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Unravelling topography around subduction zones from laboratory models

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Abstract

The relief around subduction zones results from the interplay of dynamic processes that may locally exceed the (iso)static contributions. The viscous dissipation of the energy in and around subduction zones is capable of generating kilometer scale vertical movements at the surface. In order to evaluate dynamic topography in a self-consistent subduction system, we carried out a set of laboratory experiments, wherein the lithosphere and mantle are simulated by means of newtonian viscous materials, namely silicone putty and glucose syrup. Models are kept in their most simple form and are made of negative buoyancy plates, of variable width and thickness, freely plunging into the syrup. The surface of the model and the top of the slab are scanned in three dimensions. A forebulge systematically emerges from the bending of the viscous plate, adjacent to the trench. With a large wavelength, dynamic pressure offsets the foreside and backside of the slab by ~ 500 m on average. The suction, that accompanies the vertical descent of the slab depresses the surface on both sides. At a distance equal to the half-width of the slab, the topographic depression amounts to \sim 500 m on average and vanishes at a distance that equals the width of the slab. In order to explore the impact of slab rollback on the topography, the trailing edge of the plates is alternatively fixed to (fixed mode) and freed from (free mode) the end wall of the tank. Both the pressure and suction components of the topography are $\sim 30\%$ lower in the *free* mode, indicating that slab rollback fosters the subsidence of upper plates. Our models are compatible with first order observations of the topography around the East Scotia, Tonga, Kermadec and Banda subduction zones.

Key words: subduction, dynamic topography, dynamic pressure, forebulge, analogue modeling

1 1 Introduction

The topography results from a variety of processes that, around subduction 2 zones more than anywhere else, have strong spatial gradients. At the surface 3 of the Earth, the conjunction of these processes not only produces the most 4 important deviations from the geoid (outlined by the 5-10 km deep trenches), but also the largest topographic slopes, offshore and onshore. The topographic 6 expression of subduction zones is viewed as the juxtaposition of a depressed 7 bathymetry of the overriding plate, a deep trench, an outer rise (or forebulge). 8 This structure correlates well with the gravity signal, in particular long wave-9 length geoid highs that correspond to the density anomalies of the subducted 10 slabs, overprinted by sharp free air lows over the trenches that highlight the 11 dynamic nature of the topographic depression, and an intermediate scale free 12 air low that highlights the dynamic deflection of the overriding plate [1-5]. 13

In fact, the processes that generate the total relief can be separated into the 14 static components of the relief, that are primarily due to the lateral density 15 variations within the lithosphere, and the more elusive dynamic topography 16 that is, within its common geophysical sense, the response of the surface to 17 the stresses that arise from the underlying mantle flow [6-9]. The process 18 is presumably rather well known in theory, and a vast amount of work has 19 focussed on explaining a variety of transgressive episodes thanks to models 20 of dynamic topography around subduction zones [10-12,5,13-16]. However, 21 the magnitude and wavelength remains highly uncertain (see e.g. Krien and 22 Fleitout [17]). Indeed, even if many of the cited applications are appealing, 23 Wheeler and White [18] conversely found no significant dynamic topography 24 in South East Asia, where it is presumably represented at best, above the 25 largest concentration of slabs at present-day. Uncertainty persists for several 26 reasons. 27

First, the observation of the topography of the Earth around subduction zones
is blurred by the convolution of complex mechanisms, and therefore requires
meticulous analysis of, for instance, the admittance of topography and gravity

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³¹ signals [19]. But only a clear conception of the structure of the lithosphere
³² at a global scale, and at a degree that is almost always beyond our current
³³ knowledge, could definitely solve this issue.

Second, confusion may arise from the definition of dynamic topography. In fact, several components of the topography have a dynamic origin, and coining it to the sole contribution of mantle flow underneath the lithosphere is not only restrictive but misleading. In particular around subduction zones, a variety of dynamic processes lead to the formation of, for the most obvious parts, the forebulge and the trench.

Third, a variety of studies have individually explored the different mechanisms, 40 predicting a plausible relief that integrates all such processes is theoretically 41 rendered possible thanks to numerical models, even in three dimensions. How-42 ever, at this stage, many technical challenges (free surface condition, three-43 dimensional aspect) or mechanical issues (one-sided subductions, trench be-44 havior, etc...) make numerical simulations around subduction zones neither 45 definitive nor consensual. In fact, only few attempts were done to capture all 46 the elements of the topography around subduction zones together [3, 4, 20, 21]. 47 48

Analogue models may offer an alternative. In this paper, we thus build upon 49 classic analogue models of subduction zones [22–24] to unravel the topography 50 around subduction zones. The following experiments therefore represent a first 51 attempt to model the topography around subduction zones self-consistently, 52 *i.e.* by examining the case of *free* subductions, wherein the dynamics is only 53 driven by the buoyancy of the slab and resisted by the viscous flow in the 54 surrounding mantle. Such setting is rendered possible thanks to the advantages 55 of laboratory models. 56

57 2 The models

58 2.1 Experimental setup

We carried out a set of 13 experiments that essentially reproduce the lines 50 of the experiments of [22] or [24] (Supplementary material 1). We use silicone 60 putty (Rhodrosil Gomme, PDMS + iron fillers) and glucose syrup to model the 61 lithosphere and the upper mantle, respectively. Silicone putty is a viscoelastic 62 material but its Maxwell time (< 1 s) precludes any elastic behavior in our 63 models lasting several minutes. Glucose syrup is a transparent Newtonian low-64 viscosity and high-density fluid. These materials have been selected to achieve 65 the standard scaling procedure for stresses scaled down for length, density and 66

viscosity in a natural gravity field as described by Weijermars and Schmeling
[25] and Davy and Cobbold [26].

