1 **Subduction initiation at the corner of small oceanic basin**

2 **Miao Dong[1,2]*, Tianyao Hao[1,2]*, Yue Li[1, 2], Jian Zhang[2], and Gui Fang[3]**

3 [1]Key Laboratory of Petroleum Resource Research, Institute of Geology and Geophysics, Chinese
4 Academy of Sciences, Beijing 100029, China

5 [2]University of Chinese Academy of Sciences, Beijing 100049, China

6 [3]PetroChina Hangzhou Research Institute of Geology, Hangzhou 310023, China

7 Corresponding author: Miao Dong (dongmiao@mail.iggcas.ac.cn)

8 Tianyao Hao (tyhao@mail.iggcas.ac.cn)

9 **Key Points:**

10 • In small ocean basins subduction initiates at the apex of the corner, regardless of its size
11 or angle at the corner.

12 • The smaller the angle of the corner in the oceanic basin, the more likely subduction is to
13 initiate.

14 • An angle at the corner greater than 120 degrees is less likely to lead to the subduction
15 initiation.

Abstract

In Southeast Asia, emerging subduction zones often appear to begin at the corners of small oceanic basins, which have a triangular-indenter continent–ocean boundary geometry. To investigate the influence of a triangular indenter on subduction initiation, we performed a series of three-dimensional numerical simulations with varying indenter angles and base lengths. The results show that the apex of the indenter constitutes the initial location of subduction, irrespective of the angle or the extent of the indenter. Smaller angle indenters are more likely to facilitate subduction initiation. At the same time, wide acute angle indenters are difficult to form. Our findings suggest that triangular indenter structures may facilitate subduction initiation in smaller basins; however, the role such indenters in subduction initiation is limited in larger basins. Our results emphasize the importance of accounting for the three-dimensional geometry of a subduction zone when examining its subduction dynamics and geological features.

Plain Language Summary

In Southeast Asia, new subduction zones near small ocean areas and near locations prone to subduction have a unique and common feature—subduction starts at triangular indenter–shaped continent–ocean boundaries. To fully understand how these triangular indenter shapes affect the initiation of subduction, we employed advanced computer simulations. We varied the angles and lengths of the indenters in our models. We discovered that, no matter the size of the indenter, subduction began at the apex of the indenter. Interestingly, smaller indenters are especially good at initiating subduction. However, forming a wide indenter with small angles in nature appears to be very difficult. This study indicates that the indenter shape helps subduction start in small ocean areas but is not as important in larger ocean areas. This insight helps us better understand how subduction works in different locations on the Earth.

1 Introduction

Plate tectonic activity is an essential prerequisite for Earth habitability and sets Earth apart from other planets (Korenaga, 2012). As the foundation of plate tectonics, understanding the initiation of subduction remains a significant challenge and frontier in the field of Earth science (Toth and Gurnis, 1998; Gurnis, 2004; Stern, 2004; Korenaga, 2013; Stern and Gerya, 2018). However, one of the most notable difficulties in subduction initiation research is the lack of "direct observations" (Mueller and Phillips, 1991). Regions that are actively undergoing subduction initiation, such as Puysegur, can very rarely be directly observed (Gurnis et al., 2004; Shuck et al., 2022). Therefore, the subduction initiation process is usually studied using various techniques such as numerical simulations, physical simulations, and petrology (McKenzie, 1977; Bercovici, 2003; Niu et al., 2003; Agard et al., 2007, 2016; Ishizuka et al., 2011; Gerya et al., 2015; Maunder et al., 2020; Zhou et al., 2020; Dong et al., 2022) because mature subduction zones have undergone long periods of tectonic evolution, resulting in the disappearance of most structural features dating from the initial stage of subduction. Therefore, it is important to observe and study subduction initiation in areas where subduction initiation is either in progress or has recently been completed (Hall, 2019; Shuck et al., 2022).

Southeast Asia is home to several small oceanic basins and subduction zones that are relatively young (Figure 1a; Hall, 1996; 2012; Hall and Spakman, 2015; Lai et al., 2021; Li et al., 2023). Examples include the Cotabato and Sulawesi subduction zones, which were initiated during the Pliocene or Late Miocene (Silver et al., 1983; Kopp et al., 1999; Schlüter et al., 2001)

59 and have subduction slabs with a maximum depth in the middle of the trench and a gradual
60 decrease in length along both sides (Figure 1c and 1d). Other regions have ongoing subduction
61 initiation, such as the Tolo Trough (Figure 1b), where a portion of the continental crust is
62 migrating over the oceanic crust of the Northern Banda Sea (Silver et al., 1983; Hall, 2019;
63 Husson et al., 2022). In areas such as the Sula Deep (Figure 1b), which has abnormally deep
64 water and steep terrain, subduction initiation seems probable in the future (Hall, 2019). Despite
65 differences in their subduction initiation stages, these regions share similar structural
66 characteristics, with oceanic lithosphere subducting beneath either a relic arc or a continental
67 fragment. Moreover, and more importantly, subduction initiation, either ongoing or imminent, is
68 consistently located in the corners of these oceanic basins (i.e., there is a triangular indenter).

69 Subduction initiation is a complex process that is affected by multiple factors, including
70 the density differences between the plates, thermal structure, and weak zones (Niu et al., 2003;
71 Nikolaeva et al., 2010; Leng and Gurnis, 2015; Zhou et al., 2020). For example, Nikolaeva et al.
72 (2010, 2011) conducted numerical simulations of subduction initiation in a passive continental
73 margin and proposed that subduction initiation is facilitated by a thick crust and a thin, hot
74 lithosphere. Similarly, Leng and Gurnis (2015) concluded that, based on numerical simulations,
75 subduction initiation is easier in arc regions than in passive margins. The overriding plates in the
76 small, mostly island arc, subduction zones in Southeast Asia are consistent with the results of
77 these studies. However, these studies were based on two-dimensional (2D) numerical models.
78 Some lateral structural geometry changes affecting subduction initiation may require three-
79 dimensional (3D) numerical models. With the rapid development of computing power, more 3D
80 models are now being used to study subduction initiation (Gerya et al., 2015; Zhou et al., 2018;
81 2020; Almeida et al., 2022; Riel et al., 2023).

