Shocks in a box 3D: Experimental insights into seismotectonic segmentation and synchronization of megathrust earthquakes in subduction zones

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Introduction

Subduction zones show an intrinsic relationship between forearc anatomy and slip during great megathrust earthquakes. Basin-centred asperities, coastal hypocentres and peninsulas coinciding with segment boundaries are manifests of this relationship suggesting that subduction earthquakes follow to first-order a temporally stable slip pattern of asperities and barriers which might be inferred from structural observations. Along strike of a subduction zone, however, temporally persistent asperities may fail in various modes including independent (mono-)asperity failure, sequences of triggered mono-asperity failures as well as synchronized (multi-)asperity failure. Depending on the mode and size of failures a pattern of variable magnitude earthquakes will emerge with the appearance of random, clustered or quasi-periodic recurrence. Because of limited observational records, the recurrence behaviour of subduction megathrust earthquakes remains however enigmatic. Here we use simulated earthquake sequences generated by elastoplastic granular wedges as labscale analogue models of subduction forearcs featuring megathrust earthquake cycles. Based on earlier quasi-2D models we expanded our simulation approach including a full 3D setup allowing for simulation of along-strike segmentation and non-plane strain deformation.

Model Setup

Here we present first results of 3D experiments on the feedback between seismogenic and tectonic processes under orthogonal convergence and triggering of multi-asperity failure.

Subduction zone forearc models made of sugar, rice, rubber and silicone and scaled for elasticity, strength and body forces are setup in a 1 m (~ 300 km) long and 60 cm (~ 180 km) wide box on top of a 15° dipping basal conveyer plate pulled at a constant rate of 0.05 mm/s (~ 60 mm/a). Horizontal surface deformation is monitored using particle image velocimetry (PIV).

The model setup includes two asperities characterized by velocity weakening / stick slip and surrounded by velocity strengthening /creeping barriers (Figure 1). We varied two parameters: The asperity distance (or barrier width) and the asperity strength contrast (depth difference). Accordingly, the asperities are coupled by static stress transfer in the order of 0.001 to 0.1 % of their total strength typical for natural asperities about tens of kilometres apart.

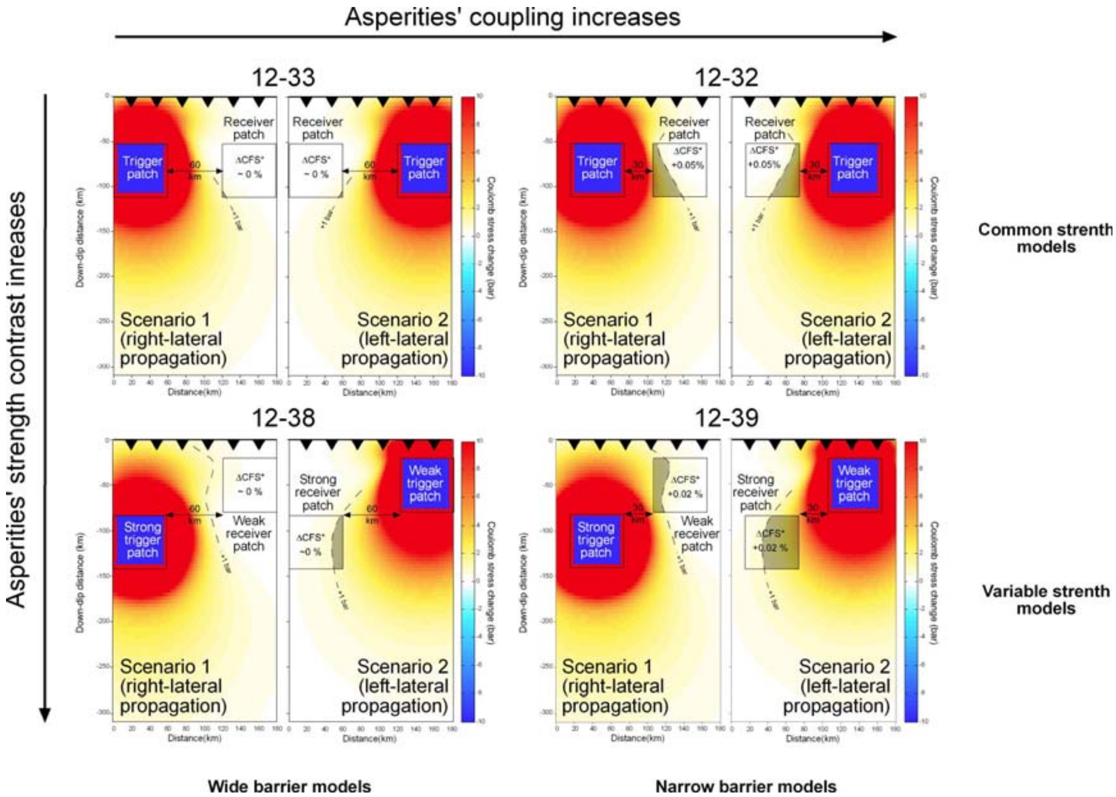

Figure 1: *Analogue model setup: Two asperities are coupled by static stress transfer (ΔCFS* = Coulomb failure stress change relative to absolute asperity strength). Parameter values given at natural scale.*

Experimental observations

Though the plate kinematic setup is plane strain (orthogonal convergence), the non-plane strain character of elastic deformation and stress changes during the seismic cycle drive along-strike localization of deformation at the peripheries of the simulated ruptures. Over multiple seismic cycles this results in trench-parallel morphostructural segmentation of the model wedge with areas of extension (basins) overlying seismic asperities and areas of shortening (ridges) marking the creeping barriers at depth (Figure 2).