⁶⁹ The scale factor for length is 1.5×10^{-7} (1 cm in the experiment corresponds ⁷⁰ to 66 km in nature) (Table 1). Densities and viscosities are assumed to be ⁷¹ uniform over the thickness of the individual layers and are considered to be ⁷² averages of the actual values. For the reference model, described hereafter, ⁷³ the negative buoyancy of the lithosphere is -91 kg/m³ (Table 1). The viscosity ⁷⁴ ratio between the slab and the surrounding mantle (η_l/η_m) is 1.4×10^4 . This ⁷⁵ value appears to be an upper bound according to recent studies [21,27–30].

76 2.2 Experimental procedure

The system is disposed in a 80 cm wide square tank (fig. 1). The experimental 77 subduction is always initiated by artificially forcing the leading edge of the 78 silicone plate into the glucose downward to a depth of 3 cm (corresponding 79 to about 200 km in nature). We complemented the standard setup [22] by 80 adding a laser scan (put the reference of the old laser? I don't have 81 them) above the tank and digitize the deforming topography. The laser is 82 capable of acquiring the topography with a maximum horizontal resolution 83 of 0.13 mm. The precision of punctual topographic data is 0.05 mm (this is 84 for new laser), which considerably improves when a statistical treatment is 85 applied. In the following, we refer to the side of the unsubducted portions of 86 the plate as the foreside and conversely, the backside is the region above the 87 sunken slab (fig. 1). 88

For modeling conveniency, each experiment is separated into two sub-expe-89 riments. The first stage of the experiments takes place within the framework 90 of fixed edge subduction sensu Kincaid and Olson [31], i.e. the trailing edge of 91 the slab is attached to the tank in order to preclude any trenchward motion 92 of the silicone plate. When steady state is reached (when the generic S shape 93 of the retreating slab is reached and the geometry remains unchanged in the 94 referential of the moving trench), the shape of the silicone slab is scanned 95 before the surface is spray-painted (in order to overcome optical issues due to 96 the translucency of the glucose syrup) and scanned as well. When all measure-97 ments are done, the trailing edge of the silicone slab is freed from the tank, and 98 the subduction enters a *free edge* mode for a second sub-experiment. Because 99 the surface remains painted from the first stage, it is technically impossible to 100 scan the surface of the slab at depth without strongly damaging the experi-101 ment. Only the topography of the surface of the model is thus acquired when 102 a new steady state is reached. 103

104 2.3 Force balance

Our simplified subduction system is designed in order to impose a straight-105 forward force balance that approximately reproduces that of plate tectonics: 106 the slab drives the flow in the glucose syrup and is resisted by the viscous 107 dissipation in the glucose syrup and slab. It simply reads $F_{sp} + F_{rp} = F_v + F_b$, 108 where F_{sp} is the slab pull force, with $F_{sp} = (\rho_l - \rho_m)gWz_s \frac{H}{\sin\alpha}$, where g is 109 the gravitational acceleration, H and W the thickness and width of the slab, 110 z_s the depth of the leading edge of the slab ($z_s = D$ in steady state, where 111 D is the thickness of the glucose syrup layer), and α the dip of the slab. 112 $F_{rp} = (\rho_l - \rho_m)g\frac{H^2}{2}$ is the ridge push force, which in the *free* mode is negligible 113 with respect to the slab pull force [22]. In the *fixed* subduction mode, the situ-114 ation differs because of the no motion boundary condition. This kinematic (as 115 opposed to dynamic) condition implies that F_{rp} constantly adjusts to balance 116 the trenchward force that applies to the plate. That force is the opposite of 117 the integral of the trench perpendicular component of the horizontal shear 118 stresses underneath the lithosphere. These stresses result from the underlying 119 viscous flow in the syrup, ultimately excited by the subduction of the slab. 120 Paradoxically in that mode, the sign of F_{rp} implies that, as opposed to the 121 situation on Earth, it is a resisting force. 122

 F_b is the bending force of the silicone slab. Funiciello et al. [27] computed the 123 total value of F_b by integrating its local values along the bent lithosphere, 124 such that $F_b = \int_i \frac{2}{3} W \eta_l v_{sub} (H_i/r_i)^3 di$, where H_i is the varying thickness of the 125 slab alongside the slab length and r_i is the varying radius of curvature. η_l is 126 the dynamic viscosity of the silicone putty and v_{sub} is the subduction velocity. 127 The viscous dissipation due to slab bending in our models (10 to 30% [27]) 128 is possibly slightly overestimated compared to that of the Earth. First, it is 129 counted twice because the plate bends at the surface, but also at the bottom 130 of the tank, where the slab retrieves a flat, horizontal geometry. In addition, 131 because our slab to mantle viscosity ratios, when scaled to the Earth, are in 132 the high end of the inferred range of values [27,32,30], the bending force may 133 be high. In real Earth, it is now thought that the bending dissipates less than 134 $\sim 25\%$ of the energy [29], and even more likely between 5 and 20\% [33]. 135

Last, the viscous force F_v that stirs the glucose syrup is more difficult to assess; there is no proper analytical solution besides scaling F_v with $\eta_m v$ (where v is the rate at which the slab rolls back). Indeed, this is particularly unfortunate because that viscous flow is responsible for the long wavelength dynamic distortion of the surface.