82 Marques et al. (2014) used three 3D models to investigate subduction initiation at a
83 passive continental margin (where the angle is zero between the trace of the curved section of the
84 margin and the *z*-axis of the model), as well as other models at different angles to the *z*-axis.
85 Their results showed that a straight passive margin is more susceptible to subduction initiation
86 than a curved passive margin. However, these models did not incorporate geometric shapes such
87 as a "triangular indenter," which refers to a specific location where the oceanic plate boundary
88 geometry exhibits a change in direction, causing it to zigzag toward the continent and form an
89 angle. Significantly, the small oceanic basins in Southeast Asia differ significantly from the long,
90 generally straight margins of the Atlantic. In Southeast Asia, the continent–ocean boundaries are
91 typically much narrower, formed more quickly, and are much steeper (Hall, 2019). Currently,
92 there are no numerical models available to validate the observed subduction-prone corners in
93 Southeast Asia.

2   Model setup

95 We employed the massively parallel finite element code ASPECT (Bangerth et al., 2020;
96 Heister et al., 2017; Kronbichler et al., 2012) to construct and execute our 3D numerical
97 geodynamic model (Figure 2a). The left side of the model represents the oceanic plate, composed
98 of the oceanic crust (10-km thick) and the suboceanic lithospheric mantle. The right side of the
99 model represents the overriding plate, comprising the upper crust (25-km thick), lower crust (15-
100 km thick), and lithospheric mantle (40-km thick). This configuration creates a substantial density
101 contrast between the overriding plate and the oceanic plate (Figure 2b). We adopted this specific
102 setup for the overriding plate model based on previous studies (Nikolaeva et al., 2010; Marques

103 et al., 2014), allowing the model to achieve completion within a short time. Detailed information
104 concerning the initial model design, equations, and parameters can be found in the Supporting
105 Information Text S1.

106   A 10-km-thick weak zone between the oceanic plate and the overriding plate is included
107 in our model to ensure that subduction initiation can be completed. Typically, the boundary
108 between the oceanic plate and the passive continental margin is not vertical in the z-direction and
109 part of the oceanic plate extends below the continental plate (Nikolaeva et al. 2010, 2011;
110 Marques et al., 2013; 2014). Nevertheless, for the small basins in Southeast Asia, the overriding
111 plates may closely resemble the lithosphere of relic arcs. Therefore, we adopted a similar
112 approach to that of Leng and Gurnis (2015) by vertically dividing the plates according to their
113 weak zones; this allowed us to isolate just the impact of the indenter geometry on subduction
114 initiation.

115   In our models, the geometry of the indenter is defined by the angle α and width D of the
116 base extent of the corner (Figure 2c). Model 0 (a straight ocean–continent boundary, invariant in
117 the *z*-direction) serves as the reference model to evaluate the influence of the indenter. Models 1,
118 2, and 3 have a width D of 200 km, with α values of 120°, 90°, and 60°, respectively. Models 4,
119 5, and 6 have a width D of 115.4 km, with α values of 120°, 90°, and 60°, respectively. Model 7
120 shares the same apex positions as Models 1 and 5, with an α value of 60°. Models 8, 9, and 10
121 have a width D of 346.4 km, with α values of 120°, 90°, and 60°, respectively.

3 Results

123   In this study, we designated the time at which the sinking oceanic slab reaches a depth of
124 200 km as the completion time of subduction initiation (Figures 3a and S1), serving as a metric
125 to evaluate the level of difficulty for each model to achieve subduction initiation. Because the
126 temporal resolution of our model output is 0.1-Myr intervals, there may be an associated error of
127 ±0.1 Myr in the recorded time (Table 1).

128   In comparison to the reference model (Model 0), characterized by a straight ocean–
129 continent boundary, the majority of the models featuring an indenter structure demonstrated
130 accelerated subduction initiation. Only Model 1 exhibited a longer initiation period than the
131 reference model. Note that, because of the marginal error of 0.1 Myr, the subduction initiation
132 times in Models 4 and 8 can be approximated as being similar to those of the reference model.
133 Interestingly, Models 1, 4, and 8 share the same angle of 120°.

134   In the simulations involving Models 1, 2, and 3, all featuring an indenter structure with a
135 consistent base extent of 200 km, we observed that a larger angle (α) was correlated with
136 extended durations for completing subduction initiation. This trend was also evident in other
137 models with varying D values, such as Models 4, 5, and 6, as well as Models 8, 9, and 10.
138 Accordingly, we conclude that, for indenter structures sharing the same base extent, a smaller
139 angle tends to lead to quicker subduction initiation.

140   Despite these results, no consistent pattern emerged for models with the same angle but
141 differing base lengths. For example, when considering an angle of 120°, Model 1, with $D = 200$
142 km, required 5.0 Myr to achieve initial subduction. In contrast, Model 4, with a smaller indenter,
143 and Model 8, with a wider indenter, both exhibited shorter subduction initiation times.

144   The results for models featuring a 90° angle diverged from those with a 120° angle.
145 Notably, Model 2, with a indenter base extent of 200 km, exhibited a higher probability of

146   subduction initiation than both the narrower indenter (Model 5) and the wider indenter (Model 9),
147   which required more time to complete initial subduction than Model 2. Nevertheless, all models
148   with a 90° angle accomplished initial subduction more rapidly than Model 0.

149   In the case of models with an angle of 60°, analogous to those with an angle of 90°, the
150   model (Model 3) with $D = 200$ km completed subduction initiation faster, whereas both of the
151   narrower indenters (Models 6 and 7) and the wider indenter (Model 10) exhibited lengthier
152   subduction initiation times. However, the time difference was not as pronounced as observed in
153   models with a 90° angle. Considering the potential error of 0.1 Myr, Models 3 and 10 are
154   reasonably similar. Consequently, the relationship between the time required for initial
155   subduction completion and the base extent D is not linearly dependent given a constant indenter
156   angle.

157   Analyzing models sharing the same apex position (h), yet varying in angle, we reached
158   similar conclusions. For example, Models 1, 5, and 7, possessing identical apex positions,
159   demonstrated that a smaller angle leads to a briefer duration for initial subduction. However,
160   within the context of models with the same angle, the discrepancy in the subduction initiation
161   time arising from different h values did not adhere to a linear pattern.

4 Discussion

4.1 Influence of the 3D indenter geometry on subduction initiation

164   In a 3D model, the magnitude of the vertical downward force (the y-component) can be
165   amplified or diminished given the presence of a horizontal component (the z-component). This
166   component, a representation of the third spatial dimension lacking in a 2D model, influences the
167   distribution of forces within the 3D framework.

