

Strain signals governed by frictional-elastoplastic interaction of the upper plate and shallow subduction megathrust interface over seismic cycles

Ehsan Kosari^{1,1}, Matthias Rosenau^{2,2}, and Onno Oncken^{3,3}

¹Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences

²Helmholtz Center Potsdam - GFZ German Research Center for Geosciences

³GeoForschungsZentrum Potsdam

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Abstract

Understanding the behavior of the shallow portion of the subduction zone, which generates the largest earthquakes and devastating tsunamis, is a vital step forward in earthquake geoscience. Monitoring only a fraction of a single megathrust earthquake cycle and the offshore location of the source of these earthquakes are the foremost reasons for the insufficient understanding. The frictional-elastoplastic interaction between the interface and its overlying wedge causes variable surface strain signals such that the wedge strain patterns may reveal the mechanical state of the interface. We employ Seismotectonic Scale Modeling and simplify elastoplastic megathrust subduction, generate hundreds of analog seismic cycles at laboratory scale, and monitor the surface strain signals over the model's forearc over high to low temporal resolutions. We establish two coseismically compressional and extensional wedge configurations to explore the mechanical and kinematic interaction between the shallow wedge and the interface. Our results demonstrate that this interaction can partition the wedge into different segments such that the anlastic extensional segment overlays the seismogenic zone at depth. Moreover, the different segments of the wedge may switch their state from compression/extension to extension/compression domains. We highlight that a more segmented upper plate represents megathrust subduction that generates more characteristic and periodic events. Additionally, the strain time series reveals that the strain state may remain quasi-stable over a few seismic cycles in the coastal zone and then switch to the opposite mode. These observations are crucial for evaluating earthquake-related morphotectonic markers (i.e., marine terraces) and short-term interseismic GPS time-series onshore (coastal region).

1 **Strain signals governed by frictional-elastoplastic interaction of the upper plate and**
2 **shallow subduction megathrust interface over seismic cycles**

3 **Ehsan Kosari** ^{1,2†}, **Matthias Rosenau** ¹, **Onno Oncken** ^{1,2}

4 ¹Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany.

5 ²Department of Earth Sciences, Freie Universität Berlin, Berlin, Germany.

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7 †Corresponding author: Ehsan Kosari (ehsan.kosari@gfz-potsdam.de)

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9 **Key Points:**

- 10 • Analog earthquake cycle experiments provide observations to evaluate the surface strain
11 signals from the shallow megathrust.
- 12 • The extensional segment of the forearc overlays the seismogenic zone at depth.
- 13 • The strain state may remain quasi-stable over a few seismic cycles in the coastal zone.

14 **Abstract**

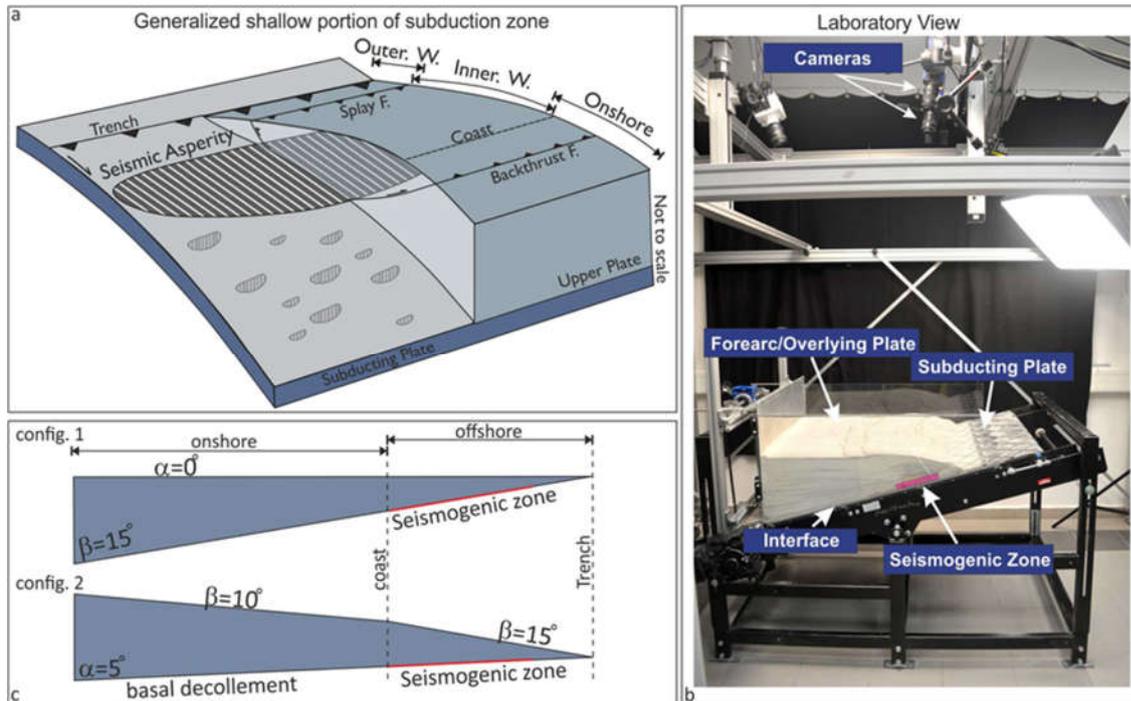
15 Understanding the behavior of the shallow portion of the subduction zone, which generates the
16 largest earthquakes and devastating tsunamis, is a vital step forward in the earthquake geoscience.
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18 the source of these earthquakes are the foremost reasons for the insufficient understanding. The
19 frictional-elastoplastic interaction between the interface and its overlying wedge causes variable
20 surface strain signals such that the wedge strain patterns may reveal the mechanical state of the
21 interface. We employ Seismotectonic Scale Modeling and simplify elastoplastic megathrust
22 subduction, generate hundreds of analog seismic cycles at laboratory scale, and monitor the surface
23 strain signals over the model's forearc over high to low temporal resolutions. We establish two
24 coseismically compressional and extensional wedge configurations to explore the mechanical and
25 kinematic interaction between the shallow wedge and the interface. Our results demonstrate that
26 this interaction can partition the wedge into different segments such that the anlastic extensional
27 segment overlays the seismogenic zone at depth. Moreover, the different segments of the wedge
28 may switch their state from compression/extension to extension/compression domains. We
29 highlight that a more segmented upper plate represents megathrust subduction that generates more
30 characteristic and periodic events. Additionally, the strain time series reveals that the strain state
31 may remain quasi-stable over a few seismic cycles in the coastal zone and then switch to the
32 opposite mode. These observations are crucial for evaluating earthquake-related morphotectonic
33 markers (i.e., marine terraces) and short-term interseismic GPS time-series onshore (coastal
34 region).

35 **1 Introduction**

36 Estimating the interseismic coupling is the foremost approach to evaluate the earthquake potential
37 of subduction megathrusts (e.g., Chlieh et al., 2008; Moreno et al., 2010; Wallace et al., 2012;
38 McCaffrey et al., 2013; Métois et al., 2013; Schmalzle et al., 2014). While both up-dip and down-
39 dip limits of megathrust ruptures are typically located offshore and near the shore, respectively,
40 centuries-long recurrence intervals of the subduction megathrust earthquakes and geodetically
41 insufficiently instrumented seafloors prevent us from achieving sufficient details of the shallow
42 part of the megathrust (Kosari et al., 2020; Williamson & Newman, 2018). For instance, a weakly
43 coupled interface had been predicted in NE Japan based on the incomplete interseismic geodetic
44 measurements before the 2011 Tohoku-Oki megathrust event (e.g., Loveless & Meade, 2011).

45 However, the slip models of the earthquake itself derived from rare offshore geodetic data
46 suggested a coseismic trench-breaching rupture (e.g., Ozawa et al., 2011; Simons et al., 2011; Sun,
47 Wang, Fujiwara, Kodaira, & He, 2017). Besides short-term (geodetic) elastic surface deformation
48 information, it is considered worthwhile to explore long-term (geologic) permanent deformation
49 signals for potential diagnostic patterns linked to megathrust behavior (Geersen et al., 2018; Jara-
50 Muñoz et al., 2015; Madella & Ehlers, 2021; Malatesta et al., 2021; Melnick et al., 2018; Molina
51 et al., 2021; Normand et al., 2019; Ott et al., 2019; Saillard et al., 2017). Hence, for the sake of
52 completeness of seismotectonic insights, long-term geological information should be referred to.
53 Elastoplastic deformation is the dominant process in the shallow portion of the subduction zones
54 (Wang & Hu, 2006), and the mechanical properties of the wedge and megathrust govern the strain
55 pattern in the upper plate. The strain signals could be accumulated over a single or many seismic
56 cycles and preserved as morphotectonic features (i.e., extensional, compressional, and shear
57 markers) (Baker et al., 2013; Delano et al., 2017; Loveless et al., 2009; Loveless et al., 2010;
58 Rosenau & Oncken, 2009), representing the mechanical state of the forearc (Cubas et al., 2013a
59 and 2013b). In an earthquake cycle, the mechanical state might be highly variable in the upper
60 plate (Kopp, 2013; Melnick et al., 2009). In other words, the rate-strengthening and rate-
61 weakening portions of the megathrust cause time and space variable strain fields and rates over the
62 forearc during a seismic cycle. For instance, the coastal region can typically be under compression
63 during the interseismic period and under extension during and immediately following the
64 coseismic stage. Understanding how this leads to coastal topography and offshore bathymetry as
65 a persistent marker over many seismic cycles is vital. Eventually, this may lead to incremental
66 upper plate evolution towards its critical geometry and shape the forearc morphology (Cubas et
67 al., 2013a and 2016; Wang & Hu, 2006).

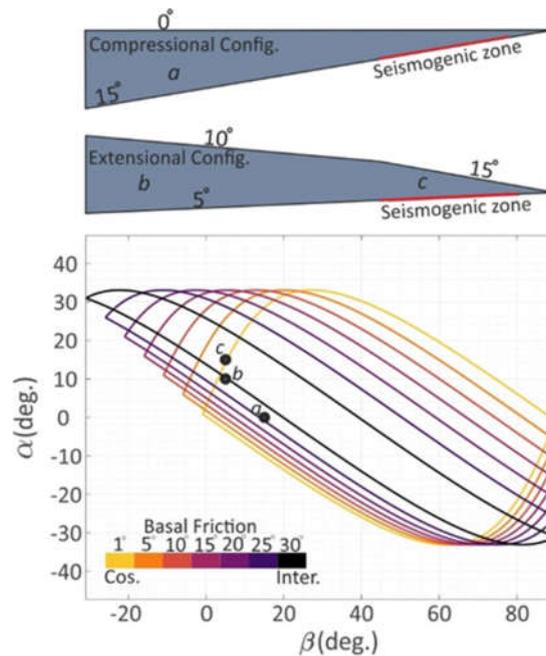
68 It is not fully transparent that to what extent we may infer the seismic potential of the shallow
69 (offshore) portion of the megathrust via onshore observations. Furthermore, the potential temporal
70 linkage between strain states (elastic and plastic) at the positions of the coast, inner-, and outer-
71 wedge is not resolved. Finally, could permanent surface deformation (i.e., plastic strain) be reliably
72 used as a clue for inferring the zones with megathrust earthquake potential? In an attempt to answer
73 these questions, we employ Seismotectonic Scale Modeling (Rosenau et al., 2017 and 2009) to
74 generate physically self-consistent analog megathrust earthquake ruptures and seismic cycles at
75 the laboratory scale (Figure 1).

