Thermo-mechanical laboratory modelling of continental subduction: first experiments

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Abstract: Thermo-mechanical physical modelling of continental subduction is performed using new temperature sensitive analogue materials to model the lithospheric layers. The initially horizontal lithosphere model is underlain by the liquid asthenosphere and subjected to a constant vertical thermal gradient. The lithosphere contains three layers: the very weak sedimentary layer, the crust made of a stronger material in which strength reduces with depth due to the temperature increase, and the lithospheric mantle, made of a still stronger material with strength also droping with depth. During subduction, the temperature of all layers increases, causing reduction of their strength and limiting the depth of crustal subduction. The crust subducts to more than 100 km-depth and then undergoes large and complex deformation, including the upward ductile flow of the deeply subducted portions and a localised failure of the upper crust at depth of a few tens of kilometres. This deformation is accompanied by (is part of) the delamination of the crustal and mantle layers which can be stopped by the break off of the subducted continental mantle and the previously subducted oceanic lithosphere. The modelling reveals an interesting burial/exhumation evolution of the sedimentary cover. During initial stages of continental subduction the sediments of the continental margin are dragged to the overriding plate base and are partially accreted at the lower part of the interplate zone (at 60-70 km-depth). These sediments remain there until the beginning of delamination which results in the reduction of the coupling between the crust and the dense mantle, and in the growth of the interplate pressure between the subducted crust and the overriding plate. This pressure squeezes the underplated sediments out. A small amount of these sediments is rapidly extruded along the interplate zone to about 20 km-depth.

Introduction

Previously performed physical modelling of continental subduction suggested existence of two principal regimes of this process characterised by different mechanisms for exhumation of high-pressure rocks (Chemenda et al, 1996). The regime is defined by the interplate pressure which is inversely proportional to the pull-force. The latter depends on the difference between the average density of the subducting lithosphere and the surrounding mantle. In both regimes the continental crust reaches a critical depth proportional to its strength (~200 km) and fails, forming a major crustal thrust. In the case of high interplate pressure (highly compressional regime), the failure occurs in front of the subduction zone and the uplift (exhumation) of the subducted crust is only possible with erosion of the forming relief. If the interplate pressure is low (low compressional regime), the failure of the crust occurs under the base of the overriding plate and is followed by the buoyancy driven uplift of the subducted crust between the subducting and overriding plates.

Although the results of this modelling seem to correspond quite well to the available geological data, it was purely mechanical (isothermal) and did not consider any change in the mechanical properties of the subducting material. In the real conditions, however, both pressure and temperature increase during subduction, causing the rheology of the subducting crust and the mantle to change. Experimental studies of the coesite aggregates show in particular, that the strength of the crustal rocks reduces from ca. 100 MPa at the mid-crustal level (Ranalli and Murphy, 1987) to about 10 MPa (Stockert and Renner, 1998; Renner et al, 2001) at 750±150°C and P=3 GPa (corresponding to ca. 100 km-depth). Such strong change in the mechanical properties should certainly affect the subduction and exhumation processes, which therefore must be addressed by thermo-mechanical modelling.

In this paper we describe the set-up of such modelling and report the first results. They confirm that in a low compressional regime of continental subduction, a coherent slice of the subducted continental crust rises between the plates, althought both its volume and exhumation-depth are smaller than in the isothermal experiments. The crust subducted to more than 70 km-depth follows different evolution, undergoing intense plastic deformation and upward flow. The sedimentary material buried to these depth experiences still greater deformation: it is squeezed by the thickening and moving up crust and extruded upwards, overtaking the rising crust.

Set-up of thermo-mechanical experiments

A scheme of the experiment is shown in Figure 1. It is similar to the mentioned isothermal experiments. The principal difference is that the lithospheric layers are made of new temperature sensitive materials (hydrocarbon compositional systems) and that the whole model is subjected to a vertical thermal gradient. The subducting plate comprises oceanic and continental parts. The oceanic lithosphere is one layer, while the continental lithosphere is composed of three layers.