168   For the first few timesteps (less than 1 Myr), the continental plate undergoes rapid
169   vertical movement to reach isostatic equilibrium (Figures 4b, S2b, and S3b). Subsequently, the
170   primary driving force, originating from the density contrast between the oceanic and continental
171   plates (Figure 2b), causes the overriding plate to overthrust onto the oceanic plate, inducing
172   downward bending of the latter. Particularly at the apex of the indenter, a focusing effect
173   facilitates the dipping of the indenter. As subduction initiation progresses, the leading edge
174   increases its buoyancy contrast with the surrounding mantle, intensifying the bending and the
175   downward pull of the plate.

176   As subduction initiation progresses, the indenter area on the surface gradually decreases
177   (Figures 4b, S2b, and S3b). However, the extent of this reduction varies among the models with
178   different angles. Models with smaller initial angles experience greater reductions in the extent of
179   the indenter (D) and in the reduction of h (Δh). In models with large angle indenters, the force
180   component in the z-direction is smaller than that in the x-direction. While the apex position of the
181   indenter has a force in the z-direction on both sides that pushes the oceanic plate downward, this
182   force is too small to change the deformation of the overriding plate in the indenter. As a result,
183   the change in the length h is relatively small and the overriding plate moves toward the oceanic
184   plate along the x-direction, with the continent–ocean boundary shape remaining largely
185   unchanged (Figure 4b). Therefore, large-angle indenters have little effect on subduction initiation
186   because they lose the focusing effect of the indenter as nearly the entire margin geometry
187   becomes triangular. According to our numerical simulations, the indenter does not promote
188   subduction initiation when the angle of the indenter exceeds 120°.

189   In the case of a small angle indenter, the component of the force in the *z*-direction is
190 sufficiently large to induce deformation of the overriding plate. Consequently, the oceanic
191 lithosphere at the apex of the indenter is compressed by the overriding plate on both sides,
192 causing the apex position of the indenter to gradually close. This leads to the oceanic plate at the
193 apex sinking rapidly into the asthenosphere. As the plate reaches asthenospheric depths, the
194 buoyancy contrast and viscosity contrast between the subducting plate and the surrounding
195 mantle increase. Consequently, slab pull becomes increasingly significant. Therefore, the sooner
196 the oceanic plate at the indenter enters the asthenosphere, the earlier the entire subduction system
197 will form (Figures 3a and S1).

198 4.2 Initial subduction starts at the indenter point

199   In all models, the apex position of the indenter is the site at which the model plate first
200 begins to bend downward, irrespective of the angle or extent of the indenter. The subducting slab
201 reaches a depth of 200 km first at the midsection of the plate (as shown in Figure 3b). This is
202 consistent with the conditions observed in the Celebes Sea, where the subducted slab has reached
203 the deepest point at middle of the trench both in the Cotabato and North Sulawesi subduction
204 zones.

205   The current plan views of the subduction zones appear to be relatively flat without
206 prominent indenters (gray areas in Figure 1c). However, this does not indicate the shape of the
207 plate prior to subduction. On the basis of the Slab2.0 model, we can calculate the length of the
208 subducted slab along the trench-normal direction. Then, we can reconstructed the slab to its pre-
209 subduction shape (Figure 1d). We can see that there is a triangle indenter at the front end of the
210 reconstructed plate for both Cotabato and North Sulawesi (red areas in Figure 1c). The longest
211 slab, corresponding to the location where the subduction initiation first starts, is the apex of the
212 indenter. This is consistent with our simulation results, which show that subduction initiation
213 starts at the apex of the indenter.

214   Our modeling results also correspond to the conditions observed in the North Banda Sea.
215 The region's deepest points correspond to indenter apex positions (Figure 1b). The northeastern
216 indenter of this region (the Sula Deep) exhibits depths exceeding 5800 m, characterized by slope
217 gradients of up to 13° (Hall, 2019). These gradients are likely related to slab pull at depth
218 resulting from roll back in the Banda Sea (Husson et al., 2022). The Tolo Trough, located at the
219 western edge, exhibits average slope gradients of 7–8° near its deepest segment. Rudyawan and
220 Hall (2012) have documented thrusting in this region, consistent with downslope movement of a
221 thrust sheet and the displacement of continental crust onto the North Banda Sea oceanic crust.

222   Both numerical simulations and geological observations consistently indicate that
223 subduction initiation predominantly takes place at the indenter apex, irrespective of the indenter
224 angle or extent. This phenomenon arises from the inherent property of the indenter geometry,
225 which concentrates stress at its vertices, particularly during the initial stage of subduction
226 (Figures 4a, S2a, and S3a). The apexes of indenters, where stress concentrates, are more
227 susceptible to deformation than other areas. In addition, the stress concentration in the corner of
228 an indenter with a smaller angle is greater; this is the primary reason why the corner model with
229 a smaller angle is more likely to speed up subduction initiation.

230   Although an acute angle indenter geometry can easily trigger subduction initiation, this
231 structure is unstable because it is easily compressed by both sides of the plate (Figure 4).

232 Consequently, forming a wide range of such sharp indenters in actual geological cases is
233 challenging. If these structures were to form during oceanic plate development, before reaching
234 significant size, intense stresses would rapidly compress the indenter area, particularly at the
235 apex, potentially leading to subduction. As a result, such large acute angle indenter structures are
236 not observed on the Earth's surface at present.

237 The promotion of subduction initiation by an indenter primarily relies on the negative
238 buoyancy of the plate bending downward at the apex position. In smaller basins (hundreds of
239 kilometers in size), inverting the short margin necessitates a smaller force, allowing a small acute
240 or right-angled indenter to facilitate subduction initiation. However, in larger basins (several
241 thousands of kilometers in scale), inverting the entire long margin demands a larger force,
242 indicating the need for a large acute angular indenter. Unfortunately, such a large indenter
243 formation is improbable. Therefore, while the triangular indenter structure may facilitate
244 subduction initiation in smaller basins, its role in larger basins is limited.

245 4.3 Model limitations

246 In this study, all of the simulations accounted for the weak zone at the ocean–continent
247 boundary, with different indenter geometries corresponding to various weak zone configurations.
248 However, these models are idealized. In geological settings, the strength of the ocean–continent
249 boundary relies on inherited structures and the degree of serpentinization, which may not
250 uniformly exhibit low strength across the entire boundary. Consequently, subduction initiation is
251 more likely to occur where weak strength areas are present (Zhou et al., 2020).

252 While our models were designed to simulate spontaneous subduction, it is crucial to
253 acknowledge that small basins, often situated amidst numerous active plates, can experience
254 influences from surrounding plate activities during subduction initiation (Dong et al., 2022).
255 Quantifying external forces acting in different directions within a 3D model is complex.
256 Therefore, we intentionally omitted external forcing, focusing solely on assessing the impact of
257 the indenter geometry on subduction. Further research involving more complex structures and
258 boundary conditions closer to those of natural subduction zones is necessary to enable a
259 comprehensive understanding of subduction initiation dynamics.