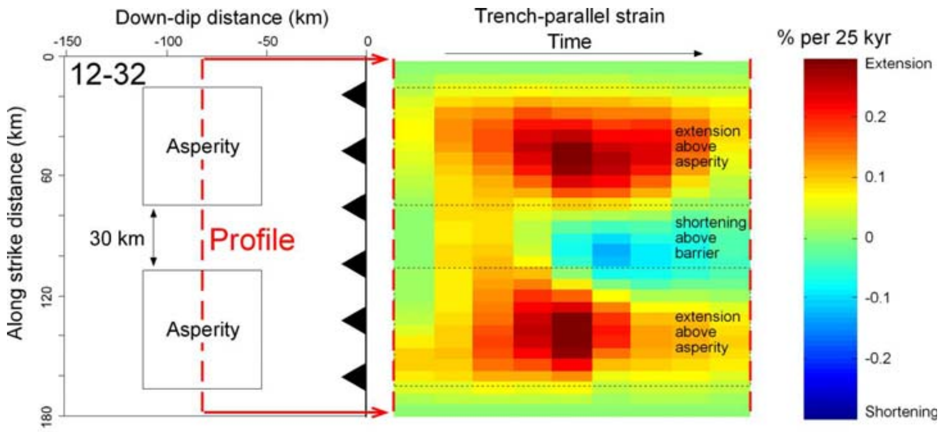

Figure 2: *Example of evolution of along-strike morphotectonic segmentation reflecting the seismogenic behaviour at depth. Parameter values given at natural scale.*

The size of the barriers, forearc strain rate as well as the strength contrast between neighbouring asperities control whether asperity failure occurs randomly, clustered or synchronized. Cross-forearc shortening tends to introduce randomness into the recurrence pattern which systematically evolves via clustering towards quasi-periodic, synchronized failure in the case of asperities strongly coupled by stress transfer. Coupling of weak and strong segments supports synchronization.

In terms of probability theory, the earthquake recurrence pattern of seismotectonically segmented forarcs is suggested to be described by a bimodal probability density function (PDF). We use the gamma function with coefficients of variation varying from CV ~ 0.2 (quasi-periodic), 1 (random) to 2 (clustered) as a unifying recurrence model (Figure 2) and favour a composite PDF (cPDF) with components of quasi-periodic and clustered behaviour to adequately describe the recurrence behaviour of megathrust earthquakes.

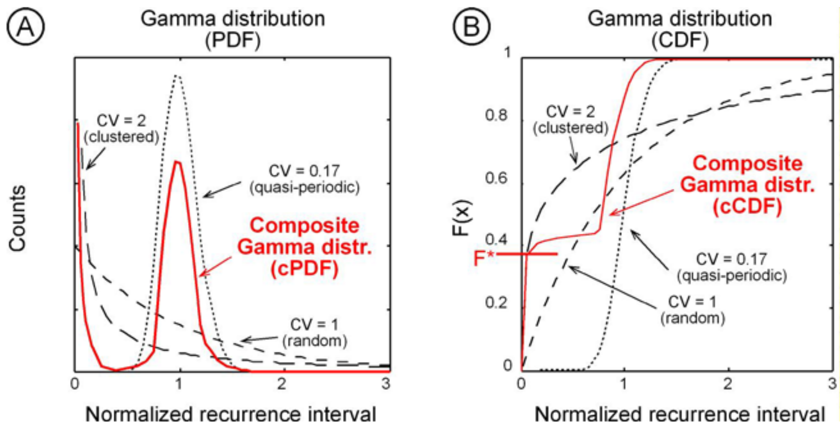

Figure 3: *Statistical models (A: probability density function (PDF), B: cumulative distribution function (CDF)) proposed in this study to describe the recurrence behaviour of multi-asperity subduction megathrust earthquakes. All simulated earthquake sequences are characterized by a bimodal PDF which can be described by a composite Gamma probability density function (cPDF). The peak ratio of the bimodal cPDF and synchronization probability (1-F*) vary systematically according to the asperities relative stress coupling.*

Discussion and conclusions

The experiments suggest that along-strike morphotectonic segmentation of subduction zone forearcs reflect the distribution of seismic and aseismic (creeping) portions of the plate interface. This is consistent with natural observations of morphologic and bathymetric features of the upper plate being related to the seismogenic behaviour at depth and has important implications for mapping future earthquake slip based on structural observations. Furthermore, the recurrence behaviour of megathrust earthquakes seems to be intrinsically related to the geometric distribution of seismic and aseismic patches along the megathrust allowing refinement of time-dependent probabilistic forecast based on past observations. Giant earthquakes including the failure of several asperities in a single event requires a high degree of asperity synchronization which is supported by narrow barriers, minor upper plate tectonic deformation and strength heterogeneity along the plate interface.