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78 Figure 1: a: Generalized shallow portion of the subduction zone. The structures in the upper plate and
 79 subducting plate are simplified. This schematic has been considered as a base for our analog seismotectonic
 80 model. b: Laboratory view of our experiment. The main part of the analog model is labeled in the image. c:
 81 2d view of the two evaluated configurations in this study. The projection of the down-dip limit of the stick-
 82 slip materials is defined as the coastal area. Alpha (α) and beta (β) represent the surface and basal
 83 decollement, respectively.

84 This method has been used to study the interplay between short-term elastic (seismic) and long-
 85 term permanent deformation (Rosenau and Oncken 2009). For mimicking the megathrust seismic
 86 cycle and its associated surface deformation, we use a zone of velocity weakening (stick-slip) and
 87 an elastoplastic wedge while the wedge is continuously compressed via a basal conveyor belt
 88 (Kosari et al., 2020; Rosenau et al., 2019). A stereoscopic image correlation technique has been
 89 used to monitor the surface deformation of the analog model (Adam et al., 2005). Generating
 90 hundreds of seismic cycles and monitoring the associated surface deformation allows us to unwrap
 91 the surface signals related to frictional properties at depth (velocity weakening versus velocity
 92 strengthening).

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95 Figure 2: Mechanical states of a wedge introduced by the critical taper theory for coseismically
 96 compressional and extensional experiments. The areas within the envelopes characterize stable regimes.
 97 The areas above and below the envelopes indicate unstable extensional and compressional regimes,
 98 respectively. The positions on the envelopes represent critically stable domains.

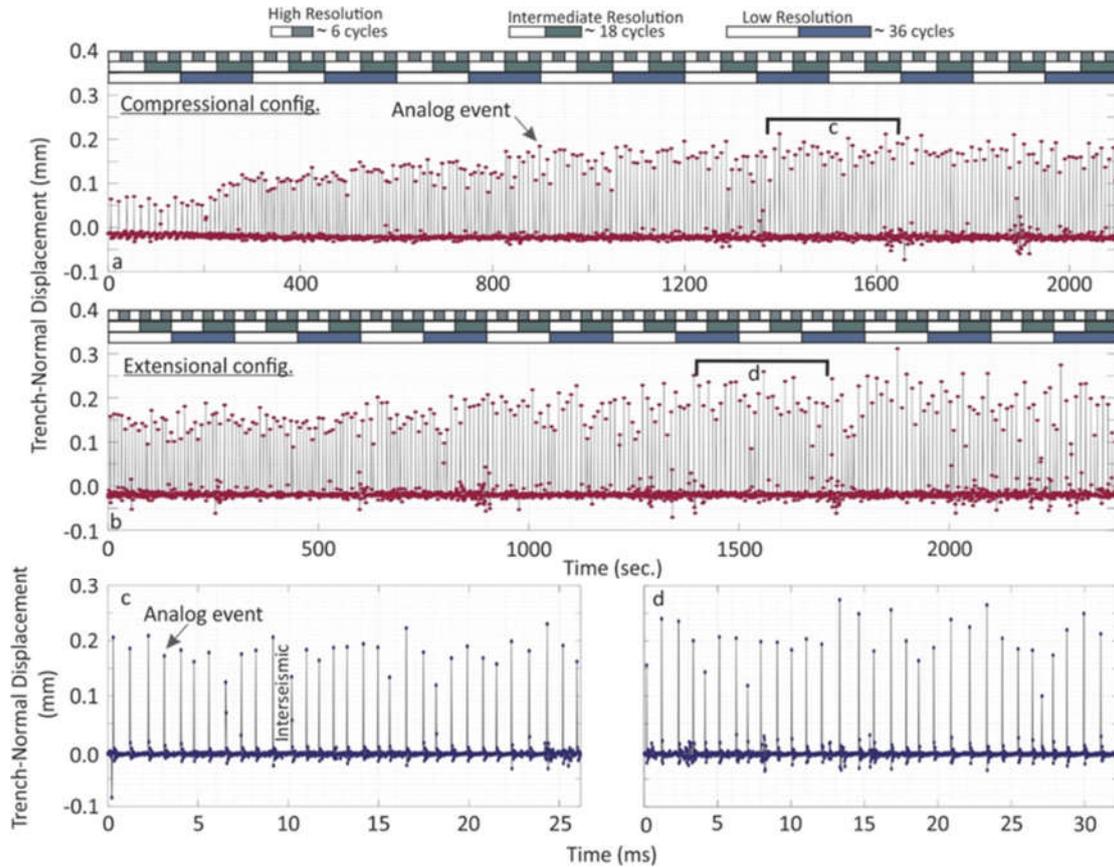
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100 2 Seismotectonic Scale Modeling and Monitoring Techniques

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102 Seismotectonic scale modeling is a unique technique to forward model the tectonic evolution over
 103 seismic cycles (e.g., Rosenau et al., 2017, and references therein). The approach has been used to
 104 study the interplay between short-term elastic (seismic) and long-term permanent deformation
 105 (Rosenau & Oncken, 2009), earthquake recurrence behavior and predictability (Corbi et al., 2020;
 106 2019; 2017; Rosenau et al., 2019), the linkage between offshore geodetic coverage and coseismic
 107 slip models (Kosari et al., 2020) and details of the seismic cycle (Caniven & Dominguez, 2021).
 108 Analog models are downscaled from nature for the dimensions of mass, length, and time to
 109 maintain geometric, kinematic, and dynamic similarity by applying a set of dimensionless numbers
 110 (King Hubbert, 1937; Rosenau et al., 2009; 2017). The models generate a sequence of tens to
 111 hundreds of analog megathrust earthquake cycles, allowing the analysis of the corresponding
 112 surface displacement from dynamic coseismic to quasi-static interseismic stages.

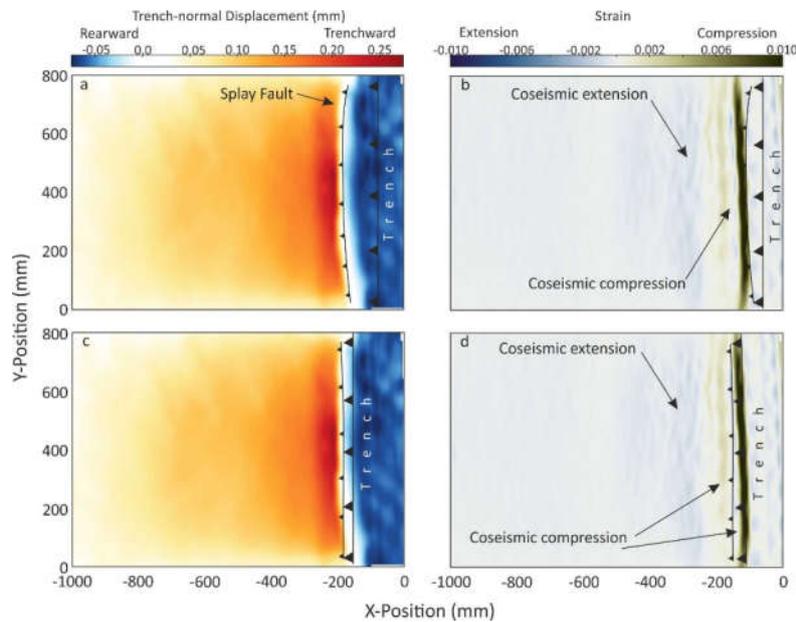
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 115 Figure 3: Analog earthquake catalog derived from surface displacement above the stick-slip zone on the
 116 model surface. The displacements larger than 0.05 millimeters represent an analog megathrust event ($M_w \geq 8$
 117 at nature scale). Distance between two analog events represents the interseismic period in our experiments.
 118 a and b: all the events that occurred over model evolution from compressional and extensional experiments,
 119 respectively. Temporal processing windows for three different resolutions are differentiated by scale bars
 120 (see figures 7 and 8 for more details). c and d: a selected set of 30-32 analog megathrust events for evaluating
 121 surface displacement over the seismic cycles from both configurations, respectively.

122 In the 3-D experimental setup introduced in Kosari et al. (2020), a subduction forearc model is set
 123 up in a glass-sided box (1,000 mm across strike, 800 mm along strike, and 300 mm deep) on top
 124 of an elastic basal rubber conveyor belt (the model slab), and a rigid backwall. A wedge made of
 125 an elastoplastic sand-rubber mixture (50 vol.% quartz sand G12: 50 vol.% EPDM-rubber) is sieved
 126 into the setup representing a 240 km long forearc segment from the trench to the volcanic arc
 127 position (Figure 1).

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 130 Figure 4: Surface horizontal displacement (a and c) and strain (b and d) maps derived from the extensional
 131 configuration. The upper panel represents the case of a megathrust event in which slip propagates on the
 132 splay faults (non-trench-reaching). The lower panel represents a megathrust event in which the slip reaches
 133 the trench (trench-reaching slip). The compressional (outer-wedge) and extensional (inner-wedge)
 134 segments.

135 At the base of the wedge, zones of velocity weakening controlling stick-slip (“seismic” behavior)
 136 are realized by emplacing compartments of “sticky” rice (“seismogenic zone”), which generate
 137 quasi-periodic slip instabilities while sheared continuously (Figure 1), mimicking megathrust
 138 earthquakes of different sizes and frequency (Figure 3). Large stick-slip instabilities are assumed
 139 to represent almost complete stress drops and recur at low frequency (~ 0.2 Hz) at a prescribed
 140 constant convergence rate of $50 \mu\text{m/s}$. This stick-slip behavior is intended to mimic rare great (M8-
 141 9) earthquakes with century-long recurrence intervals. The wedge itself and the conveyor belt
 142 respond elastically to these basal slip events similar to crustal rebound during natural subduction
 143 megathrust earthquakes. Upper plate faults (in our case, an “inland” backthrust fault and “offshore”
 144 forethrust and backthrust faults) emerge self-consistently downdip and up-dip of the seismogenic
 145 zone over multiple seismic cycles, as the effect of transient compression as documented in earlier
 146 papers (Kosari et al., 2020; Rosenau et al., 2009, 2010; Rosenau & Oncken, 2009).