260 **5 Conclusions**

261 In this study, we simulated a series of numerical models to investigate the relationship
262 between the triangular indenter geometry and subduction initiation. The results of the study
263 suggest the following conclusions.

264 (1) In small oceanic basins, subduction initiates at the apex of the indenter, regardless of
265 its size or angle.

266 (2) A small angle indenter in an oceanic basin is favorable to subduction initiation.

267 (3) An indenter with an angle of more than 120° does not facilitate subduction initiation
268 and may instead hinder it.

269 **Acknowledgments**

Open Research

279 The code (ASPECT v2.3.0, Wolfang et al., 2021) used in this study is available at
280 https://doi.org/10.5281/zenodo.5131909.

References

282 Agard, P., Jolivet, L., Vrielynck, B., Burov, E., Monie, P., 2007. Plate acceleration: the obduction trigger? Earth
283   Planet. Sci. Lett. 258, 428–441. https://doi.org/10.1016/j.epsl.2007.04.002
284 Agard, P., Yamato, P., Soret, M., Prigent, C., Guillot, S., Plunder, A., Dubacq, B., Chauvet, A., Monie, P., 2016.
285   Plate interface rheological switches during subduction infancy: control on slab penetration and metamorphic
286   sole formation. Earth Planet. Sci. Lett. 451, 208–220. https://doi.org/10.1016/j.epsl.2016.06.054
287 Almeida, J., Riel, N., Rosas, F. M., Duarte, J. C., & Kaus, B. (2022). Self-replicating subduction zone initiation by
288   polarity reversal. Communications Earth & Environment, 3(1), 55. https://doi.org/10.1038/s43247-022-00380-2
289 Bangerth, W., Dannberg, J., Gassmoeller, R., & Heister, T. 2020. ASPECT v2.2.0. (version v2.2.0). Zenodo.
290   https://doi.org/10.5281/ZENODO.3924604
291 Bercovici, D., 2003. The generation of plate tectonics from mantle convection. Earth Planet. Sci. Lett. 205, 107–
292   121. https://doi.org/10.1016/S0012-821X(02)01009-9
293 Dong, M., Lü, C.C., Zhang, J., & Hao, T., 2022. Downgoing plate-buoyancy driven retreat of North Sulawesi
294   Trench: Transition of a passive margin into a subduction zone. Geophys. Res. Lett. 49, e2022GL101130.
295   https://doi.org/10.1029/2022GL101130
296 Gerya, T., Stern, R.J., Baes, M., Sobolev, S., Whattam, S., 2015. Plume-induced subduction initiation triggered plate
297   tectonics on Earth. Nature 527, 221–225. https://doi.org/10.1038/nature15752
298 Gurnis, M., Hall, C., Lavier, L., 2004. Evolving force balance during incipient subduction. Geochem. Geophys.
299   Geosyst. 5, Q07001. http://dx.doi.org/10.1029/2003GC000681
300 Hall, C. E., Gurnis, M., Sdrolias, M., Lavier, L. L., Müller, R. D., 2003. Catastrophic initiation of subduction
301   following forced convergence across fracture zones. Earth Planet. Sci. Lett. 212, 15-30.
302   https://doi.org/10.1016/S0012-821X(03)00242-5
303 Hall, R., 1996. Reconstructing cenozoic SE Asia. Geol. Soc. Lond., Spec. Publ. 106, 153–184.
304   https://doi.org/10.1144/gsl.sp.1996.106.01.11
305 Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean,
306   Tectonophysics, 570-571, 1-41. https://doi.org/10.1016/j.tecto.2012.04.021
307 Hall, R., 2019. The subduction initiation stage of the Wilson cycle, Geological Society, London, Special
308   Publications, 470(1), 415-437. https://doi.org/10.1144/SP470.3
309 Hall, R. & Spakman, W., 2015. Mantle structure and tectonic history of SE Asia. Tectonophysics 658, 14-45.
310   https://doi.org/10.1016/j.tecto.2015.07.003
311 Hayes, G. P., Moore, G. L., Portner, D. E., Hearne, M., Flamme, H., Furtney, M., & Smoczyk, G. M., 2018. Slab2, a
312   comprehensive subduction zone geometry model, Science, 362(6410), 58-61.
313   https://doi.org/10.1126/science.aat4723
314 Heister, T. Dannberg, J., Gassmöller, R., & Bangerth, W., 2017. High Accuracy Mantle Convection Simulation
315   through Modern Numerical Methods-II: Realistic Models and Problem. Geophysical Journal International, 210,
316   833-851. https://doi.org/10.1093/gji/ggx195
317 Husson, L., Riel, N., Aribowo, S., Authemayou, C., de Gelder, G., Kaus, B. J. P., Mallard, C. Natawidjaja, D. H.,
318   Pedoja, K. & Sarr, A. C. (2022). Slow geodynamics and fast morphotectonics in the far East Tethys.
319   Geochemistry, Geophysics, Geosystems, 23(1), e2021GC010167. https://doi.org/10.1029/2021GC010167
320 Ishizuka, O., Tani, K., Reagan, M. K., Kanayama, K., Umino, S., Harigane, Y., Sakamoto, I., Miyajima, Y., Yuasa,
321   M., Dunkley, D. J., 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island
322   arc. Earth Planet. Sci. Lett. 306(3-4), 229-240. https://doi.org/10.1016/j.epsl.2011.04.006