141 2.4 Limitations of the model

Before going further, a few limitations that are intrinsic to our models should 142 be outlined. First of all, the seldom discussed surface tension [34,35] affects 143 the dynamics of our experiments. In a sense, surface tension can conversely 144 be regarded as fortunate, because it coincidentally holds at the surface the 145 silicone plates, whose buoyancies fall within the desired range of exploration, 146 and let them sink beyond. However this is not an Earth-like property and 147 as such it may alter the interpretation of subduction dynamics. In addition, 148 the paint layer may also modify the surface tension of the fluid with respect 149 to the experiments that are exempt of paint. The effect of surface tension is 150 critical only when the slab buoyancy forces are low enough to be comparable 151 to that of surface tension. It could explain the non-linear behaviour of some 152 analogue models. For instance, in the experiments of Schellart [23], subduction 153 kinematics do not scale linearly with slab buoyancy, that is presumably the 154 only varying parameter of the experimental serie. However, such non linearities 155 are not striking in the experiments of Funiciello et al. [22]: during the early 156 stages of subduction, trench retreat rates seemingly increase almost linearly 157 with the slab pull force. Therefore, we assume that the role of surface tension, 158 although non negligible [35], doesn't significantly bias our results, but should 159 be carefully considered when full parametric studies are carried out. 160

Second, our models have no overriding plates. In precursory models, [36] suc-161 cessfully overcame this issue by adding a viscous upper plate and measuring 162 the elevation changes throughout the experiment. This was suited for their 163 applied experiments, but added some noise to the results. Here instead, as in 164 the seminal experiments of subduction zones [22–24], we simplify the models 165 in order to extract the quintessential processes that shape the surface of the 166 Earth around subduction zones, but also to evaluate the feasibility of such 167 technique from a general standpoint. We are well aware that introducing up-168 per plate changes the subduction dynamics [17,37,38], but a full parametric 169 study, that would explore a variety of boundary conditions (including upper 170 plates) is beyond the scope of this paper. 171

Third, the tank is not infinite, which often appears satisfying enough for the 172 study of subduction dynamics in general [22–24]. However, given that the very 173 distribution of the stresses within the flowing glucose syrup controls the to-174 pography, its perturbation by the non-infinity of the tank plays a role. This 175 imposed condition nevertheless partly compares to real Earth, wherein slabs 176 neither sink into an infinite mantle nor evolve within a domain bounded by 177 undeformable, finite boundaries. This intermediate situation is often mislead-178 ing when comparing real Earth subduction dynamics to simplified models that 179 display framed isolated systems. 180

181 **3 Results**

All our models follow comparable evolutions. Once steady state is reached, the 182 slab is folded twice, at the surface and at the bottom of the tank, where it lit-183 erally unfolds. Subduction freely occurs: it is driven by the sole slab buoyancy 184 and resisted by the viscous flow in the glucose syrup. The slab enters a classic 185 rollback subduction mode. The trench therefore retreats while the slab sweeps 186 back into the glucose syrup, which in turn is displaced from the foreside to 187 the backside of the model thanks to a combination of toroidal and poloidal 188 flows [39,40,28] (fig. 2). When it enters the *free* subduction mode, the plate 189 moves trenchward, therefore reducing the rates of slab rollback ($\sim 12\%$ for 190 model 1 for instance). The slab consequently becomes steeper. The dynamics 191 of subduction, *i.e.* the motion of the slab and the viscous flow in the glucose 192 syrup, excited by the very motion of the slab, alter the static force balance 193 and reshape the surface of the Earth. Our models allow to unravel the various 194 components. 195

¹⁹⁶ 3.1 Departure from isostasy as an indicator of the force balance in the system

The depth h of the silicone layer relative to the glucose syrup is in principle, 197 in isotatic conditions, determined by the buoyancy of the layer, such that h =198 $\int_{H} \frac{\rho_l - \rho_m}{\rho_m} dz$, where ρ_m and ρ_l are the densities of the glucose syrup and of the 199 silicone putty, H being the thickness of the silicone layer. Indeed, unsubducted 200 portions of the slab lay at greater depths than the adjacent glucose syrup. This 201 component dominates at the large scale and explains the first order observation 202 of the topography (figs. 2, 3 and 4). (Note that, unlike the Earth's lithosphere, 203 the silicone layer is not bounded by neighboring plates and therefore elevation 204 decreases stepwise from the adjacent glucose syrup. This discontinuity would 205 cause the silicone plate to subduct if surface tension was not high enough 206 to prevent this from happening, as illustrated by the meniscuses that make 207 the transition from the elevation of the glucose syrup to that of the silicone 208 plate, fig. 4b). Note that this it is not surface tension that plays this role on 209 Earth but the fact that oceanic plates are not in isolation from one another. 210 It is simply the lateral continuity of the lithospheres that prevents the lighter 211 underlying mantle from welling above the plates. 212

A closer examination of the topography reveals that it departs from isostasy at different spatial scales, that are due to the dynamic evolution of the system. The viscous dissipation of the energy modifies the static equilibrium. It bends the silicone plate, which produces some relief, and stirs the glucose syrup, which also deforms the surface. In the glucose syrup, the viscous dissipation can be separated into the poloidal (in the vertical plane) and toroidal (in the horizontal plane) components. The retrograde motion of the slab into the syrup modifies the horizontal stress field and its descent into the fluid induces the vertical one. The convolution of these dynamic processes causes, across subduction zones on Earth, a variety of features that can be deciphered thanks to our integrative experiments.