147 Two different wedge geometries have been realized: a compressional configuration represents a
 148 transiently compressional wedge, and an extensional configuration, which is transiently
 149 extensional according to Coulomb wedge theory (Figure 2). In the first configuration, hereafter

150 named “compressional configuration”, a flat-top ($\alpha=0$) elastoplastic wedge overlies a single large
151 rectangular in map view stick-slip patch (Width*Length=200*800 mm) over a 15-degree dipping
152 conveyor belt. In the second configuration, hereafter named “extensional configuration”, the
153 surface angle of the elastoplastic wedge varies from onshore ($\alpha=10$) to offshore ($\alpha=15$) segments
154 over a 5-degree basal decollement. The stick-slip zone in both configurations represents a system
155 of a homogeneous seismogenic zone with a temperature-controlled depth range and no variation
156 along strike generating M9 type megathrust events (Figure 1). According to Coulomb wedge
157 theory (Dahlen et al., 1984), the shallow wedge part of the compressional configuration overlying
158 the seismogenic zone is compressional in the interseismic stage when the basal friction angle in
159 the seismogenic zone is high (about 30°) and stable during the coseismic stage when the basal
160 friction in the seismogenic zone drops to zero. The coastal part of the wedge in the compressional
161 configuration is compressional throughout the seismic cycle as the basal friction is high and rate-
162 independent here. The extensional configuration, in contrast, has a coastal wedge that is stable
163 throughout the seismic cycle, whereas the shallow wedge overlying the seismogenic zone is stable
164 interseismically but becomes extensional during the coseismic stage. Both models produce trench-
165 reaching and non-trench-reaching slip analog megathrust events and push their overlying wedges
166 to compressional and extensional strain states (Figure 4).

167 To capture horizontal micrometer-scale surface displacements associated with analog earthquakes
168 and interseismic intervals at microsecond scale periods, a stereoscopic set of two CCD (charge-
169 coupled device) cameras (LaVision Imager pro X 11MPx, 14 bit) images the wedge surface
170 continuously at 4 Hz. To derive observational data similar to those from geodetic techniques, that
171 is, velocities (or incremental displacements) at locations on the model surface, we use digital image
172 correlation (DIC) (Adam et al., 2005) via the DAVIS 10 software (LaVision GmbH,
173 Göttingen/DE) and derive the 3-D incremental surface displacements at high resolution (<0.1 mm)
174 (Figure 3).

175 To calculate strain, we use the infinitesimal strain tensor because the condition of small strain is
176 met when resolving strains across the forearc during the interseismic period:

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$$\begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix}$$

180 where ε_{xx} represent the partial derivation of the trench-normal surface velocity component $\frac{\partial V_x}{\partial x}$
 181 showing trench-normal shortening: positive and negative values respectively represent
 182 compression and extension.
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185 **3 Results and Interpretations**

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187 The models' observations are presented in succession from long-term to short-term. First, we show
 188 how the upper plate structures evolve in a sequence over hundreds of analog earthquake cycles.
 189 We evaluate the spatial correlation between upper plate strain and topography evolution
 190 concerning locking and slip at the interface. Afterward, we spatially and temporally zoom in on a
 191 subset of seismic cycles to explore how strain states vary in different segments of the upper plate
 192 across seismic cycles. Eventually, the strain cycles in different wedge segments (i.e., outer-wedge,
 193 inner-wedge, and coast) are compared to check how similar they respond to the earthquake cycles
 194 in a homogeneous wedge with internal discontinuities (i.e., upper plate faults).

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196 **3.1 Model Evolution from long to short timescales**

197 **3.1.1 Wedge anatomy: Final geometry, surface strain distribution, and structures formed**

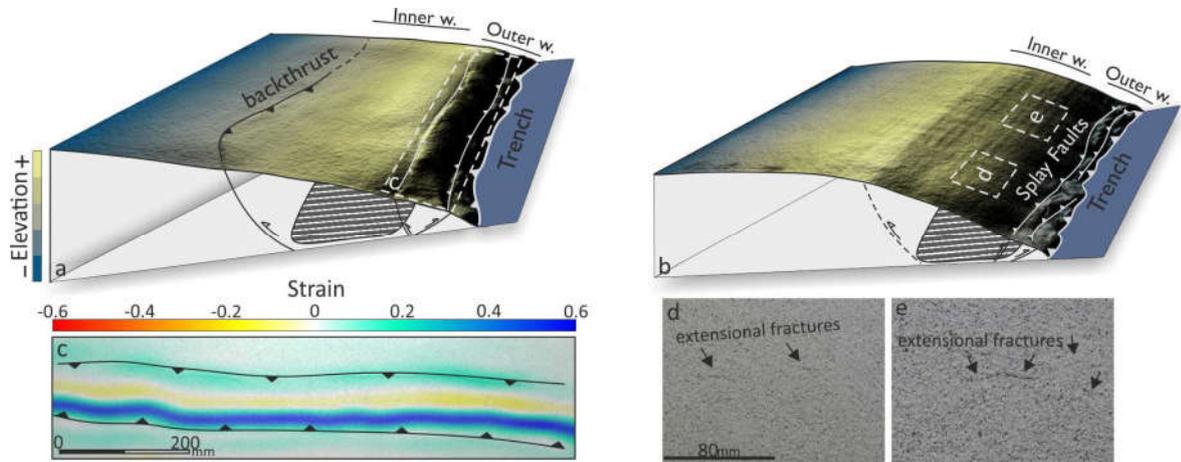
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199 The cumulative strain pattern maps illustrate the long-term (hundreds of analog earthquake cycle)
 200 strain distribution in the upper plate (Figure 6). In the compressional configuration, three different
 201 wedge segments are observed: a compressional domain in the outer-wedge, an extensional domain
 202 in the inner-wedge, and a compressional domain in the coast. The outer-wedge compressional
 203 segment overlies the shallow creeping portion of the interface. Further rearward, the compression
 204 domain grades into an extensional domain in the inner-wedge overlying the velocity-weakening
 205 zone on the interface at depth. In our experiments, two main mechanisms could cause the
 206 permanent extensional strain in the inner-wedge: A minor anelastic component of the mainly
 207 elastic coseismic extension and the activity of splay fault-related folds. A compressional segment
 208 has also been observed in the coastal area, which may appear on the model's surface as a backthrust
 209 fault rooting in the frictional transition zone at the down-dip limit of the velocity weakening zone

210 (Figures 6).

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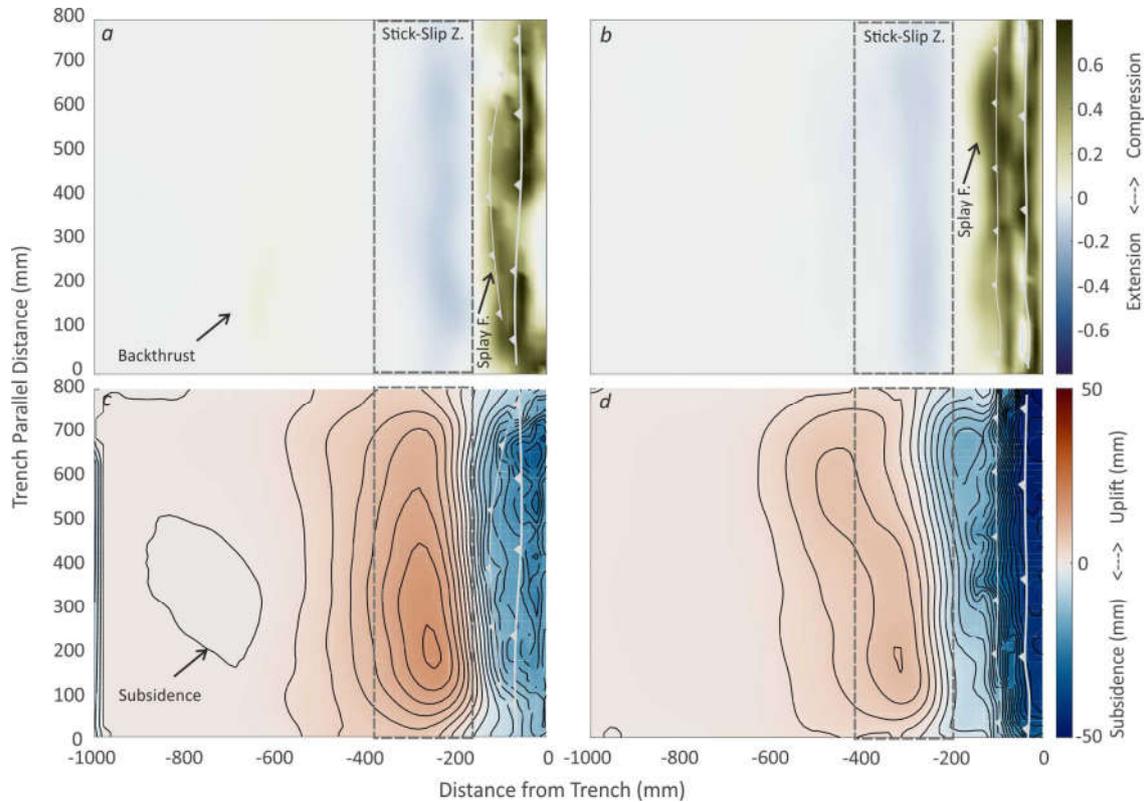
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214 Figure 5: Final surface topography of compressional (a) and extensional (b) configurations. Backthrust and
 215 the splay faults are rooted in the down-dip and up-dip limit of the stick-slip zone. The splay faults separate
 216 the outer-wedge from the inner-wedge. The strain field generated by the activity of the splay faults is
 217 visualized in c. the ridge-shape structure represents extensional strain. Examples of the surface coseismic
 218 extensional fracture are shown in d and e.

219 Localization of deformation has segmented the upper plate into three main segments. The outer-
 220 wedge is underthrust and subsided. The inner-wedge, which is bounded by the up-dip splay fault
 221 and downdip backthrust fault, has accumulated the deformation during seismic cycles through
 222 internal deformation and vertical displacement due to the activity of the backthrust faults. Further
 223 rearward (landward), subsidence occurs in the footwall of the backthrust fault (Figure 6). In the
 224 compressional configuration, where the backthrust is developed, the subsiding area is relatively
 225 wider (S1).