323   Kopp, C., Flueh, E. R., & Neben, S., 1999. Rupture and accretion of the Celebes Sea crust related to the North
324   Sulawesi subduction combined interpretation of reflection and refraction seismic measurements. Journal of
325   Geodynamics, 27(3), 309-325. https://doi.org/10.1016/S0264-3707(98)00004-0
326   Korenaga, J., 2012. Plate tectonics and planetary habitability: current statusand future challenges. Ann. N.Y. Acad.
327   Sci. 1260, 87-94. https://doi.org/10.1111/j.1749-6632.2011.06276.x
328   Korenaga, J., 2013. Initiation and evolution of plate tectonics on Earth: theories and observations. Annu. Rev. Earth
329   Planet. Sci. 41, 117–151. https://doi.org/10.1146/annurev-earth-050212-124208
330   Kronbichler, M., Heister, T., & Bangerth, W., 2012. High Accuracy Mantle Convection Simulation through Modern
331   Numerical Methods. Geophysical Journal International, 191, 12–29. https://doi.org/10.1111/j.1365-
332   246X.2012.05609.x
333   Lai, C.-K., Xia, X.-P., Hall, R., Meffre, S., Tsikouras, B., Rosana BalangueTarriela, M. I., et al., 2021. Cenozoic
334   evolution of the Sulu Sea arc-basin system: An overview. Tectonics, 40, e2020TC006630.
335   https://doi.org/10.1029/2020TC006630
336   Leng, W., & Gurnis, M., 2015. Subduction initiation at relic arcs. Geophys. Res. Lett. 42(17), 7014-7021.
337   https://doi.org/10.1002/2015gl064985
338   Li M, Huang S, Hao T, Dong M, Xu Y, Zhang J, He Q, Fang G., 2023. Neogene subduction initiation models in the
339   western Pacific and analysis of subduction zone parameters. Science China Earth Sciences, 66(3): 472–491,
340   https://doi.org/10.1007/s11430-022-1065-1
341   Marques, F. O., Nikolaeva, K., Assumpção, M., Gerya, T. V., Bezerra, F. H. R., do Nascimento, A. F., & Ferreira, J.
342   M., 2013. Testing the influence of far-field topographic forcing on subduction initiation at a passive margin.
343   Tectonophysics, 608, 517-524. https://doi.org/10.1016/j.tecto.2013.08.035
344   Marques, F. O., Cabral, F. R., Gerya, T. V., Zhu, G. &May, D. A., 2014. Subduction initiates at straight passive
345   margins. Geology, 42, 331-334. https://doi.org/10.1130/G35246.1
346   Maunder B, Prytulak J, Goes S, et al. Rapid subduction initiation and magmatism in the Western Pacific driven by
347   internal vertical forces. Nature Communications, 2020, 11: 1874. https://doi.org/10.1038/s41467-020-15737-4
348   McKenzie, D.P., 1977. The initiation of trenches: a finite amplitude instability. In: Talwani, M., Pittman, W.C.
349   (Eds.), Island Arcs, Deep Sea Trenches, and Back-Arc Basins. Maurice Ewing Ser. I. AGU, Washington, D.C.,
350   pp. 57–61.
351   Mueller, S., Phillips, R.J., 1991. On the initiation of subduction. J. Geophys. Res. 96, 651–665.
352   Nikolaeva, K., Gerya, T. V., Marques, F. O., 2010. Subduction initiation at passive margins: Numerical modeling. J.
353   Geophys. Res. 115, B03406. https://doi.org/10.1029/2009JB006549
354   Nikolaeva, K., Gerya, T. V., Marques, F. O., 2011. Numerical analysis of subduction initiation risk along the
355   Atlantic American passive margins. Geology 39, 463-466. https://doi.org/10.1130/G31972.1
356   Niu, Y., O'HARA, M. J., Pearce, J. A., 2003. Initiation of subduction zones as a consequence of lateral
357   compositional buoyancy contrast within the lithosphere: a petrological perspective. Journal of Petrology, 44(5),
358   851-866. https://doi.org/10.1093/petrology/44.5.851
359   Riel, N., Duarte, J. C., Almeida, J., Kaus, B. J., Rosas, F., Rojas-Agramonte, Y., & Popov, A. (2023). Subduction
360   initiation triggered the Caribbean large igneous province. Nat Commun 14, 786 (2023).
361   https://doi.org/10.1038/s41467-023-36419-x
362   Rudyawan, A., & Hall, R. (2012). Structural reassessment of the South Banggai-Sula area: no Sorong fault zone. In:
363   Proceedings of the Indonesian Petroleum Association, 36th Annual Convention, Indonesian Petroleum
364   Association, Jakarta, Indonesia, IPA12-G-030 1–17.
365   Sandwell, D. T., Smith, W. H. F., 2009. Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge
366   Segmentation versus spreading rate. J. Geophys. Res. Atmosphere, 114(B1): B01411.
367   https://doi.org/10.1029/2008JB006008
368   Schlüter, H. U., Block, M., Hinz, K., Neben, S., Seidel, D., & Djajadihardja, Y., 2001. Neogene sediment thickness
369   and Miocene basin-floor fan systems of the Celebes Sea. Marine and petroleum geology, 18(7), 849-861.
370   https://doi.org/10.1016/S0264-8172(01)00027-7
371   Seton, M., Müller, R. D., Zahirovic, S., Williams, S., Wright, N. M., Cannon, J., Whittaker, J. M., Matthews, K. J.,
372   & McGirr, R. (2020). A global data set of present-day oceanic crustal age and seafloor spreading parameters.
373   Geochemistry, Geophysics, Geosystems, 21(10), e2020GC009214. https://doi.org/10.1029/2020GC009214
374   Shuck, B., Gulick, S.P.S., Van Avendonk, H.J.A. et al., 2022. Stress transition from horizontal to vertical forces
375   during subduction initiation. Nat. Geosci. 15, 149–155. https://doi.org/10.1038/s41561-021-00880-4
376   Silver, E. A., Mccaffrey, R., Smith, R. B., 1983. Collision, Rotation, and the Initiation of Subduction in the
377   Evolution of Sulawesi, Indonesia. J. Geophys. Res. 88, 9407-9418. https://doi.org/10.1029/JB088iB11p09407
378   Stern, R. J., 2004. Subduction initiation: spontaneous and induced, Earth Planet. Sci. Lett., 226(3-4), 275-292.

379   https://doi.org/10.1016/s0012-821x(04)00498-4
380 Stern, R. J., Gerya, T., 2018. Subduction initiation in nature and models: A review, Tectonophysics, 746, 173-198.
381   https://doi.org/10.1016/j.tecto.2017.10.014
382 Toth, J., Gurnis, M., 1998. Dynamics of subduction initiation at preexisting fault zones. J. Geophys. Res. Solid
383   Earth, 103(B): 18053-18067. https://doi.org/10.1029/98JB01076
384 Turcotte, D. L., & Schubert, G., 2014. Geodynamics. Cambridge, UK: Cambridge University Press.
385 Wolfgang Bangerth, Juliane Dannberg, Menno Fraters, Rene Gassmoeller, Anne Glerum, Timo Heister, & John
386   Naliboff. (2021). ASPECT v2.3.0 (v2.3.0). Zenodo. https://doi.org/10.5281/zenodo.5131909
387 Zhou, X., Li, Z. H., Gerya, T. V., Stern, R. J., 2020. Lateral propagation-induced subduction initiation at passive
388   continental margins controlled by preexisting lithospheric weakness. Sci. Adv., 6, eaaz1048.
389   https://doi.org/10.1126/sciadv.aaz1048
390 Zhou, X., Li, Z. H., Gerya, T. V., Stern, R. J., Xu Z., Zhang J., 2018. Subduction initiation dynamics along a
391   transform fault control trench curvature and ophiolite ages. Geology, 46(7), 607-610.
392   https://doi.org/10.1130/G40154.1