The upper layer corresponds to a sedimentary cover; it is continuous and coloured in green at the continental margin and in red in the rest of the model to better visualise its

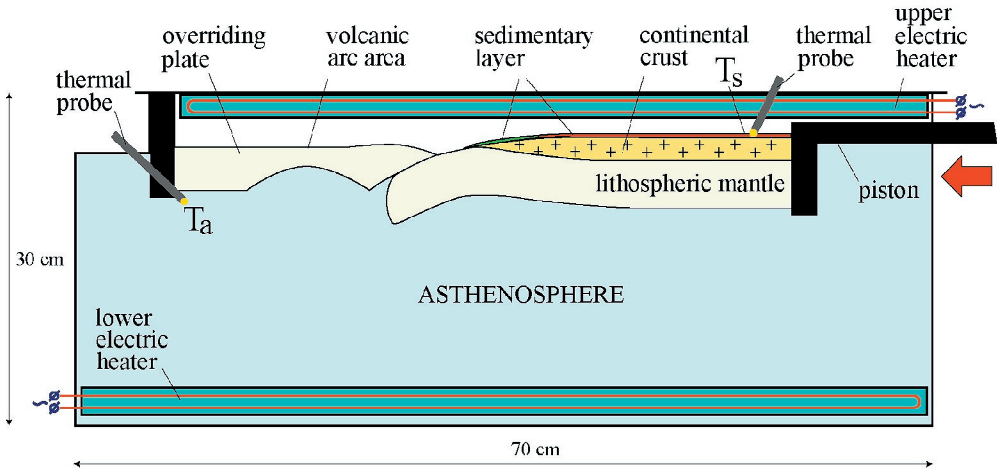

Figure 1. Scheme of the experiments. The names of model layers correspond to what they model: e.g. the continental crust means the continental crust model. The lithospheric layers are made of the hydrocarbon compositional systems. The asthenosphere is model by pure water.

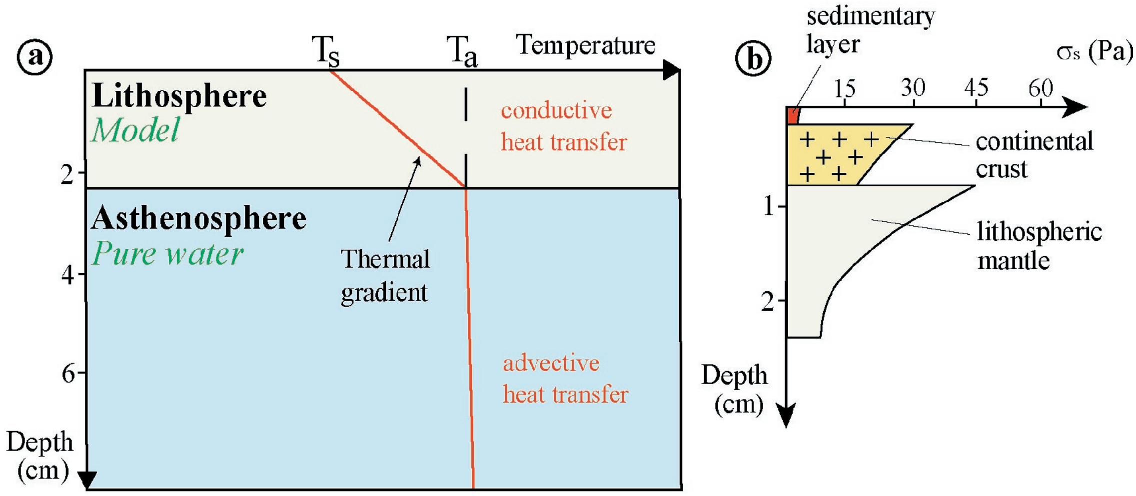

Figure 2. Thermal gradient maintained within the model (a) and strength envelope of the continental lithosphere model before subduction (b) at strain rate: ε (dot) = $2x10^{-2}$ s^{-1}

deformation during the experiment. The whole crust is made of a single material in contrast with the isothermal experiments where two different materials were used to simulate the strong upper crust and the weak lower crust. The rheological stratification (reduction of strength with depth) of the crust is now achieved in a more continues and natural manner due to the temperature gradient. The overriding lithosphere is oceanic and is thinned in the arc area as suggested by petrologic (Schmidt and Poli, 1995), geothermal (Furukawa, 1993), and seismic (Zhao et al, 1994) data as well as by the results of thermal numerical simulations (Peacock, 1996; Kincaid and Sacks, 1997). (The thinning, however is not important for the present experiments where overriding plate does not fail during subduction).