224 3.2 Trench

The most obvious feature that departs from the static topography is naturally 225 the trench (figs. 3, 4 and 5). Trench depths reach \sim 3-4 mm and do not vary 226 significantly from the *fixed* mode subduction mode to the *free* mode (fig. 4a). 227 Along-strike (parallel to the trench), the trench is almost uniformly deep; only 228 at very short distances (less than a fifth of the slab width) from the slab edges 229 does it shallow (fig. 3); this highlights that this structure is essentially two-230 dimensional, across strike. In real Earth, the depth of the trench is determined 231 by the shear coupling between the upper and lower plates on the interplate 232 fault [4,41]. Our model is purely viscous and there is therefore no proper 233 subduction fault that could be defined by a yield stress. Instead, the depression 234 results from the competition between the buoyancy stresses in the glucose 235 syrup, that tend to restore uniformity, and the shear stresses exerted by the 236 subducting slab that impose the downward flow of the glucose syrup. The 237 main difference is that the flow in the wedge has a boundary condition that is 238 more kinematic, imposed by the subduction rate, than dynamic, *i.e.* defined 239 by a shear stress. The glucose syrup at the interface therefore must flow along 240 with the subducting plate. Note that part of the apparent trench in our models 241 is a meniscus from surface tension (see above). Scaled to the Earth, predicted 242 trench depths amount to 20-25 km, which seems impressively unrealistic, but 243 is in fact only approximately two to three times larger than actual trenches 244 (after sediments are stripped off). 245

246 3.3 Viscous bulge

Adjacent to the trench is the forebulge on the silicone plate (figs. 3, 4 and 5). 247 Bulges in our experiments result from the viscous flexure of the silicone plate. 248 Their 0.15 to 0.2 mm high, 75 ± 25 mm wide, elongate bodies lie parallel to 249 the trench, at a distance that varies of ~ 50 mm in the *free* mode and ~ 44 mm 250 in the *fixed* mode. This difference arises from the fact that slabs are steeper in 251 the *free* mode, a fact that doesn't affect the elevation of the bulge that remains 252 comparable in both cases. This may be explained by the fact that subduction 253 rates play a a fundamental role. Indeed, if the rate of trench retreat is lower 254 of 12% in the *free* mode, the subduction rate remains comparable. 255

Contrarily to the trench, the bulge reaches its maximum elevation near the edges of the plate, and not in the center (figs. 3 and 5). This observation is somewhat surprising given the fact that the flexure of a viscous plate is *a priori* a two-dimensional problem and as such, there is no intrinsic reason for the bulge to have its elevation vary along-strike. It results from the interaction with the suction component, which is larger in the center of the slab that at the edges (see section 3.5).

In theory, the viscous flexure of the plate is periodic, and the magnitude of the 263 oscillation diminishes exponentially towards the foreside [42,43]. The forebulge 264 should therefore be followed by a deflection, but its magnitude is too small 265 to be detected in our experiment. Not surprisingly, the plate flexure follows 266 the universal deflection profile [42]. Scaled to the Earth, the modeled bulges 267 are 1.0 to 1.3 km high and 500 \pm 175 km large. The distance between the 268 maximum elevation of the bulge and the trench varies from ~ 335 km to ~ 300 269 km, depending on the mode. Our models here reemphasize the possibility that 270 the observed outer rises are due to the viscous nature of the lithosphere [43,41]. 271

272 3.4 Overpressure

The depth of the silicone plate is systematically offset by $\sim 100 \ \mu m$, with 273 respect to the theoretical, isostatic depth, when the subduction occurs in a 274 fixed mode, and is 30% smaller on average in the *free* subduction mode (fig. 275 4a). This is a first order response of the topography to the underlying force 276 balance, in the glucose syrup. The retrograde motion of the slab compresses 277 the glucose syrup in the foreside and conversely, extends it in the backside. The 278 situation is somewhat similar to that of a channel flow between the slab itself 279 and the end wall of the tank, such that $\frac{dp}{dy} = 12\eta_m \frac{\bar{v}}{L^2}$, where $\frac{dp}{dy}$ is the pressure gradient in the channel parallel to the slab, η_m is the dynamic viscosity of the 280 281 glucose syrup, \bar{v} is the mean velocity in the channel, and L is the width of the 282 channel. Mass conservation imposes that $\bar{v}L = u\frac{W}{2}$, where u is the horizontal velocity of the slab and $\frac{W}{2}$ is the half width of the slab. The mean pressure 283 284 in the channel is $\bar{p} = \frac{3}{2} \eta_m \frac{uW^2}{L^3}$. That dynamic pressure is compensated by a 285 mean deflection of the surface that reads 286

287
$$\bar{\delta}_z = \frac{3\eta_m}{2\rho_m g} \frac{uW^2}{L^3}.$$
 (1)