393 References From the Supporting Information

394 Hirth, G. & Kohlstedt, D., 2003. Rheology of the upper mantle and the mantle wedge: a view from the
395   experimentalists. in Inside the Subduction Factory (ed. Eiler, J.) Vol. 183 of Geophysical Monograph
396   (American Geophysical Union)
397 Gleason, G. C., & Tullis, J., 1995. A flow law for dislocation creep of quartz aggregates determined with the molten
398   salt cell. Tectonophysics, 247(1-4), 1-23. https://doi.org/10.1016/0040-1951(95)00011-B
399 Glerum, A. C., Thieulot, C., Fraters, M., Blom, C., Spakman, W., 2018. Nonlinear viscoplasticity in ASPECT:
400   benchmarking and applications to subduction. Solid Earth 9, 267–294. https://doi.org/10.5194/se-9-267-2018
401 Wilks, K. R., & Carter, N. L., 1990. Rheology of some continental lower crustal rocks. Tectonophysics, 182(1-2),
402   57-77. https://doi.org/10.1016/0040-1951(90)90342-6
403 Ranalli, 1995. Rheology of the Earth. 2nd ed. London: Chapman & Hall.
404 Rybacki, E., Gottschalk, M., Wirth, R., Dresen, G., 2006. Influence of water fugacity and activation volume on the
405   flow properties of fine-grained anorthite aggregates. J. Geophys. Res. Solid Earth, 111, 3663.
406   https://doi.org/10.1029/2005JB003663
407

408   **Figure 1**. (a) Oceanic basins and subduction zones in Southeast Asia. The ages of the oceanic
409   basins are taken from Seton et al. (2020). NBS indicates the North Banda Sea, and SBS indicates
410   the South Banda Sea. (b) Bathymetric image of the North Banda Sea and surrounding regions,
411   taken from Fig. 7 in Hall (2019). (c) Subducted Celebes Sea Plate in the North Sulawesi and
412   Cotabato trenches (the gray irregular polygons indicate the shape of the subducting plate
413   projected onto the surface, while the red irregular polygons are reconstructions of the subducted
414   plate). (d) Diagram of subducted plate reconstruction to the surface. The black line represents the
415   subducted slab. The calculated length is shown on the surface as a red line. The slab dip along
416   the C–D profile was not certain from earthquake events and was extracted from the Slab2 model
417   (Hayes et al., 2018).

418   **Figure 2.** (a) Initial stage showing the triangular indenter structure to simulate curved margins,
419   the base length of the indenter (D), and the angle of the indenter (α). A zoom-in of the
420   computational mesh shows that the minimum resolution is ~3 km. (b) Plate strength and density
421   contrast between the oceanic and overriding plates. (c) Indenter geometries in different model
422   experiments.

423   **Figure 3**. (a) Final results of Models 0–3 showing only the oceanic crust and suboceanic
424   lithospheric mantle. Models 1–3 have the same D (200 km) and different angles (α). (b) Sections
425   through end results (at 3.2 Myr) for Model 2 at $y = 0$ km (front), $y = 200$ km (middle), and $y =$
426   400 km (back). The oceanic slab reaches a depth of 200 km faster in the middle than in the front
427   and back. The colors indicate the composition, as defined in Figure 2a.

428   **Figure 4**. Sections through models at $z = 0$ km. (a) Shear stresses (τ_{xy}) on the surfaces of Models
429   1, 2, and 3 at the initial stage. (b) Evolution of the indenter geometry. The dashed lines represent
430   the lengths of D and h in the initial stage. Δh represents the decrease in the length of h. The black
431   arrows indicate the velocity.

Figure 1.

(a)

(b) Sula Deep, North Banda Sea, Tolo Trough

(c) Celebes Sea, Cotobato Trench, North Sulawesi Trench, 40 km, 80 km

(d)

Figure 2.

(a)

2000 km

400 km

z

x

0

y

Oceanic Plate

D

h

α

Overriding Plate

Close up view

15 km

25 km

35 km

200 km

- oceanic crust
- upper crust
- lower crust
- subcontinental lithospheric mantle
- weak zone
- suboceanic lithospheric mantle
- asthenospheric mantle

(b)

Plate Strength Contrast (MPa)

0   200   400   600

Depth(km)

0

20

40

60

80

100

0   200   400   600

Density Contrast (kg/m³)

(c)

0

D

h

1 2 3

4 5 6

7

8 9 10

Figure 3.

(a)

Model 0(t=4.7 Myr)