The lithospheric plates are underlain by the low-viscosity asthenosphere, which is pure water. Convergence is driven by a piston moving at a constant rate throughout the experiments, and the pull force generated by both subducted oceanic lithosphere and the continental lithospheric mantle. Upper and lower electric heaters (Fig. 1) are used to create a vertical thermal gradient in the model shown in Figure 2a. The temperature is controlled and maintained by high precision thermal probes and auto-adaptive thermo-regulator: temperature T_s is imposed at the lithosphere surface and the asthenosphere is maintained at temperature Ta. The thermal gradient inside the model induces a vertical variation of mechanical properties in each layer: the strength of the crustal layer drops from 30 to 15 Pa between the top and the base (Fig. 2b). The lithospheric mantle strength reduces from 45 Pa at the "Moho" to 8 Pa at the base. T_s = 37°C and T_a = 42°C are maintained constant throughout the experiments.

Similarity criteria

The mechanical similarity criteria met in this modelling are the following (Chemenda et al., 2000):

$$\begin{aligned}&\sigma_s/\ \rho_s g H_s = \text{const},\ \sigma_c/\ \rho_c g H_c = \text{const},\\&\sigma_l/\ \rho_l g H_l = \text{const},\ \rho_l/\rho_a = \text{const},\ \rho_l/\rho_c = \text{const},\\&H_l/H_c = \text{const},\ Vt/H_l = \text{const},\ VH/\kappa = \text{const};\end{aligned} \quad (1)$$

where σ_s, σ_c and σ_l are the average yield limits under normal loading of the sedimentary cover, the crust, and the mantle, respectively; H_s, H_c and H_l, are the thicknesses of the sedimentary cover, the crust, and the mantle, respectively. ρ_s, ρ_c, ρ_l and ρ_a are the densities of the sedimentary cover, the crust, the mantle and the asthenosphere. V is the convergence rate, t is the time, κ is the thermal diffusivity of the lithosphere and H is the thickness of the whole continental lithosphere. Table 1 shows the parameters values assumed for the prototype and the model which satisfy the similarity conditions (1).

Experimental results

We report here the results of one representative experiment (Figs. 3, 4 and 5). The initial stages of this experiment (Figs. 3a to c) are the same as in the purely mechanical modelling. At stage c the subducting

Parameters	*Prototype*	*Model*
σ_s (Pa)	3.4×10^7	3
σ_c (Pa)	2.65×10^8	23
σ_l (Pa)	3.5×10^8	30
ρ_s (kg/m^3)	2.8×10^3	0.86×10^3
ρ_c (kg/m^3)	2.8×10^3	0.86×10^3
ρ_l (kg/m^3)	3.4×10^3	1.03×10^3
ρ_a (kg/m^3)	3.3×10^3	1×10^3
H_s (m)	5.25×10^3	1.5×10^{-3}
H_c (m)	2.3×10^4	6.5×10^{-3}
H_l (m)	5.25×10^4	1.5×10^{-2}
V	3 cm/year	3×10^{-5} m/s
$\hat{I}$ (m^2/s)	1×10^{-6}	8×10^{-8}
t	1 m.y	4.6 min

Table 1. Parameter values adopted for the model and nature. σ_s, σ_c and σ_l are the average yield limits under normal loading of the sedimentary cover, the crust, and the mantle, respectively; H_s, H_c and H_l, are the thickness of the sedimentary cover, the crust, and the mantle, respectively. ρ_s, ρ_c, ρ_l and ρ_a are the densities of the sedimentary cover, the crust, the mantle and the asthenosphere. V is the convergence rate, t is the time and κ is the thermal diffusivity of the lithosphere.