226 Both compressional and extensional configurations demonstrate uplift and extension above the
 227 seismogenic zone embraced by shortening domains inland and near the trench. However, the
 228 compressional domain further rearward (onshore) is smaller in the extensional configuration.
 229 Close to the trench, conversely, the upper plate shortens and subsides. In the compressional
 230 configuration, the shortening in the transition zone from the shortening domain to the extension
 231 domain is accommodated by a pop-up structure forming a conjugated forethrust and backthrust
 232 couple. However, the pop-up structure itself generates a local surficial extension domain between

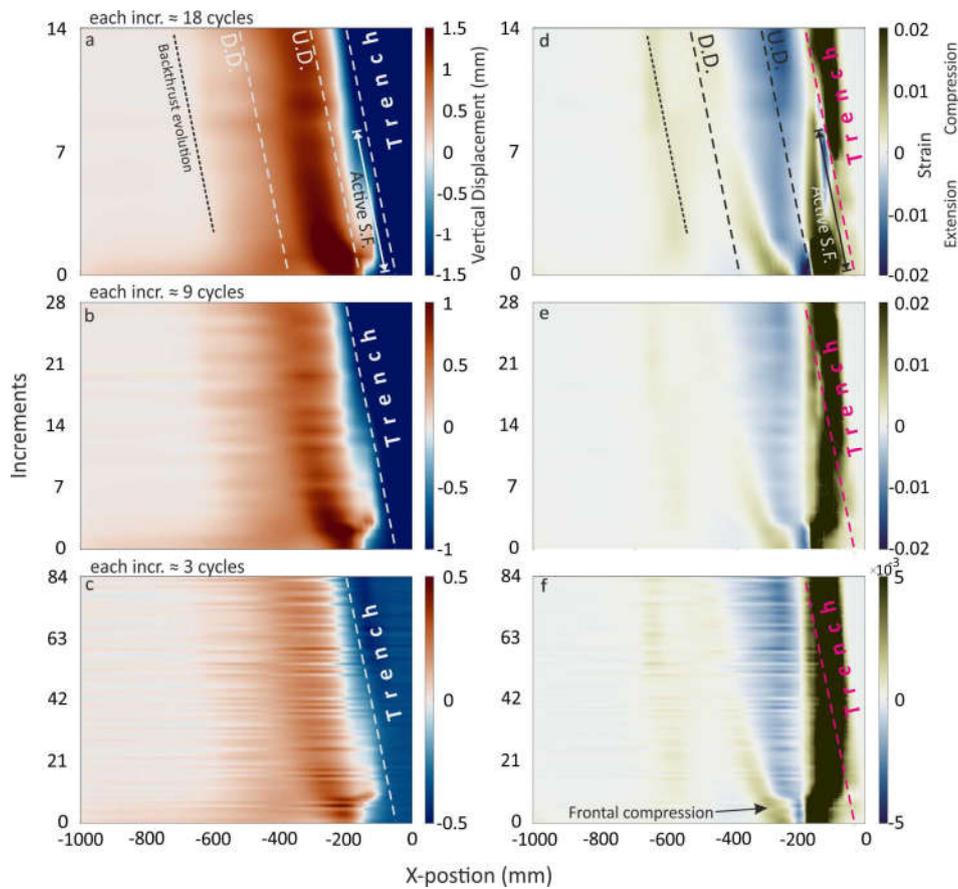
233 its boundary faults (Figure 5). In the extensional configuration, the forethrusts are the only
 234 structures accommodating forearc shortening. In the compressional configuration, the backthrust
 235 fault is the main structure accommodating wedge shortening.



236
 237 Figure 6: Final surface deformation maps from compressional (a and c) and extensional (b and d)
 238 configurations. The approximate location of the stick-slip zone at depth is projected on the model surface
 239 as a dashed rectangle. a and b: Surface strain maps from both configurations. Green and blue represent
 240 compression and extensional domains, respectively. The outer-wedge is experienced (splay fault and trench
 241 domains) compression. Inner-wedge is recorded permanent extension. The activity of the backthrust is
 242 evident in the compressional configurations. c and d: permanent vertical deformation in the absence of
 243 erosion in the system. The outer- and inner-wedge represent permanent subsidence and uplift, respectively.
 244 The slight subsidence zone onshore may represent a forearc basin at the natural scale.

245 246 3.1.2 Upper plate faults evolution over time 247

248 During model evolution, the first structures appear in the vicinity of the deformation front (near
 249 the trench). In the compressional configuration, near the trench, a trenchward-dipping (backthrust)
 250 and a rearward-dipping (forethrust) thrust faults form shortly after each other. These two trench-
 251 parallel faults, likely conjugate at depth, create a ridge-shaped structure (Figure 3). The structures

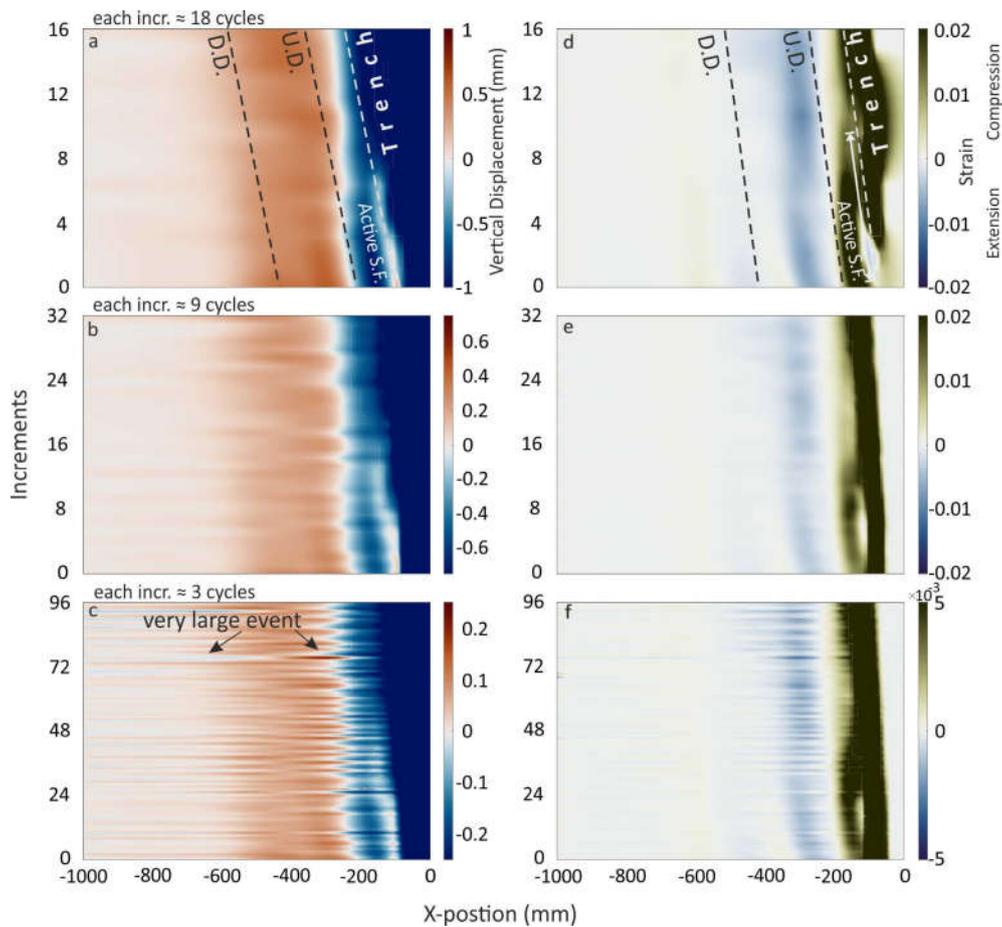


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253 Figure 7: Incremental surface vertical displacement and strain over time from the compressional
 254 configuration with different temporal resolutions (3, 9, and 18 analog earthquake cycles). Up-dip (U.D.)
 255 and down-dip (D.D.) of the stick-slip zone at depth have been projected on the surface. a-c represents
 256 vertical uplift (warm color) and subsidence (cold color). The activity of the splay fault (S.F.) is evident
 257 while it is gradually deactivated and the whole slip is transferred on the megathrust. d-f represents surface
 258 strain maps with different temporal resolutions.

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260 are formed above the upper basal frictional transition. The stick-slip (seismogenic) zone represents
 261 high basal friction in a long-term (interseismic) interval relative to the interface's uppermost
 262 portion, which creeps interseismically. This frictional contrast thus leads to a sharp slip rate
 263 variation and stress concentrations along the interface where thrusts nucleate. Another active
 264 trenchward-dipping thrust fault (backthrust) forms further rearward in the wedge, representing the
 265 onshore segment of the forearc. Again, the frictional contrast between the velocity weakening
 266 portion of the interface (seismogenic zone) and the downdip limit of this portion controls the origin
 267 of the backthrust, thereby accommodating the difference in slip rate (Figures 5 and 6). The thrust



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269 Figure 8: Incremental surface vertical displacement and strain over time from an extensional configuration
 270 with different temporal resolutions (3, 9, and 18 analog earthquake cycles). Up-dip (U.D.) and down-dip
 271 (D.D.) of the stick-slip zone at depth have been projected on the surface. a-c represents vertical uplift (warm
 272 color) and subsidence (cold color). The activity of the splay fault (S.F.) is evident while it is gradually
 273 deactivated and the whole slip is transferred on the megathrust. d-f represents surface strain maps with
 274 different temporal resolutions.

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276 system accommodates shortening, causing uplift and steepening of the wedge over the course of
 277 the experiment consistent with the predicted transiently compressional initial geometry.

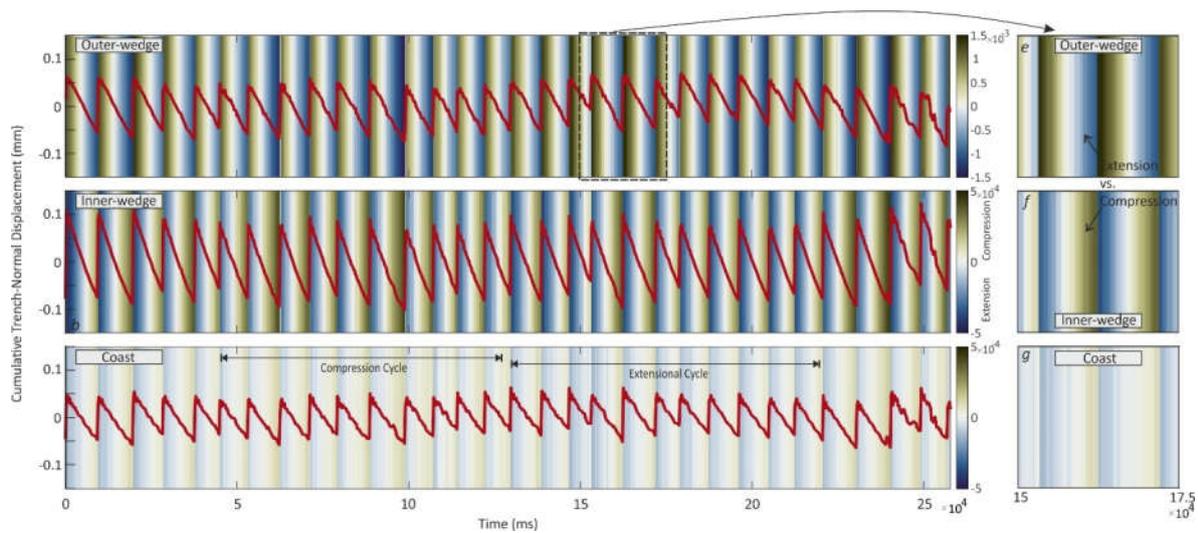
278 In the extensional configuration, a splay forethrust forms at the up-dip limit of the seismogenic
 279 zone (Figure 3). In contrast to the compressional wedge, a backthrust does not form at the down-dip
 280 limit of the seismogenic zone consistent with its stable geometry according to Coulomb wedge
 281 theory. These faults show thrust mechanisms and form in the immediate up-dip and down-dip
 282 of the seismogenic zone.

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3.1.3 Long-term wedge deformation: Long-term surface displacement signals reflecting forearc evolution.