²⁸⁸ *u* is counted negative on the backside and positive on the foreside, therefore ²⁸⁹ the two effects amplify the total elevation offset between the front and back ²⁹⁰ of the slab, which therefore approximately equals $2\bar{\delta}z$ (if the slab plunges into ²⁹¹ the syrup at an equal distance from each end of the tank). It gives a order of ²⁹² magnitude for $2\bar{\delta}z$ of 5 to 100 μm depending on the experimental values. The

scaled magnitude of the offset is thus 35 to 700 m, depending on the forces 293 at play and on the subduction mode. These results are in the lower bound 294 of our observations which reveals that this approximation may not be robust 295 enough to be further developed. In particular, because the finite geometry of 296 the tank in which the channel is embedded is not accounted for, the channel 297 flow analogy does not permit to explain the uplifted topography outside the 298 channel proper, on the glucose syrup adjacent to the slab. It is nevertheless 299 obviously related to the same overpressure induced by the retrograde motion 300 of the slab (fig. 1). Indeed in our models, the overpressure effect occupies the 301 entire surface of the tank. It induces an overall tilt of the surface and is not 302 restricted to the surface of the plate. This figure only partly compares to real 303 Earth where plates do not subduct in bounded domains (but neither sink in 304 an infinite mantle). 305

Because in the *free* subduction mode, part of the pressure is released when 306 the slab is free to move trenchward (*free subduction*), the elevation offset is 307 lower than the offset in the *fixed* mode (trench migration rates, and therefore 308 pressure, are lower); it then amounts to ~ 500 m on average. This can per-309 haps be more clearly conceived by stating this in a more rigorous way, that 310 reverses causes and consequences: the very reason why trenches roll back at 311 lower rates in the *free* subduction mode than in the *fixed* mode is indeed the 312 pressure drop between the fore and backsides of the slab. Overpressure on the 313 foreside, underpressure on the backside partly work to maintain the slab at a 314 central location in the tank. In the particular case where the pressure gradient 315 balances the slab normal component of the slab pull force, no roll back occurs 316 [20]; this situation is never met in our models. 317

318 3.5 Suction

At second glance, second order deflections burst out: the topography shows 319 a large scale deflection centered on the trench (figs. 2 and 3), the wavelength 320 of which is much larger than that of the trench. This is the dynamic re-321 sponse of the topography to the vertical motion of the slab, a largely debated 322 feature on Earth's subduction zones [3-5,44,18,45]. It is often referred to as 323 dynamic topography, despite the fact that the other topographic features, be-324 sides isostasy, are also *dynamic* in essence. The descent of the slab induces 325 stresses that are compensated by a vertical deflection of the topography δ_z , 326 so that $\delta_z = \sigma_{zz}/\rho_m g$, where σ_{zz} is the vertical stress due to the poloidal flow 327 in the glucose syrup. If forms a depression that is visible in both the foreside 328 and backside of the trench (figs 3 and 4). In the *fixed* subduction mode, the 329 measured magnitude of the deflection in our experiments is around 75 ± 50 330 μm at a distance W/2 (half width of the slab) from the trench, depending on 331 the forces in the presence and setting. This corresponds to 500 ± 330 m when 332

scaled to the Earth. The deflection reaches its largest magnitude in the center. 333 above the slab, and vanishes laterally, both along- and across-strike. The lat-334 eral extent of the anomaly is theoretically infinite in a linear viscous flow but 335 visual inspection of our experiments reveal that the magnitude of the dynamic 336 deflection becomes negligible at an approximate distance W from the trench. 337 On the foreside, the dynamic deflection combines with the short-wavelength, 338 large-magnitude features that are the trench itself and the forebulge (fig. 5). 339 Note that it shall not be confused with the secondary harmonic oscillation 340 of the viscous flexure, because the magnitude is incompatible. Typically, the 341 universal deflection curve for a viscous bulging gives a ratio between the mag-342 nitudes of the forebulge and of the depression that follows of about 1/100 [43] 343 after [42], which is considerably less than the 20 to 30% given by the ratio 344 between the elevation of the forebulge and the deflection. 345

Free subduction mode (fig. 3b) also naturally produces suction, but *fixed* sub-346 duction systems display wider and deeper dynamic deflections than free mode 347 ones by about 30%. The shape of the deflection relates to the distribution of 348 the mass anomalies at depth and therefore to the shape of the slab in our 349 experiments. Because in the *free* subduction mode, slabs are steeper [22], the 350 mass excess lays, on a map view, closer to the trench. This makes the wave-351 length of the dynamic deflection shorter. In addition, in the *free* subduction 352 mode, the total mass is smaller because the slab is steeper, and therefore 353 shorter (total mass varies like $D \sin \alpha$, where α is the slab dip angle). In our 354 experiments, slab dip increases from $\sim 60^{\circ}$ to $\sim 80^{\circ}$ between the *fixed* and 355 free modes (Ben, can you put in the correct values??. This decreases the 356 total mass anomaly by $\sim 15\%$, the slab pull by a similar amount and, if the 357 geometry remained the same, the magnitude of the dynamic deflection too. 358 Because the shape of the slab also changes in the experiment, the modification 359 is not linear, and the deflection in the *free* mode is also sharper. 360

Dynamic deflections are time-dependent and the successive scans that we per-361 formed during the transition from a *fixed* subduction mode to a *free* subduc-362 tion mode are also available. Similarly, we performed some experiments during 363 which the buoyancy of the slab that enters the subduction varies. This also 364 induces transient behaviors. Typically, the slab is made up of a succession of 365 segments of low and high buoyancies (models 12 and 13, see parameters in 366 Supplementary material 1). We monitored the transient topographic response 367 to the dynamics of subduction through time. As expected, low buoyancy seg-368 ments are accompanied by smaller dynamic deflections than high buoyancy 369 ones, and reciprocally. These transient regimes shall be compared to the geo-370 logical record around subduction zones. But this step shall not be envisioned 371 before steady regimes are understood and identified on Earth. 372