Model 1 (t=5. 0 Myr)
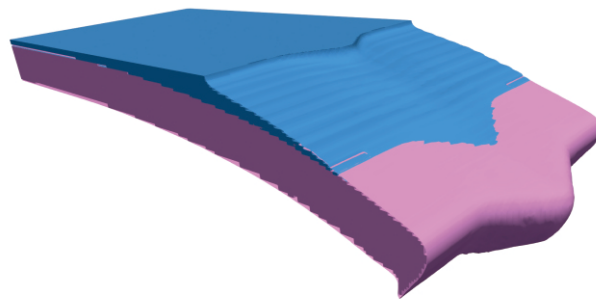
Model 2 (t=3.2 Myr)
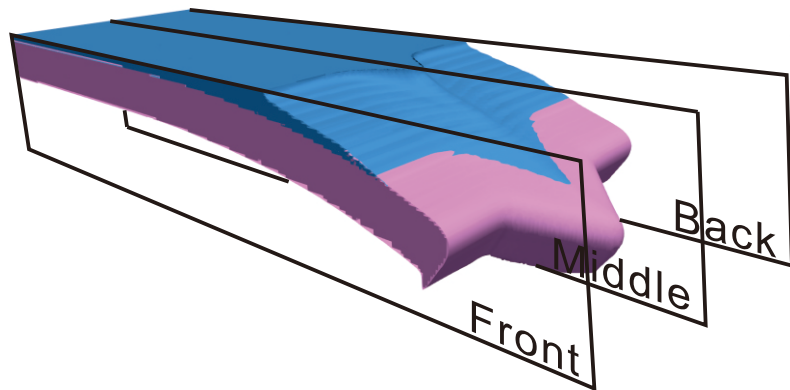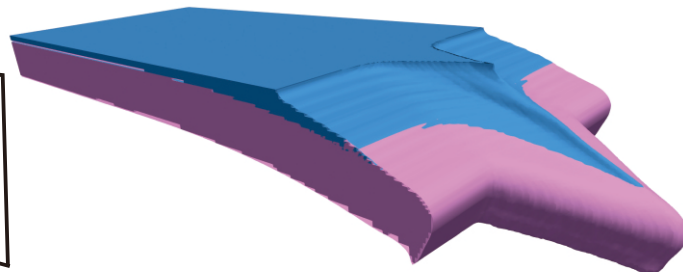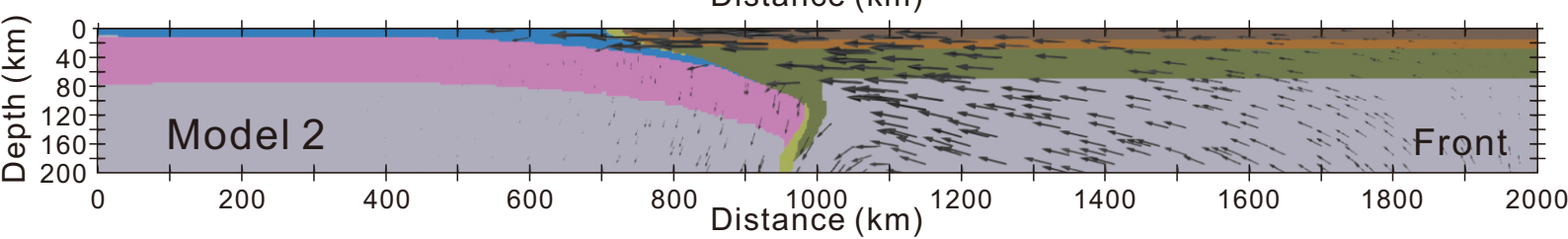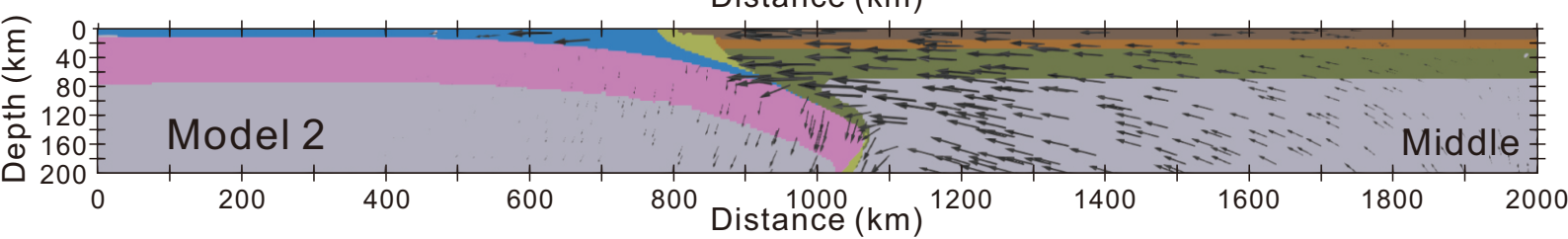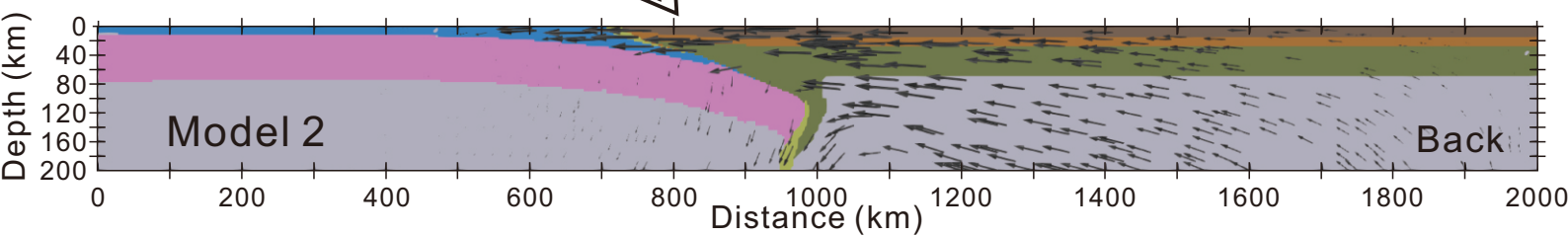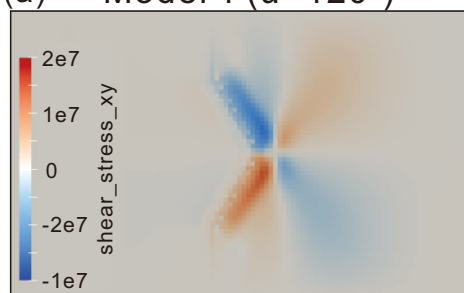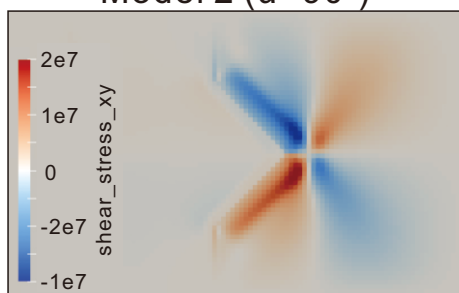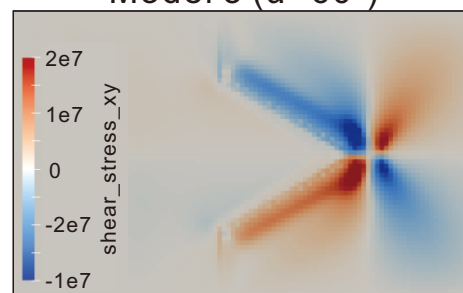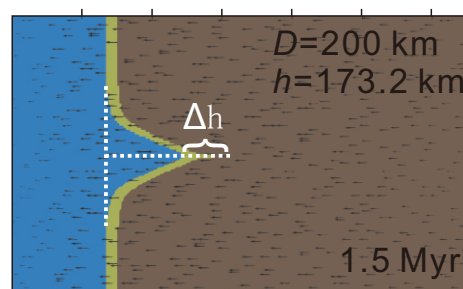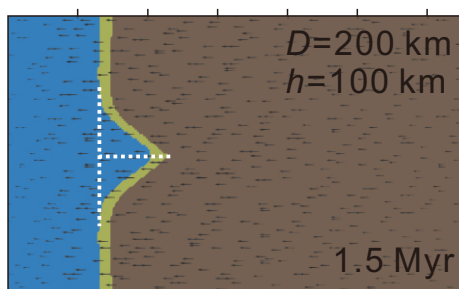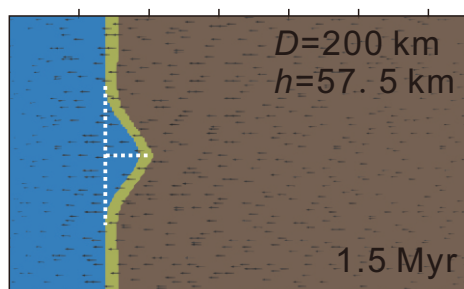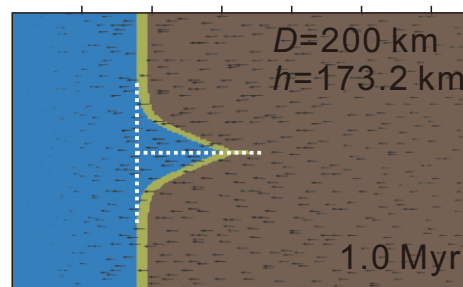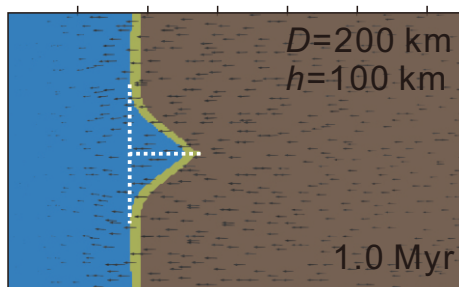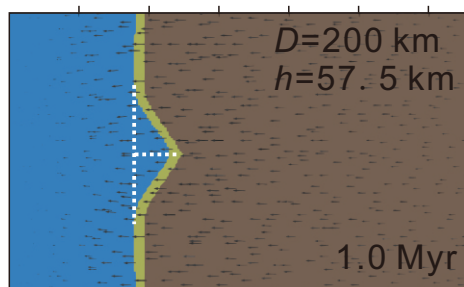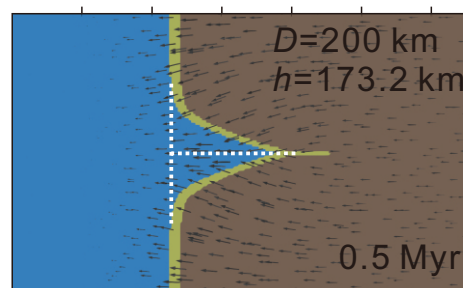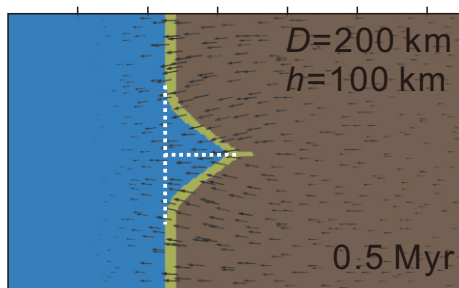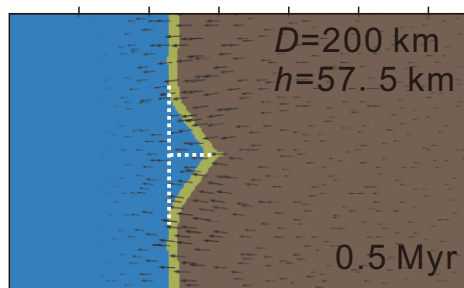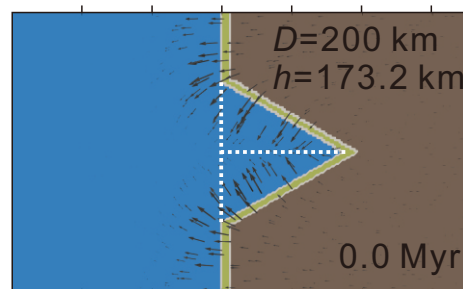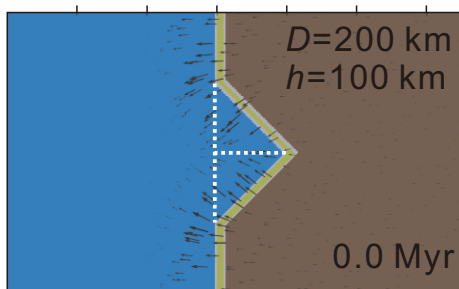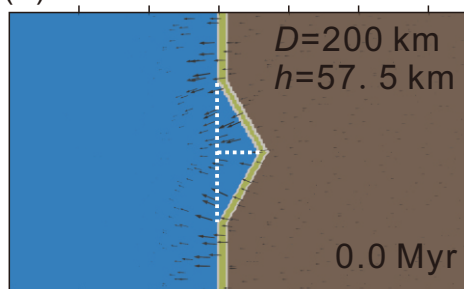
Back