To visualize the long-term behavior (i.e., integrating multiple seismic cycles) of the models, forearc wedge differential surface displacement (horizontal and vertical) of increments lasting 150, 75, and 25 seconds are plotted. This covers about 18, 9, and 3 megathrust analog earthquake cycles, respectively (Figures 7 and 8), to illustrate how the wedge evolution is recorded by observational data with different temporal resolutions typical of geomorphological methods (e.g., terrace uplift). In both configurations, the long-term vertical displacement can be temporally divided into two parts depending on whether the upper plate faults are active or inactive. In the case of an active splay fault, the horizontal trenchward displacement terminates at the location of the splay fault (Figure 4), and the zone of maximum uplift is in the hanging-wall of the splay fault (Figures 7 and 8). The splay fault activity decreases over time until it dies, and subsequently, the whole slip is consumed on the interface (i.e., megathrust). Namely, a non-trench-reaching megathrust earthquake system turns into a trench-reaching system over time. The evolution of the backthrust can also be tracked in all temporal resolutions of topography evolution derived from the compressional configuration (Figure 7). The zone of maximum topography correlates with the zone of the maximum extensional segment of the upper plate in both configurations. In the compressional configuration, this extensional zone becomes wider and more pronounced over time, while the width of the zone remains relatively constant over time in the extensional configuration.

Further rearward to the coastal region, the strain evolves differently in the compressional and extensional configurations: In the compressional configuration, the initially extensional strain is replaced by a compressional domain over the entire inner-wedge. The maximum compressional strain appears in the coastal region where the backthrust is formed. The frontal compressional domain diminishes while the compressional wedge is evolving. This is in good agreement with the activity of the up-dip splay fault over its lifetime. The strain pattern over the inner-wedge illustrates that this wedge segment gradually evolves to a more compressional regime. In contrast, there is no significant frontal compressional domain in the extensional configuration (Figure 8), and the inner-wedge is rather in an extensional state. Although the coastal region in the extensional configuration similarly shows a compressional state, the backthrust fault does not appear in the wedge at the down-dip limit of the stick-slip zone.



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317 Figure 9: Compressional configuration; Trench-normal displacement time-series (red plot) is overlaid on
 318 the strain time-series (background color map) over tens of analog earthquake cycles in different segments
 319 of the upper plate. The magnitude of the strain in the outer-wedge is one order larger than the inner-wedge
 320 and coast. Note that the outer- and inner-wedge show opposite strain state over the earthquake cycle
 321 (compressional versus extensional). The compression and extensional supercycles in the coastal region are
 322 shown in the lower panel. Please see the text for the discussion.

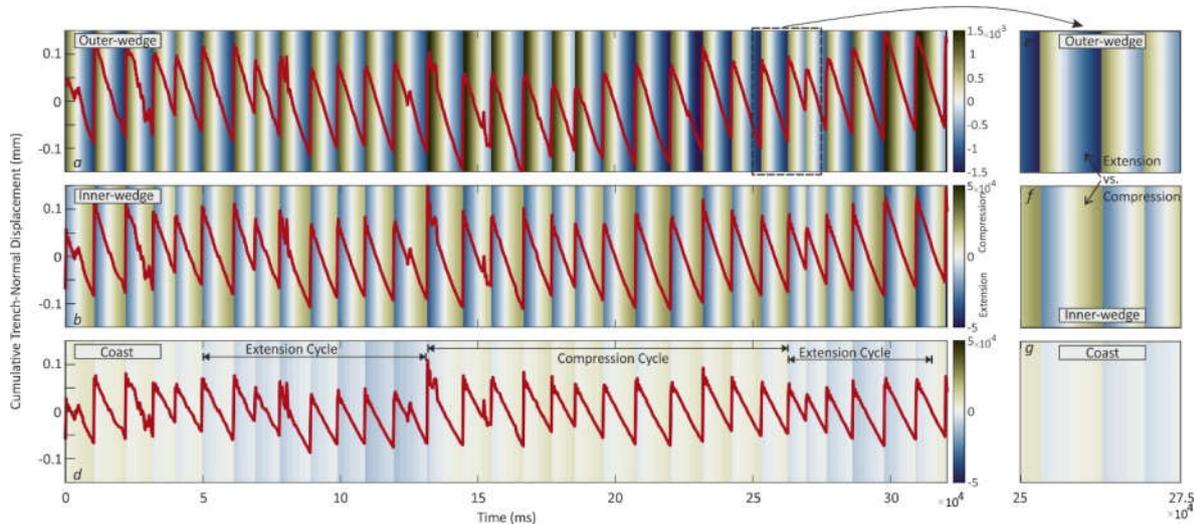
323 3.1.4 Short-term wedge deformation: Strain pattern over seismic cycles

324 3.1.4.1 Extensional features in the shallow segment of the forearc

325 The extensional features have generally been observed as extensional fractures or/and crestal
 326 normal faults in the frontal wedge domain of the models (Figure 5 and S2). The latter may form
 327 above the frictional transition zone at the up-dip limit of the velocity-weakening zone. The activity
 328 of the forethrust splay faults plays the main role in their formation being located in the crestal zone
 329 in the hanging-wall of the splay fault. This fracture zone reflects the splay fault's activity and,
 330 consequently, the up-dip limit (frictional transition) of the velocity-weakening portion of the
 331 interface. The extensional features form and develop trench-parallel inelastically over the
 332 interseismic interval and are active in opposite modes during the coseismic and postseismic stages,
 333 i.e. coseismically extensional and postseimically compressional. The responsible formation
 334 mechanism is the splay forethrust the activity of which generates fault-related folds (fault-
 335 propagation fold) (S2).

336 Consequently, a local extensional regime forms at the hinge zone of the fault-related fold and may
 337 lead to the crestal normal faults. In the coseismic interval, a sudden slip on the splay fault and
 338 megathrust enhances these extensional fractures. The slip on the faults terminates at the frictional

339 transitional border. Hence, a compressional strain regime appears in the forelimb of the fault-
 340 related fold.



341
 342 Figure 10: Extensional configuration; Trench-normal displacement time-series (red plot) is overlaid on
 343 the strain time-series (background color map) over tens of analog earthquake cycles in different segments
 344 of the upper plate. The magnitude of the strain in the outer-wedge is one order larger than the inner-wedge
 345 and coast. Note that the outer- and inner-wedge show opposite strain state over the earthquake cycle
 346 (compressional versus extensional). The compression and extensional supercycles in the coastal region are
 347 shown in the lower panel. Please see the text for the discussion.

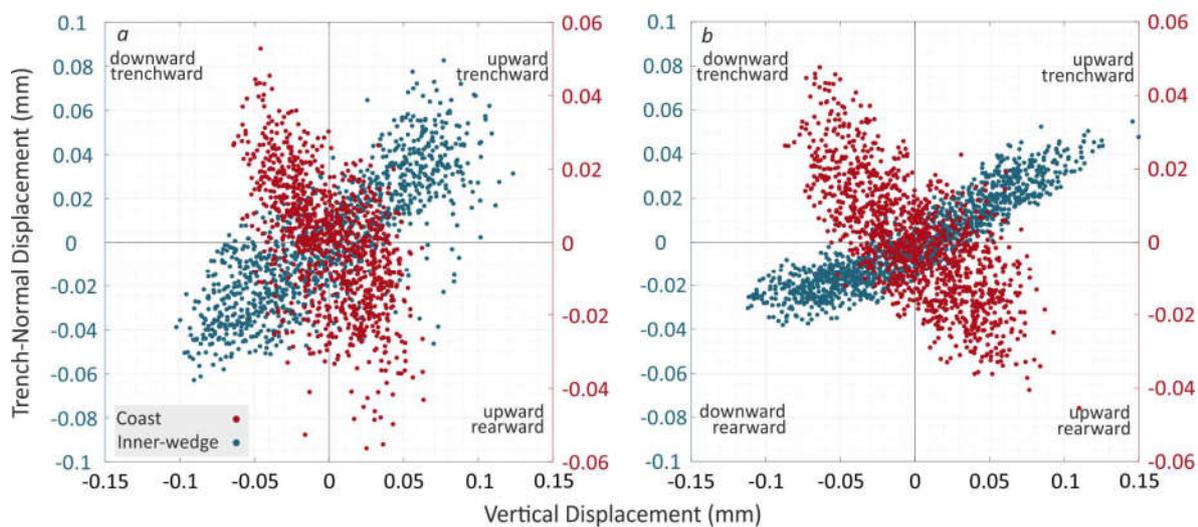
348 The fractures appear in the inner-wedge segment of the model forearc where they overly the
 349 velocity-weakening portion of the interface at depth. The extensional fractures in the inner-wedge
 350 above the seismogenic zone form coseismically where the maximum extensional strain occurs in
 351 the forearc and is partially preserved as anelastic deformation (i.e., normal faulting) in the inner-
 352 wedge in each earthquake cycle. In contrast, during the interseismic period, this segment of the
 353 forearc is mainly under compression.

354 3.1.4.2 Strain-state cycle over the seismic cycle

355
 356 Here we have visualized the average value of the strain over three different segments of the upper
 357 plate forearc to take a closer look at the strain evolution at the timescale of individual seismic
 358 cycles (Figures 9 and 10). In general, the strain rate reduces rearward from the trench toward the
 359 coast, consistent with the dominance of elastic loading at the seismic cycle timescale. The outer-
 360 wedge shows strains opposite to those of the coast and inner-wedge (Figures 9 and 10). The inner-

361 wedge and coast are under compression when the outer-wedge is experiencing extension during
 362 the interseismic period—this is a general pattern over many seismic cycles. In each cycle, the
 363 inner-wedge undergoes extension coseismically, then gradually moves to a neutral state and finally
 364 shifts to a stably compressional state and stays in this regime until the next seismic event occurs.
 365 In contrast, the outer-wedge is under compression during the earthquake and subsequently
 366 experiences neutral and extensional states in the interseismic interval. In both segments, the strain
 367 state shows a regular cycle and follows the same earthquake cycle trend.

368



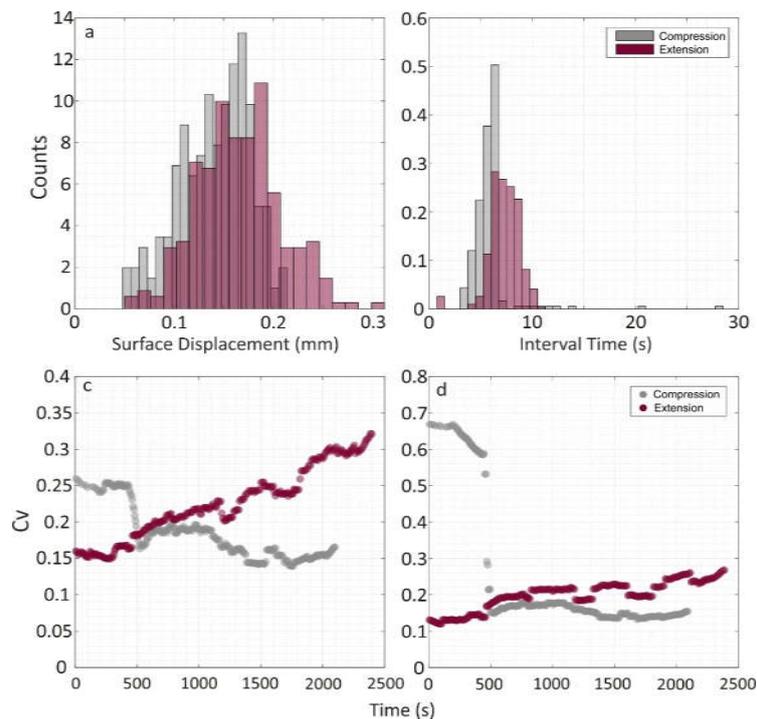
369

370 Figure 11: Comparison between surface displacements (horizontal and vertical) in the inner-wedge and
 371 coast segments. The segments demonstrate opposite trends: the coast moves trenchward while subsiding
 372 (and vice versa), but the inner-wedge moves trenchward while moving upward.