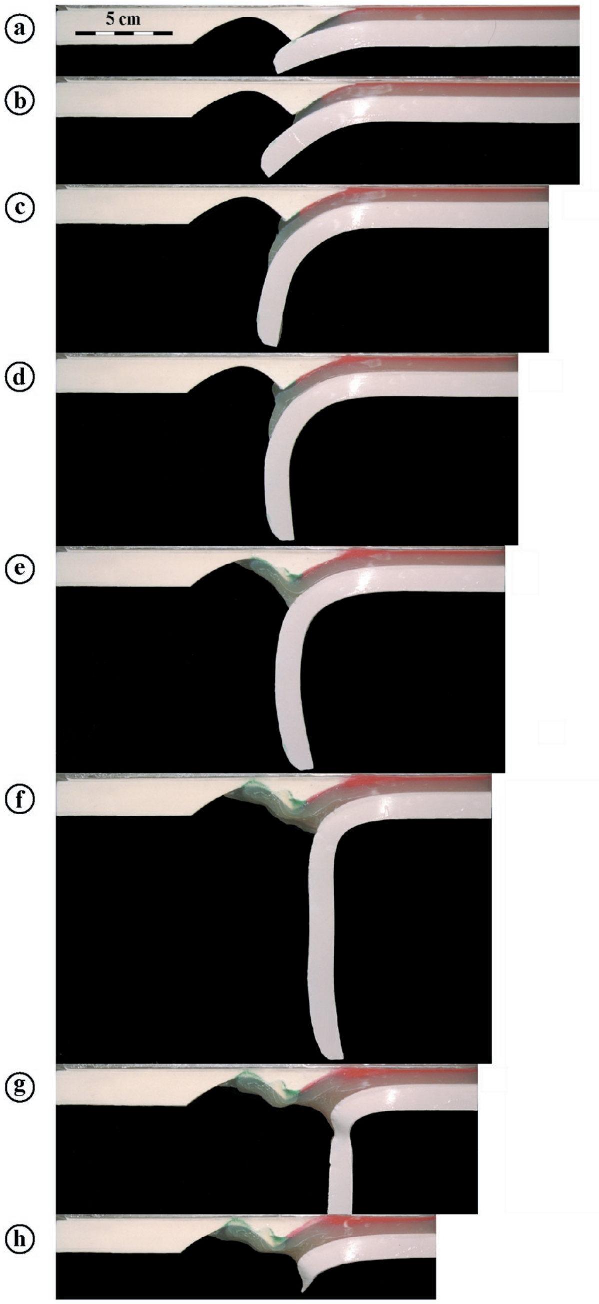

Figure 3. Experimental result: a to h, photos of successive stages of the continental subduction. The model parameters are indicated in Table 1.

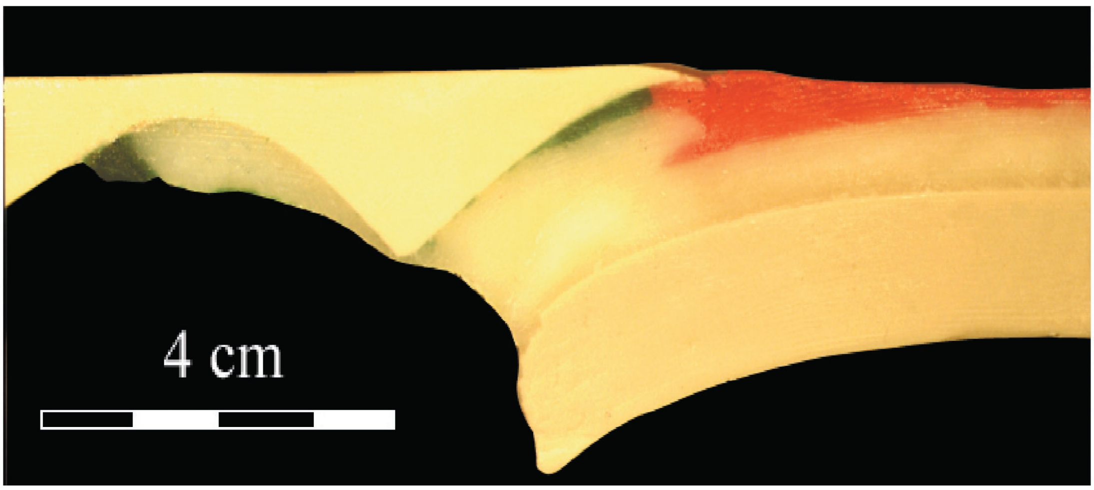

Figure 4. Cross-section of the middle part of the model at the last stage (h in Fig. 3) of the experiment. (**Select image to view movie**)

