$ to $\sim 6 \text{ km}$ for $M > 0.65$. Therefore the thermal state of the Andaman Sea back-arc area is unlikely to account for the observed spacing of ASSC faults. We instead put forward sedimentation as a viable explanation, provided magmatic input at the ASSC is sufficiently robust to impart fault throw rates comparable to the deposition rate. While the ASSC may be a rare example of a back-arc spreading center with focused magmatic accretion and intense sedimentation, similar retrogradations between these processes can be expected in the early stages of oceanic accretion while incipient spreading centers remain close to continental sediment sources.

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