373 In the down-dip segment, which is treated as underlying the coastal area in our experiment (cf.
 374 Fig. 1), the strain state cycle differs from that of the two shallower (offshore) segments of the upper
 375 plate. Although the strain magnitude is approximately an order of magnitude smaller, its pattern
 376 may be closer to the inner-wedge than to the outer-wedge.

377 Interestingly, the strain state represents not only an asymmetric cyclic pattern over stick-slip cycles
 378 but also a longer cycle (hereafter called “supercycle”) (Figures 9 and 10). In the coastal segment,
 379 unlike the other upper plate segments, the extensional and compressional portions of the strain do
 380 not balance over a few cycles but show multi-cycle long compressional and extensional
 381 supercycles. The supercycle appears sharper in the extensional configuration, where the backthrust
 382 is not developed. It may, therefore, be due to the activity of the backthrust that perturbs the

383 supercycle. The surface displacements in the coastal zone and the inner-wedge represent opposite
 384 trends (Figure 11). In the coseismic period, the coast, which overlies the down-dip limit of the
 385 stick-slip zone, moves trenchward while subsiding (and vice versa in the interseismic period), but
 386 the inner-wedge, which overlies the stick-slip zone, moves trenchward while moving upward. This
 387 implies that coseismic uplift and subsidence patterns indicate the location of the slipped zone at
 388 depth. The possible primary mechanisms for the supercycle will be discussed in the discussion.
 389



390

391 Figure 12 : Size and frequency distributions (a and b) and coefficients of variation (Cv) of recurrence
 392 intervals and size (c and d) of analog megathrust events for compressional and extensional configurations.

393 3.2 Frequency and size distributions of analogue megathrust events

394

395 To explore the possible relationship between moment release patterns and forearc configurations,
 396 we compare the frequency and size of analog megathrust events and their coefficients of variations
 397 (Cv). This coefficient is defined as the ratio of the mean to the standard deviation of the data, from
 398 both compressional and extensional configurations (Kuehn et al., 2008; Rosenau & Oncken, 2009).
 399 We have defined a moving window to calculate the coefficient of variation over the size and
 400 frequency of events. The coefficient of variation generally exhibits an inverse relationship (i.e.,

401 negative correlation) with the periodicity of the frequency-size distribution. In particular, a $C_v >$
402 0.5 indicates random events while a $C_v < 0.5$ characterizes periodic events.

403 The results of the size and frequency distribution and temporal evolution of the frequency-size
404 distributions are plotted in figure 12. Accordingly, the extensional configuration is characterized
405 by relatively larger event size and longer recurrence. In the C_v plots of the compressional
406 configuration (Figure 12 c and d), a sharp reduction is clear. Its timing shows a good agreement
407 with the evolution of the main upper plate structures (i.e., backthrust fault). The C_v of the
408 compressional configuration is generally lower than that of the extensional configuration,
409 indicating that the first is more periodic. Although both configurations demonstrate rather periodic
410 behavior (i.e. $C_v < 0.5$), the recurrence pattern of the extensional configuration, unlike the
411 compressional configuration, evolves over time towards higher variability. The C_v values for the
412 extensional configuration systematically increase and are characterized by a C_v higher than 0.15.
413 In contrast, in the compressional configuration, the values stay in a range of 0.15-0.2. A similar
414 trend is also observed in the size distributions of both models. The compressional configuration
415 does not show a significant evolution over time; however, an increasing trend is observed towards
416 higher coefficients (i.e., less characteristic events over time) in the extensional configuration.

417

418 **4 Discussion**

419

420 **4.1 Mechanical state of the shallow forearc over the seismic cycle**

421

422 We have used critical wedge theory to design two endmember wedge geometries to see the effect
423 of (transient) instability on the long-term deformation pattern. As shown in figure 2, the wedge is
424 predicted to be critically compressive and stable during the interseismic and coseismic periods,
425 respectively, in the compressional configuration. In the extensional configuration, the onshore and
426 offshore segments of the wedge represent different states: In the coseismic period, the offshore
427 segment, unlike the onshore segment, is prone to be critically extensional. The offshore segment
428 is stable in the interseismic period, but the onshore segment tends to be critically compressional.

429 The outer-wedge segment of our model overlies the creeping portion of the interface where slip
430 instability cannot nucleate but may rupture during trench-reaching megathrust events (Cubas et
431 al., 2013a; Noda and Lapusta, 2013). This domain is near the deformation front and undergoes
432 more deformation and splay thrust faulting than the other forearc segments. This segment switches

433 its stability state from compressional critical in the interseismic stage to a coseismically stable
434 condition. Analog earthquake studies suggest that a mega-splay fault at the up-dip limit of the
435 velocity-weakening zone may act as a relaxation mechanism for coseismic compression (Rosenau
436 et al., 2009) and be activated in the early postseismic stage of a seismic cycle. These laboratory
437 observations are in good agreement with the aftershock activities after megathrust events, for
438 instance, after the Maule 2010 (Lieser et al., 2014), Antofagasta 1995 (Pastén-Araya et al., 2021),
439 Iquique 2014 (Soto et al., 2019), and Ecuador–south Colombia 1958 earthquakes (J.-Y. Collot et
440 al., 2008; Jean-Yves Collot et al., 2004). This implies that coseismic strengthening of the shallow
441 megathrust pushes the outer-wedge to a compressively critical state during large displacements on
442 the interface (Figure 10) (Hu & Wang, 2008; Wang et al., 2019; Wang & Hu, 2006). Consequently,
443 the splay fault between the outer and inner-wedge may accumulate slip during coseismic or/and
444 postseismic periods.

445 The inner-wedge is located between this forethrust splay fault and the projection of the down-dip
446 limit of the stick-slip zone to the surface or the backthrust upper-plate fault (Figure 5). This
447 segment is interseismically stable and a minimum of permanent deformation is accumulated
448 (Cubas et al., 2013b). The maximum strain is localized on the backthrust fault which is the
449 landward boundary of the inner-wedge. However, this backthrust may activate with a normal
450 faulting mechanism during or immediately after a large coseismic slip in the velocity-weakening
451 portion of the interface, similar to the activity of the Pichilemu fault shortly after the Maule 2010
452 megathrust earthquake (Fariás et al., 2011; Cubas et al., 2013b). This means that the mechanically
453 most stable segment of the entire wedge – i.e. the inner wedge - reflects the seismically most active
454 (i.e., velocity-weakening) portion of the interface. (Fuller et al., 2006).

455

456 **4.2 Seismotectonic forearc segmentation: Comparison with natural examples**

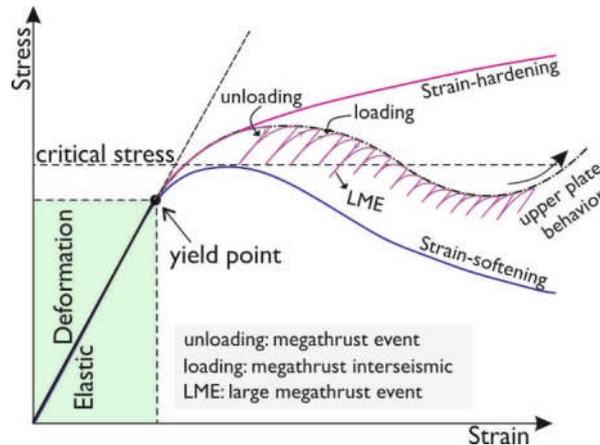
457 Our results highlight how coseismic surface deformation may contribute to the morphology of the
458 shallow (offshore) segment of the forearc. The coseismic extension that occurs offshore is mainly
459 observed in the inner-wedge, in the zone bounded by the up-dip forethrust (and/or backthrust) and
460 down-dip backthrust (Figures 5). The up-dip forethrust is the same structure that has been observed
461 in several natural examples. It has been introduced as either backstop in the 2011 Tohoku-Oki
462 earthquake region in the Japan Trench (Ito et al., 2011; Tsuji et al., 2011, 2013) or as the
463 approximate limit between the lower and middle slopes (MLS) in the north Chilean margin
464 (Maksymowicz et al., 2018; Storch et al., 2021). In the former, the fault is characterized by the

465 boundary between a soft and fractured sediment sequence abutting a less-deformed sequence on
466 the landward side. After the 2011 Tohoku-Oki event, seafloor photographs taken from the splay
467 fault (backstop) region show that extensional steep cliffs are formed coseismically due to small-
468 scale slope failure (Tsuji et al., 2013). We observe similar gravity-induced features in the forelimb
469 of the splay fault in our experiments, indicating the up-dip limit of the coseismic slip on the
470 interface. Further landward, seafloor photographs from the inner-wedge have suggested coseismic
471 anelastic extensional features with no evidence for submarine landslides and reverse faulting as
472 responsible mechanisms (Tsuji et al., 2013). This segment of the upper plate in both our models
473 and the 2011 Tohoku-Oki event overlies the zone of maximum coseismic slip.

474 Seafloor extensional features have also been documented in the regions of the Maule 2008 and
475 Iquique 2014 earthquakes in the central and northern Chilean subduction zone (Geersen et al.,
476 2016, 2018; Maksymowicz et al., 2018; Reginato et al., 2020; Storch et al., 2021). A normal
477 faulting escarpment and extensional fractures are observed on the hanging wall of the forethrust
478 splay in the Maule 2008 earthquake region (Geersen et al., 2016). Although it is not evident
479 whether the normal faults are rooted in the megathrust interface, the extensional fractures on the
480 hanging wall may be related to the activity of the splay fault. As shown in our model's results, the
481 activity of the splay fault at the up-dip limit of the rupture area may generate an extensional regime
482 in the hinge zone of the fault-related fold and forms extensional fractures. Note that these frontal
483 splay faults may be active during earthquakes and/or in postseismic intervals. In both cases,
484 however, they indicate the frictional transition zone on the plate interface and, in consequence, the
485 up-dip limit of the locked seismogenic zone. In line with our model result, the extensional basin
486 between the splay fault (backstop) and coastal region indicates the megathrust seismogenic zone
487 at depth (Moscoso et al., 2011). The large subduction earthquakes may rupture different portions
488 of the interface from the trench to the downdip end of the seismogenic zone (Lay et al., 2012).
489 Depending on the earthquake magnitude and position of the ruptured segment (i.e., the portion of
490 the megathrust interface beneath the coastal region), the extensional fractures can also be seen
491 onshore as a marker of permanent deformation (Baker et al., 2013; Loveless et al., 2005, 2009).
492 In the Iquique 2014 earthquake region (North Chilean subduction system), clear evidence of the
493 extensional features in the upper plate has been reported from offshore seismic profiles (Geersen
494 et al., 2018; Reginato et al., 2020; Storch et al., 2021). The offshore extensional features can be
495 categorized into two domains, the Middle-Lower slope transition (MLS), and Middle-Upper slope

496 segments. The former is likely formed by the activity of the large forethrust splay, which may be
 497 active during co-, post-, and interseismic intervals. The Middle-Upper slope segment overlies the
 498 main slip zone of the 2014 event. It is possibly formed coseismically and generates the sedimentary
 499 basin over hundreds of seismic cycles. This latter correlation also correlates with the gravity
 500 anomaly (Schurr et al., 2020) introduced by (Song & Simons, 2003; Wells et al., 2003).