³⁷³ 4 Comparison to the figure of the Earth

Our simple setup resembles the Earth to some extent. It therefore permits to 374 quantify the relative importance of each of the contributors that shape the 375 figure of the Earth around subduction zones. In fact, a variety of models was 376 formerly designed at the scale of the subduction zone in order to explore the 377 relationships between the slab and dynamic topography. Few of them how-378 ever challenge the technical issue of incorporating mobile trenches, although 379 it is known to affect the response of the surface topography [20]. Because 380 they generally aim at quantifying dynamic topography of the overriding plate 381 and neglect the subducting plate, most models implicitly ignore the fact that 382 they constantly modify artificially the stress balance in order to maintain a 383 no rollback condition. The consequences of this choice are not trivial : trench 384 motion controls the flow around subduction zones -and therefore the stress 385 regime- to a degree that may have a profound impact on the flow pattern in 386 the wedge [46]. Imposing trench fixity barely resembles Earth-like conditions 387 and in our models, we adopt two alternative settings. The *fixed* mode con-388 siders that the stresses that resist the displacement of the subducting plate 389 are always large enough to oppose any motion. In that case, trench migration 390 rates equal subduction rates. This example is relevant to the Earth in many 391 instances. For instance, the small-scale subduction zones that are embedded 392 into bigger systems (like the fast Hellenic subduction zone within the slow 393 Africa-Eurasia convergent system, or the East Scotia subduction zone within 394 the South Atlantic). The *free* subduction mode instead assumes that plate 395 motion is dictated by the force balance at the subduction zone itself. This 396 mode could correspond to any larger subduction system (for instance, Nazca-397 South America) under the heavy assumption that the upper plate doesn't play 398 a crucial role in the force balance. In our experiments, *fixed* subduction sys-399 tems display wider and deeper dynamic deflections than *free* mode ones. Such 400 result is beyond what could be inferred by a comparison between the Nazca 401 and Hellenic subduction zones; in that sense, analogue models are helpful to 402 overcome observational issues. 403

The forebulge is a commonly described feature and it is no surprise that it is 404 well reproduced by our models. As opposed to the more popular elastic bulge 405 [2,42,47], our models predict that outer rises emerge from the flexure of viscous 406 slabs. This idea is however not new: similar geometries have been reproduced 407 with either viscous or elastic rheologies [43], or even with composite rheologies 408 [48,49]. However, given the fact that subducting slabs are dominantly treated 409 with viscous rheologies in the litterature, it is good to recall that outer rises 410 may be caused by a process that consistently obeys the same rules. Our models, 411 as many others, is capable of predicting the variable geometry of outer rises 412 to a degree that exceeds observations. In fact, flexure models became popular 413 although they mostly apply to the Aleutian, Kuril, Bonin, and Mariana, *i.e.* 414

a selection of well-behaved subduction zones that were chosen as early as the
70's to illustrate the theory [2]. Herein we wish to emphasize that, more than
the forebulge, that almost only depends on the rheology of the subducting
plate, or even the trench, it is the surface expression of the underlying viscous
flow that those experiments reveal with a new light.

Interestingly enough, the suction deflection appears on both the back and 420 for sides of the trench. Global models that are buoyancy driven [7-9,16] also 421 show this, because slabs are the prominent features in the Earth's mantle. But 422 again, models that are designed to investigate the relationships between the 423 subducting slab and the dynamic deflection of the upper plate do not consider 424 the dynamic topography on subducting plates but only focus on upper plates. 425 Our models show that subducting plates (foreside of our models) can also be 426 deflected downward by the suction effect of the underlying mantle flow, by 427 a comparable amount. The signal is not straightforward though, because al-428 though it is of opposed sign, this depression competes with the uplift due to 429 the overpressure underneath the foreside of the slab. Therefore, the net result 430 is a global uplift of the foreside, only modulated by the shorter wavelength 431 suction topography (fig. 5). The overpressure effect is expected to uplift the 432 subducting plate at a regional scale by 100 to 600 m. Only at short distance 433 from the trench, this effect should be counterbalanced by the opposite effect 434 of the suction. 435

436

In real Earth, the signal is often too blurred to detect the competition be-437 tween the two processes. It is nevertheless true that the bathymetry, to the 438 East of the East Scotia subduction zone is ~ 5000 m deep (fig. 6a), almost 430 1000 m deeper than the surrounding portions of the Atlantic plate of similar 440 age. The Tonga and Kermadec subduction zones (considered as two different 441 subduction zones separated by a slab tear from one another at the junction 442 with the Louisville ridge) display comparable relief: the seafloor to the East of 443 the Tonga trench (fig. 6b) lies at ~ 6000 m, and to the East of the Kermadec 444 trench at 5800 m (fig. 6b). In all three cases, the seafloor lies 500 to 1000 m 445 lower (avoiding seamounts) than the surrounding portions of the oceanic plate 446 of similar age. The distance at which the depression becomes insignificant is 447 comparable to the width of the trench, which is remarkably corroborating the 448 suction effect observed in our experiments. In addition, these depressed areas 449 are possibly embedded in wider zones that are themselves possibly at higher 450 elevations than more distal portions of seafloor of similar age. The ages of the 451 foresides of the East Scotia Sea is 30 to 50 Ma, that of Tonga is 90 to 100 452 Ma, and that of Kermadec is 90 to 120 Ma. The expected depth, compared 453 to the mean depths on Earth [50] are respectively 4800 ± 400 m, 5400 ± 400 m, 454 and 5500 ± 400 m. The seafloor, in all three cases is 200 to 600 m shallower 455 than the mean values for the Earth, which is in turn comparable to the pre-456 diction of the overpressure effect from our experiments (the observed offset is 457