Middle

Front

Model 3 (t=2.1 Myr)

(b)

Model 2 · · · · · · · · · · Back

Model 2 · · · · · · · · · · Middle

Model 2 · · · · · · · · · · Front

Figure 4.

(a)

Model 1 (α=120°)   Model 2 (α=90°)   Model 3 (α=60°)

shear_stress_xy

(b)

D=200 km   D=200 km   D=200 km
h=57.5 km   h=100 km   h=173.2 km

0.0 Myr   0.0 Myr   0.0 Myr

D=200 km   D=200 km   D=200 km
h=57.5 km   h=100 km   h=173.2 km

0.5 Myr   0.5 Myr   0.5 Myr

D=200 km   D=200 km   D=200 km
h=57.5 km   h=100 km   h=173.2 km

1.0 Myr   1.0 Myr   1.0 Myr

D=200 km   D=200 km   D=200 km
h=57.5 km   h=100 km   h=173.2 km

Δh

1.5 Myr   1.5 Myr   1.5 Myr

800 1000 1200   800 1000 1200   800 1000 1200

Table 1. Description of numerical experiments with varying length and angle of the indenter

Model	D (km)	α (°)	h (km)	Time of subduction initiation ± 0.1 (Myr)
0	0	180	0	4.7
1	200	120	57.7	5.0
2	200	90	100	3.2
3	200	60	173.2	2.2
4	115.4	120	33.3	4.8
5	115.4	90	57.7	4.2
6	115.4	60	100	2.8
7	66.6	60	57.7	3.6
8	346.4	120	100	4.5
9	346.4	90	173.2	4.3
10	346.4	60	300	2.4