501



502

503 Figure 13: A suggested scenario for the coastal segment of the upper plate behavior over tens of seismic
 504 cycles. After exceeding the elastic domain, the upper plate at the location of the coast goes to the strain-
 505 hardening domain over a few seismic cycles and then moves towards the strain-softening domain. The
 506 pulses of megathrust events (loading and unloading) accelerate this switch from strain-hardening to strain-
 507 softening.

508 4.3 Forearc segmentation and temporal pattern of events

509

510 The compressional configuration establishes a clear forearc segmentation through forming up-dip
 511 (offshore) splay faults and down-dip (onshore) backthrust faults, causing the analog megathrust
 512 events to be more regular (same evolution as in Rosenau and Oncken, 2009). Lacking a backthrust,
 513 the extensional wedge does not have this clear segmentation, causing more irregular analog
 514 megathrust events. However, both are still generally periodic, i.e. $CV < 0.5$. Moreover, the forearc
 515 segment bounded by the upper plate faults overlies the seismogenic zone; hence, the frontal
 516 shortening segment (i.e., inner-wedge) of the compressional configuration behaves as a
 517 deterministic spring-slider system (Reid, 1910; Rosenau & Oncken, 2009). In the extensional
 518 configuration, the extensional fractures on the segment above the seismogenic zone indicate
 519 anelastic deformation that correlates with a more complicated temporal pattern of the megathrust
 520 events. This is equivalent to the observation of a less periodic pattern of analog earthquakes

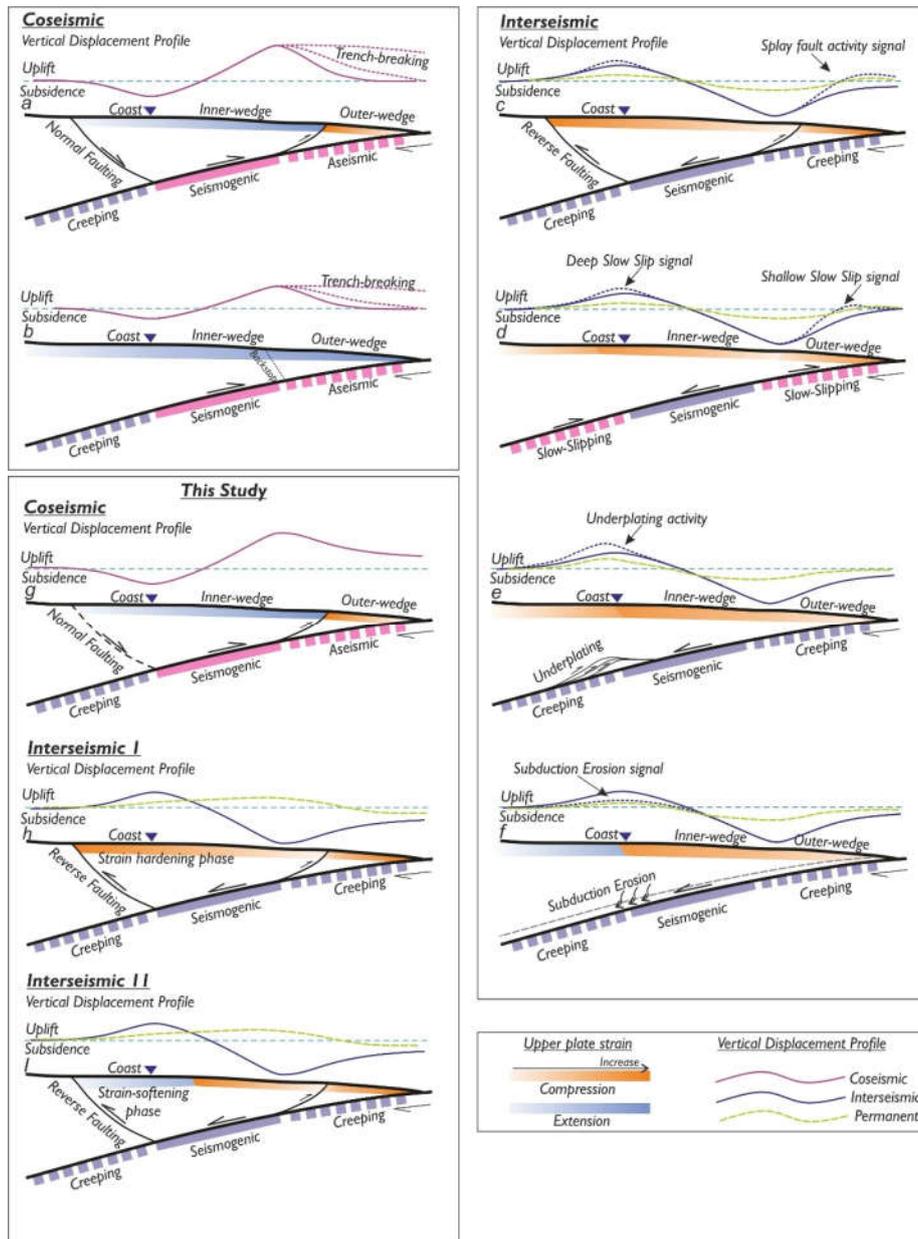
521 produced in the extensional configuration.

522 **4.4 Coastal strain cycle in response to earthquake cycle**

523 In our model, the projection of the downdip limit of the velocity weakening zone on the surface
524 represents the coastal region (Oleskevich et al., 1999; Ruff & Tichelaar, 1996). Unlike the inner-
525 wedge and outer-wedge, the coastal region reacts in an inhomogeneous pattern to the seismic
526 cycles: its strain state does not only respond to each event (i.e., megathrust earthquake), but the
527 strain state shows a “supercycle” over several cycles. In other words, a “strain-switch” from
528 compressional/extensional to an extensional/compressional state develops over a few cycles
529 (Figures 9 and 10). We hypothesize that internal deformation in the experimentally well-known
530 elastoplastic deformation cycle may be the responsible mechanism for the supercycle. The strain
531 rate in the coastal domain is at least one order of magnitude lower than that in the offshore forearc
532 segments; hence, the onshore segment needs more time to reach its yield strength and to shift
533 between strain-hardening and strain-softening periods.

534 On the other hand, a stress transfer caused by a megathrust earthquake perturbs this process and
535 accelerates/decelerates the deformation rate. When the coastal area is in a strain-hardening period,
536 megathrust coseismic pulses gradually push it toward a neutral stage approaching failure and the
537 resultant switch to strain-softening. However, a very large coseismic pulse may also quickly drag
538 it into the strain-softening domain. After the coseismic event, the coast again moves toward the
539 strain-hardening regime (Figure 13). These changes in the strain cycles reflect variability in strain
540 rate with respect to the long-term trend such that the compressional wedge is more segmented, its
541 deformation varies less compared to the unsegmented extensional wedge.

542 Observations reveal that a relatively low resolution (18 cycles in this case) may provide a good
543 overview of the wedge evolution type as outlined above. However, the details of the cycles and
544 the transient in between may be overprinted, for example, by the supercycle-related
545 uplift/subsidence and megathrust events involving splay faults. The comparison suggests that the
546 seismic cycle-to-cycle variability causes periodicity in the surface deformation at all
547 (observational) frequencies. The Northwest Coast of the Tohoku-Oki 2011 earthquake (NE Japan;
548 Japan trench) and the Pacific coast of Hokkaido (Kuril trench) have both experienced two different
549 long-term vertical movement histories. In the former case, the Pleistocene marine terrace



550

551 Figure 14: Schematic of vertical displacement and strain state during the coseismic period and interseismic
 552 interval in different segments of upper plates for different scenarios. Note that we assume the coast reflects
 553 the down-dip limit of the seismogenic zone at depth; modified after (Clark et al., 2019; Fariás et al., 2011;
 554 Herman & Govers, 2020; Madella & Ehlers, 2021; Melnick et al., 2018; Menant et al., 2020; Moreno et al.,
 555 2009; Mouslopoulou et al., 2016; Ozawa et al., 2011; Rosenau & Oncken, 2009; Simons et al., 2011; Sun
 556 et al., 2017; Wang et al., 2019; Wang & Tréhu, 2016, and many others).

557

558

559 chronology of the NE coast of Japan has experienced a constant uplift at about 0.2 m/ky.
560 (Matsu'ura et al., 2019). In contrast, the Holocene sedimentary succession in the south and central
561 Sanriku suggests subsidence at about 1 mm/yr. (Niwa et al., 2017). If this opposite long-term
562 coastal vertical movement is accurate enough, it may reflect the coastal strain supercycle in
563 response to the megathrust cycle. In the latter case, the sedimentological investigations and diatom
564 assemblages suggest pre-seismic submergence at a rate of 8–9 mm/yr. (Atwater et al., 2016; Sawai,
565 2020; Sawai et al., 2004). If this rapid subsidence occurs in each earthquake cycle, megathrust
566 coseismic and postseismic deformation should generate 4–5 m of coastal uplift in each cycle to
567 cancel out the subsidence. A similar subsidence-uplift pattern also accrued in the Aleutian-Alaska
568 subduction system (Shennan & Hamilton, 2006).

569 The above inconsistency in vertical movement of the coast occurs in subduction systems where
570 the megathrust earthquake usually ruptured the offshore (i.e., shallow) part of the interface (e.g.,
571 Japan and Alaska trenches) (Figure 14). In the cases where the megathrust earthquakes that
572 partially or fully ruptured the deep part of the interface, for instance, the Antofagasta 1995 (Chlieh
573 et al., 2004; Pritchard et al., 2002) and Illapel 2015 earthquakes (Tilman et al., 2016), marine
574 terraces recorded a more continuous uplift (with different rates) since the Pleistocene (González-
575 Alfaro et al., 2018). However, a long-term (Miocene) change in the vertical movement has been
576 recorded in some places on the Coastal Cordillera in the Chilean margin, probably caused by basal
577 erosion/accretion sequences (Encinas et al., 2012). This may imply that if the coastal area subsides
578 coseismically but uplifts over the interseismic period, the coast probably overlies the downdip
579 limit of the locked zone while the coastal region may show long-term vertical movement
580 inconsistently. If the coast moves vertically upward during both coseismic and interseismic
581 periods, upper plate thrust faults likely push the coast upward (Clark et al., 2019; Mouslopoulou
582 et al., 2016) and the coastal region continuously accumulates permanent uplift.