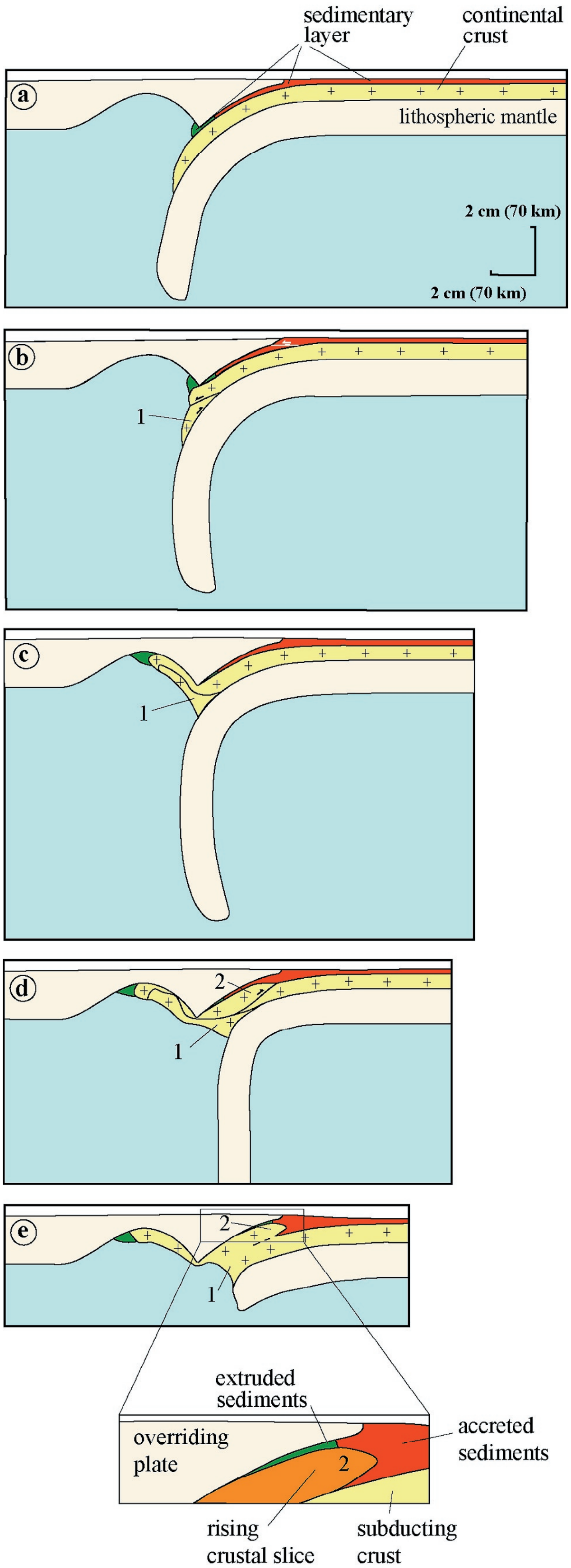

Figure 5. Drawings of the experimental photos in Fig. 3.

"sediments" reach the base of the overriding plate, being already very weak. They are partly underplated at the lower part of the interplate zone and partly accumulated at the entrance of this zone. The continental crust subducts deeper, following the subducting lithospheric mantle and reaches ~4 cm-depth (equivalent to ~130 km in nature). Then it fails and a crustal slice (unit 1 in Figs. 3d and 5b) starts to slide up, intruding the lower crust. This is the beginning of a delamination of the subducted crustal and mantle layers.

Approximately at the same stage, the sedimentary cover starts to be scraped off and accreted in front of subduction zone (Figs. 3d and 5b). The crust in the interplate zone undergoes ductile along-interplate zone shortening and thickening in the direction perpendicular to this zone. This is followed by the failure of the crust resulting in the formation of a second slice (unit 2 in Fig. 5d). This decoupled from the lithospheric mantle slice rises, pushing up and extruding the sedimentary material accumulated along the interplate zone. The deeply subducted sedimentary cover (green colour in Figs. 3f and 5d) of the continental margin therefore find itself over the crustal slice at the last stage of the experiment (Figs. 4 and 5e). During this process, the subducted lower crust continues to flow up under the upper crust, increasing the crustal thickening. The subducted lithospheric mantle then breaks off (Fig. 3g and h) after which the experiment was stopped.