 $\overline{\delta}_z$, not $2\overline{\delta}_z$ because only the overpressure on the foreside is measured). Last, 458 the inferred suction effect in the Tonga subduction zone is more pronounced, 459 by ~ 200 m, than in the adjacent Kermadec subduction zone. The subducing 460 plate in the Tonga and Kermadec subduction zones is presumably comparable 461 for it has the same nature. The only *a priori* differences between the two are 462 (i) a slightly older subducting slab in the South (Kermadec) than in the North 463 (Tonga), which should a contrario enhance the suction effect because of the 464 higher negative buoyancy, and (ii) a much faster slab rollback in the North 465 than in the South. The latter effect efficiently shapes the bathymetry: while 466 the Kermadec trench remains approximately stationary, the Tonga trench is 467 the fastest retreating trench on Earth, at about 160 mm/yr. This observation 468 supports our model results, which suggest that rollback fosters dynamic to-469 pography: dynamic deflections of the topography in the *free* subduction mode 470 are lower by $\sim 30\%$ than in the *fixed* mode. Similar conclusions where reached 471 by Russo and Silver [51], who envisioned the possibility that the shallow Nazca 472 plate could be uplifted by the underlying dynamic overpressure. These obser-473 vations certainly plead for the existence of dynamic deflection of the foreside 474 of the subduction zones too, but making the link between the two requires a 475 thorough analysis of the bathymetry and gravity. 476

On the backside however, the effects of dynamic pressure and suction have the 477 same polarity; the cumulated depression predicted by our models thus amounts 478 to 1200 ± 500 m. At large distances from the trench, only the underpressure 479 effect remains significant, with a downlift of 100 to 600 m. Many examples in 480 continental domains [12–15,36,52,53] display geological signatures that confirm 481 that upper plates are deflected by comparable magnitudes and wavelengths. 482 The long wavelengths of the afore cited examples highlight the importance 483 of the underpressure effect in continental inundation more than that of the 484 suction effect. 485

In oceanic domains, the underpressure effect on the backside is mode difficult 486 to track on Earth because few subduction zones display clear enough settings. 487 The few candidates are the Philippine plate (40-50 Ma) and the South Fidji 488 basin (20-30 Ma), that respectively lay at \sim 5900 m and \sim 4500 m. Their depths 489 are thus respectively ~ 1000 m and ~ 300 m deeper than the mean average 490 depth for seafloor of similar ages [50], which again pleads for a deflection 491 that is at least compatible with our model results. The suction effect on the 492 backside is more clearly expressed in oceanic domains. At short distances from 493 its trench, the 8000 m deep Weber trough in the Banda Sea (fig. 7a) represents, 494 in spite of its extremely young age (<3 Myrs), the deepest seafloor on Earth 495 besides trenches at present-day. It is more than 5000 m deeper than the mean 496 depth of oceanic units of similar age. Similarly, the residual topography of the 497 East Scotia sea back arc basin (fig. 7, modified after [5]) is deflected towards 498 its center by up to 1500 m at a short distance from the trench. Both examples 499 confirm that the suction effect of the underlying subducting slabs on Earth 500

⁵⁰¹ on upper plates is extremely efficient, in agreement with our models.

The topography in our models emerges from the stress balance and our scan-502 ning device allows for a three-dimensional illustration of it. Four dimensional if 503 one accounts for its time evolution. The results often go beyond observational 504 possibilities, and as such they are potentially useful. These tests revealed that 505 analogue models are capable of predicting the evolution of the topography 506 around subduction zones. Specifically, they meet the following criteria: they 507 have free surfaces, they are three dimensional, subduction process is purely 508 dynamic (no kinematic boundary condition), rollback freely occurs. This del-509 icate blend of conditions that are each individually still challenging to model 510 numerically makes our analogue models of use for the analysis and compre-511 hension of the dynamics of relief. Last, these models give a simple view of the 512 three dimensional nature of the topography around subduction zones by com-513 bining most processes that deform the surface of the Earth, but nevertheless 514 leave the possibility to extract each component independently, something that 515 is rendered difficult in real Earth, because of the uncertainty in the structure 516 of the lithosphere. 517

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	Parameters		Nature	Reference model	
g	Gravitational acceleration	m/s^2	9.81	9.81	
Length					
W	Subducting plate width	m	990000	0.15	
Н	Subducting plate thickness		100000	0.0152	
D	Upper mantle thickness		660000	0.10	
	Scale factor for length		$L_{model}/L_{nature} = 1.52 \times 10^{-1}$		
Buoyancy					
$\rho_m - \rho_l$	Subducting oceanic plate	kg/m^3	-80	-91	
			(80 Myr-old plate)		
	Scale factor for buoyancy		$\Delta \rho_{model} / \Delta \rho_{nature} \simeq 1$		
Viscosity					
η_l	Subducting oceanic plate	Pas	$1.4 imes 10^{24}$	4.2×10^5	
η_m	Upper mantle		10^{20}	30	
	Scale factor for viscosity		$\eta_{model}/\eta_{nature} = 3 \times 10^{-19}$		
Characteristic t	ime				
t t_{nature}	$/t_{model} = ((\Delta \rho g H)_{model} / (\Delta \rho g H)_{nature}) \times (\eta_{nature} / \eta_{model})$	s	$3.16 \times 10^{13} \ (1 \text{ Myr})$	55	
	Scale factor for time		$t_{model}/t_{nature} = 1.74 \times 10^{-12}$		

Table 1

Scaling of the modeling parameters in nature and in the laboratory, for the reference model.