583 Deep slow-slip events, basal accretion, interseismic crustal thickening, and upper plate faulting
584 may enhance coastal uplift at different time scales (Figure 14). Among these processes,
585 underplating may not play a significant portion in a single seismic cycle because the formation of
586 each tectonic slice (i.e., duplex) is in a Myr-scale (Menant et al., 2020; Ruh, 2020). The thermo-
587 mechanical simulations (Menant et al., 2020) suggest early and late stages of a single underplating
588 cycle respectively characterized by up to 1.5 mm/yr. uplift and subsidence (i.e., re-equilibration of
589 the forearc wedge) rate in the coastal region. This transition from uplift to subsidence (and vice

590 versa) is in the Myr-scale and represents a much lower frequency in comparison with the
 591 deformation supercycle observed in our experiments. However, to rule out and differentiate the
 592 impact of the different mechanisms involved in the vertical movement of the coastal region, a
 593 modeling approach including all the above-mentioned mechanisms is needed.

594

595

Table 1: Summary of short- and long-term forearc strain state

Configuration	Compressional config.	Compressional config.	Compressional config.	Extensional config.	Extensional config.	Extensional config.
Forearc segment	<i>Coseismic</i>	<i>Interseismic</i>	<i>Long-term permanent</i>	<i>Coseismic</i>	<i>Interseismic</i>	<i>Long-term permanent</i>
outer-wedge	Compression	From compression moves to a neutral state and finally to extension	Compression	Compression	From compression moves to a neutral state and finally to extension	Compression
Inner-wedge	Extension	From extension moves to a neutral state and finally to a stably compressional	Extensional; extensional zone becomes wider over time	Extension	From extension moves to a neutral state and finally to a stably compressional	Extensional over the seismogenic zone; surface extensional fractures
Coastal region	Extension	Extensional & compressional portions do not balance; asymmetric cyclic pattern	Multi-cycle long compressional/ extensional supercycles	Extension	Extensional & compressional portions do not balance; asymmetric cyclic pattern	Multi-cycle long compressional/ extensional supercycles; sharper supercycle

596

597

598 Although the inner-wedge and outer-wedge may show a relatively simple earthquake deformation
 599 cycle, the coastal zone in the subduction zones may also show a rather complicated pattern and
 600 trend. Where the downdip limit of seismic locking and slip is offshore, both, the deformation
 601 resulting from seismic cycle deformation and that from mass flux at the plate interface (subduction
 602 erosion vs. underplating) generate a composite, more complex kinematic record, even in our
 603 simplified seismotectonic model. This implies that predicting the interface behavior from the
 604 coastal behavior might not always provide diagnostic evidence in the case of shallow subduction
 605 earthquakes where the coast does not overlie the seismogenic zone or its downdip end. Rather,
 606 measuring surface deformation above the locked zone provides a more reliable indication of the
 607 behavior of the interface.

608 **5 Conclusion**

609

610 Our results highlight that, in the shallow portion of the subduction zone, frictional properties of
 611 the interface and mechanical characteristics of the forearc determine the surface deformation signal
 612 over seismic cycles. The mechanical and kinematic interaction between the shallow wedge and the
 613 interface can partition the wedge into different segments. These segments may react analogously

614 or oppositely over the different intervals of the seismic cycle (Table 1). Moreover, different wedge
615 segments may switch their strain state from compression/extension to extension/compression
616 domains. We emphasize that a more segmented upper plate is related to megathrust subduction
617 that generates more characteristic and periodic events.

618 Our experiments underscore that the stable part of the wedge (i.e., inner-wedge) which undergoes
619 extension coseismically overlies the seismogenic zone. However, the density of extensional
620 fractures and the number of normal faults may increase toward the limit between the inner-wedge
621 and outer-wedge due to the activity of splay faults at the up-dip limit of the seismogenic zone.

622 Over a dozen and more analog earthquake cycles, the strain time series reveal that the strain state
623 may switch the mode after remaining quasi-stable over a few seismic cycles in the coastal zone.
624 Various scenarios have been suggested, such as background seismicity, deep slow-slip events,
625 subduction accretion/erosion, as the responsible mechanism for switching the kinematic behavior
626 of the coastal domain (uplift to subsidence and vice versa). Here we additionally show that the
627 mechanical state of the plate interface beneath the coastal region, may vary over time and influence
628 the coastal region strain state. Because the strain rate here is significantly lower than in the offshore
629 segment, this may eventually lead to different observed vertical motions on the coast. Megathrust
630 events might be a driving agent that accelerates the strain state switch and pushes the coastal region
631 from a strain-hardening to strain-softening state. Our simplified experiments demonstrate that the
632 strain cycle in the coastal region may show a supercycle pattern superseding sawtooth pattern of
633 the strain cycles related to the earthquake cycle. This is geodetically relevant as the observations
634 in many subduction zones are focused in the coastal regions. Hence, it may not always be
635 straightforward to use these observations as direct evidence to assess the behavior of the shallow,
636 offshore portion of the megathrust.

637

638 **Data Availability Statement**

639 All data in this study will be published open access soon (data archiving is underway). We thank
640 GFZ Data Services for publishing the data. Meanwhile, the data set is uploaded as Supplemental
641 Material for review purposes.

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654

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Tectonics

Supporting Information for

Strain signals governed by frictional-elastoplastic interaction of the upper plate and shallow subduction megathrust interface over seismic cycles

Ehsan Kosari ^{1,2}, Matthias Rosenau ¹, Onno Oncken ^{1,2}

¹ Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany.

² Department of Earth Sciences, Freie Universität Berlin, Berlin, Germany.

Contents of this file

Figures S1 and S2

Introduction

This supporting information contains additional figures supporting the lines of argumentation in the main manuscript.

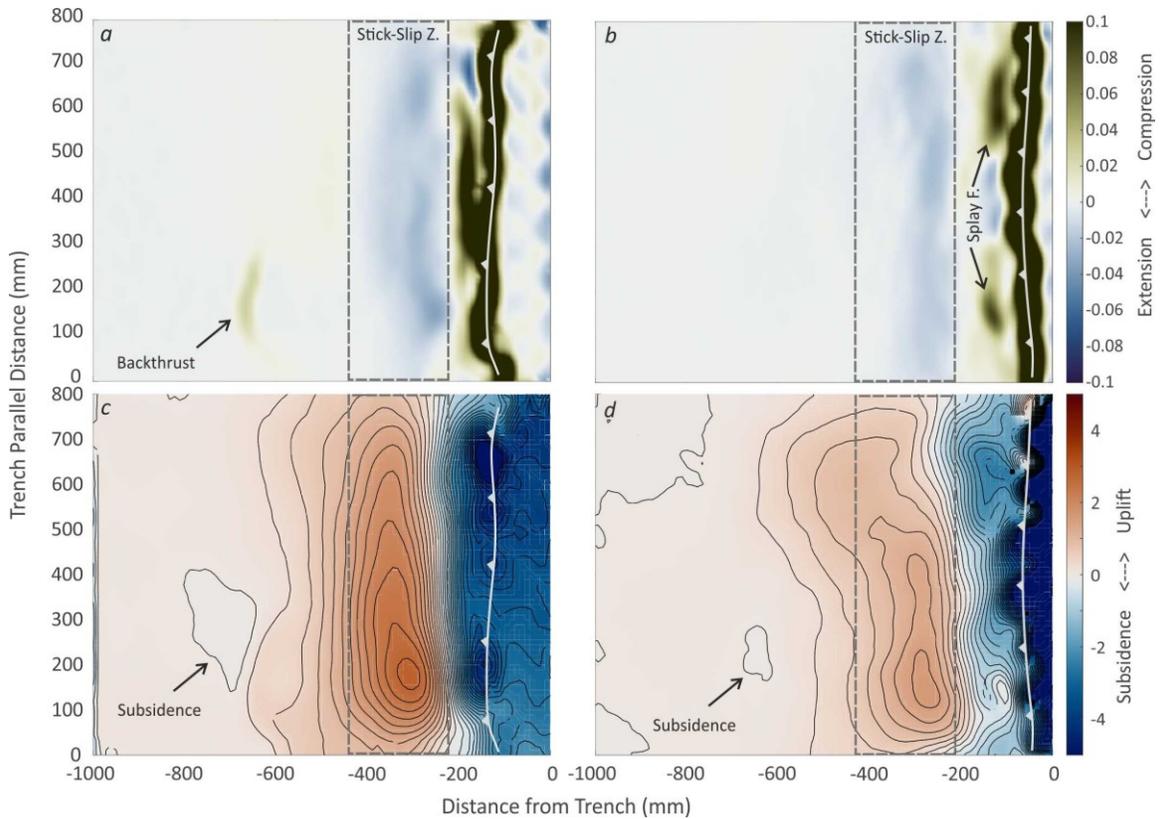


Figure S1. Surface deformation maps from compressional (a and c) and extensional configurations (b and d) over dozens of analog earthquake cycles. The approximate location of the stick-slip zone at depth is projected on the model surface as a dashed rectangle. a and b: Surface strain maps. Green and blue colors represent compression and extensional domains, respectively. The outer-wedge is experienced (splay fault and trench domains) compression. Inner-wedge is recorded permanent extension. The activity of the backthrust is evident in compressional configuration. c and d: permanent vertical deformation in the absence of erosion in the system. The outer- and inner-wedge represent permanent subsidence and uplift, respectively. The slight subsidence zone onshore may represent a forearc basin at the natural scale.

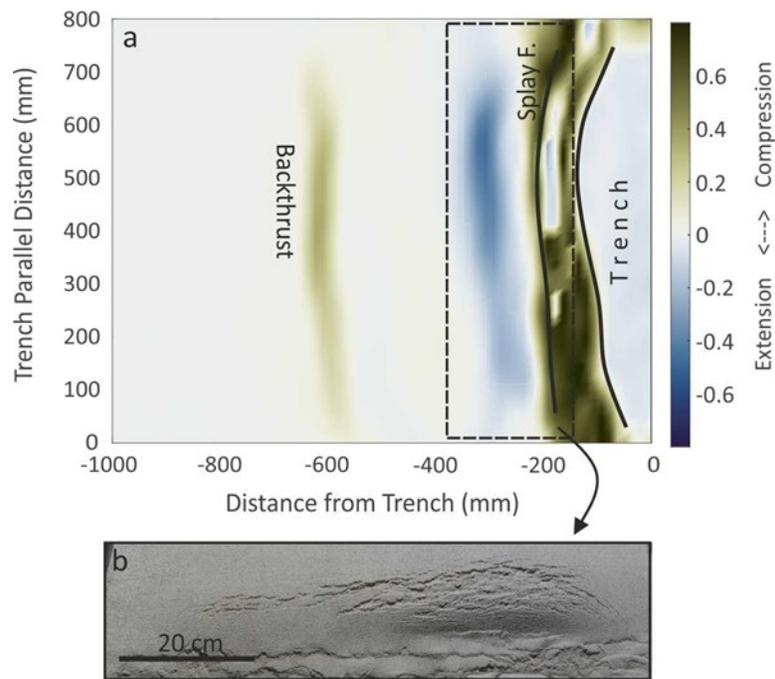


Figure S2. Surface strain map (a) and the laboratory view (b) of the extensional features from a supplemental experiment. Green and blue colors represent compression and extensional strain, respectively. The maximum extensional domain (intense blue zone) correlates with the density of fractures. The extensional structures are formed mainly due to the activity of the splay fault.