Discussion and conclusion

One can easily recognise in the thermo-mechanical experiment in Fig. 5 evolution of the continental subduction and exhumation corresponding to the low-compression regime obtained in the isothermal experiments (Chemenda et al., 1996). As in the previous experiments, starting from some depth of continental subduction, the continental crust undergoes failure and buoyancy driven uplift along the interplate zone followed by the mantle layer break off. The thermo-mechanical model, however, provides new important insights into this process.

Crustal failure and uplift have proved to be closely related to the delamination of the subducting crust and the mantle. The delamination is caused by the pull force generated by the subducted oceanic lithosphere and the continental mantle (both are denser than the asthenosphere, see Table 1) and occurs due to the large ductile deformation of the crust, especially of the lower crust as well as of the upper crust subducted into the asthenosphere (to ~100 km-depth). These warmed and weakened units flow up under the upper crust segment located between the overriding and subducting plates, being driven by the buoyancy force.

The upper crust griped between the overriding and subducting plates undergoes much smaller internal deformation in spite of the fact that, deeper than a few tens of kilometres, it is also very weak and can flow under small differential stress. The upper crust segment finally fails at about 40 km-depth, forming a coherent rising slice which reaches about 20 km-depth. Overthrusting and uplift of this slice as well as the upward flow of a deeper subducted crust correspond to the delamination of the crust and the mantle.

In the presented experiment this process was stopped by the break off which removes the pull force, the driving force of the delamination, but in other experiments conducted under slightly different conditions we obtained a total separation of the crustal and mantle layers. After the break off both the delamination and delamination-related rise of the crust were stopped. The thermo-mechanical experiments reveal also very interesting burial/exhumation evolution of the sedimentary cover. The sediments of the continental margin are dragged to the overriding plate base, are partially accreted (underplated) at the lower part of the interplate zone (at 60-70 km-depth) and partially flow under the overriding plate base, being pushed by the crust (Fig. 5b). The underplated sediments remain at their place until the beginning of the delamination and formation of the upper crustal slice 2 (Fig. 5d).

During the delamination, the coupling between the crust and the mantle reduces and the crust is not pulled down anymore by the dense mantle layer. Therefore the pressure between the crust and the overriding plate increases along the interplate zone starting form its deepest part as the delamination propagates from the overriding plate base upwards. The increasing pressure squeezes the underplated sediments of the continental margin. They are extruded upward, overtaking the rising upper crustal slice (Figs. 4 and 5e). After this rapid exhumation a small volume of the continental margin cover subducted to ~70 km-depth reaches 15-20 km-depth and finds itself above the crust exhumed from much smaller depth (ca. 40 km). The increased interplate pressure makes it difficult for new portion of the sedimentary cover to enter the interplate zone: they are scraped off and accreted in front of subduction zone (Figs. 3h and 5e). The continental margin sediments entered the asthenosphere flow up with the deeply subducted continental crust under the overriding plate into the arc area (Fig. 5d) where they can be eventually exhumed.

In the presented experiments we were not able to obtain the exhumation from depths exceeding the overriding plate thickness, i.e. 60-70 km (or probably maximum ~100 km), while in reality this depth can reach ~150 km as for example, in Dabie Shan and Kazahstan (Hacker and Peacock, 1994; Ernst and Liou, 1999). The reason is a very low crustal strength at these depths, allowing the crust to flow when it is not limited by more rigid units (overriding and subducting plates). A possible way of obtaining the exhumation of ultra-high pressure (UHP) rocks could be an integration into the modelling of one more element, the fore arc block subduction. Such a block can serve both as a rigid guide for the deep crustal subduction and exhumation, and as a thermal shield protecting the deeply subducted crust from overheating by the mantle (Chemenda et al., 1997, 2001), and thus providing a low temperature under the UHP conditions.

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