Fig. 1. Experimental setup. The subducting lithosphere is modeled by a silicone plate of density ρ_l , viscosity η_l , width W, thickness H. The mantle is simulated by means of glucose syrup of density ρ_m , viscosity η_m and thickness D. The plate is either *fixed*, *i.e.* the trailing edge is attached to the end of the tanks or *free*, *i.e.* the trailing edge freely moves. The surface topography in the experiments is monitored by a 3D laser scanner. The foreside corresponds to the region where the lithosphere has not yet been subducted and the backside is located above the sunken slab.



Fig. 2. (a) 3D view of the surface topography (color coded and magnified by a factor 10) cut along the plate centerline and velocity vectors (in blue) of the mantle flow in the vertical section (x-z) for our reference experiment with *fixed edge* conditions (model 1, see parameters in Table 1). (b) 3D view of the top of the slab shape (in black) and velocity vectors (in blue) of the mantle flow in the horizontal section (x-y) at the top of the mantle for the same model.



Fig. 3. Map view of the surface of model 1 in the *fixed* (a) and *free* (b) subduction modes. Right and left panels display the same maps but with different color palettes in order to respectively highlight the topography of the plate (right) and glucose syrup (left). The dotted lines show the location of the different swath profiles plotted in fig. 4. Areas with no topographic data are indicated in gray.



Fig. 4. Swath topographic profiles for model 1 in the *fixed* (solid line) and *free* (dotted line) subduction modes (a) in the trench-normal direction, averaged over a distance of 40 mm from the plate centerline, (b) in the trench-parallel direction in the foreside (50 mm from the trench), and (c) in the trench-parallel direction in the backside (50 mm from the trench). Note the different scales for fig. 4a and figs. 4b-c. See fig. 3 for sections location. The theoretical isostatic depth for the plate is indicated by a dashed line in the first panel.



Fig. 5. Synthetic 3D sketch of the topography around a subduction zone (bottom) in the experiments (not to scale). Black dotted lines are isodepths curves, green curves follow the local maximum topographic gradients. Black arrows denote the flow pattern from below the slab on the foreside to above the slab on the backside. Top graph shows the isolated contributors along the central cross-section AA'.



Fig. 6. Bathymetry on the foresides of the East Scotia (a) and Tonga and Kermadec (b) subduction zones. Wavelengths shorter than 100 km have been filtered out. Note the low lying areas on the foresides of each trench, ~ 5000 m deep (East Scotia), ~ 6000 m deep (Tonga) and ~ 5700 m deep (Kermadec). In all three cases, they are 800 to 1000 m deeper than the adjacent seafloor of similar age. Seafloor age from [54].



Fig. 7. Bathymetry on the backside of the Banda subduction zone (a) and residual bathymetry of the East Scotia subduction zone (b, modified after [5]). (Residual topography of the extremely young Banda back-arc basin was not computed (un-available seafloor age grid) but is expected to be almost comparable to the residual topography). Wavelengths shorter than 100 km have been filtered out. Note the \sim 8000 m deep Weber trough on the backside of Banda trench, and the \sim 1500 m residual topography in the East Scotia back arc basin.

Supplementary material 1.

Experimental parameters. (W : plate width; H : plate thickness; D : mantle thick-
ness ρ_l : plate density; η_l : plate viscosity; ρ_m : mantle density; η_m : mantle viscosity;
ρ_{ll} : light plate density).

Model	W	H	D	$ ho_l$	η_l	$ ho_m$	η_m	$ ho_{ll}$	η_l/η_m	$\rho_l - \rho_m$
	mm	mm	mm	kg/m^3	$Pa \ s$	kg/m^3	$Pa\ s$	kg/m^3		kg/m^3
1	150	15.2	100	1506	4.2×10^5	1415	30	-	14000	91
2	200	13.7	100	1468	$3.0 imes 10^5$	1415	30	-	10000	53
3	150	12.5	100	1468	$3.0 imes 10^5$	1415	30	-	10000	53
4	200	13.0	100	1506	4.2×10^5	1415	30	-	14000	91
5	200	15.5	100	1506	4.2×10^5	1415	30	-	14000	91
6	150	13.7	100	1506	4.2×10^5	1415	30	-	14000	91
7	145	15.5	100	1468	3.0×10^5	1415	30	-	10000	53
8	150	15.0	97	1506	4.2×10^5	1450	1000	-	420	56
9	200	15.0	100	1506	4.2×10^5	1450	1000	-	420	56
10	200	12.8	98	1506	4.2×10^5	1450	1000	-	420	56
11	150	13.0	95	1506	4.2×10^5	1450	1000	-	420	56
12	150	12.0	100	1506	4.2×10^5	1450	1000	1458	420	56
13	150	12.0	100	1506	4.2×10^5	1450	1000	1458	420	56