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Continental subduction and exhumation of high-pressure rocks: insights from thermo-mechanical laboratory modelling

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Abstract

Thermo-mechanical physical modelling of continental subduction is performed to investigate the exhumation of deeply subducted continental crust. The model consists of two lithospheric plates made of new temperature sensitive analogue materials. The lithosphere is underlain by liquid asthenosphere. The continental lithosphere contains three layers: the weak sedimentary layer, the crust made of a stronger material, and of a still stronger lithospheric mantle. The whole model is subjected to a constant vertical thermal gradient, causing the strength reduction with depth in each lithospheric layer. Subduction is driven by both push force and pull force. During subduction, the subducting lithosphere is heating and the strength of its layers reduces. The weakening continental crust reaches maximal depth of about 120 km and cannot subduct deeper because its frontal part starts to flow up. The subducted crust undergoes complex deformation, including indicated upward ductile flow of the most deeply subducted portions and localised failure of the subducted upper crust at about 50-km depth. This failure results in the formation of the first crustal slice which rises up between the plates under the buoyancy force. This process is accompanied by the delamination of the crustal and mantle layers of the subducting lithosphere. The delamination front propagates upwards into the interplate zone resulting in the formation of two other crustal slices that also rise up between the plates. Average equivalent exhumation rate of the crustal material during delamination is about 1 cm/year. The crust-asthenosphere boundary near the interplate zone is uplifted. The subducted mantle layer then breaks off, removing the pull force and thereby stopping the delamination and increasing horizontal compression of the lithosphere. The latter produces shortening of the formed orogen and the growth of relief. 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 deep part of the interplate zone (at 60–70 km-depth). These sediments remain there until the beginning of delamination during which the pressure between the subducted crust and the overriding plate increases. This results in squeezing the underplated sediments out. Part of them is extruded upwards along the interplate zone to about 30-km depth at an equivalent rate of 5–10 cm/year.

1. Introduction

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Discovery of coesite and diamond inclusions within rocks of the continental crust [1–3] has revealed

that the continental crust can be subducted to more than 100-km depth and then part of it can be rapidly exhumed [4–6]. Both processes, continental subduction and exhumation, have been previously studied with scaled physical modelling [7,8]. The results suggested existence of two principal regimes of continental subduction characterised by different mechanisms for the exhumation of high-pressure rocks. 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 is subducted to a critical depth proportional to its strength (~ 200 km) and fails, forming a major crustal thrust. For highly compressional regime (high interplate pressure) the failure occurs in front of the subduction zone and the uplift (exhumation) of the subducted crust is only possible when erosion partly removes 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 spontaneous rise of the subducted crust between the subducting and overriding plates. Although the results of this modelling seem to correspond quite well to the geological data in different mountain belts [8–15], they are purely mechanical (isothermal) and do not consider any change in the mechanical properties of the material during subduction. In reality, however, both pressure and temperature increase, resulting in the weakening of the subducting crustal and mantle layers. Experi-

mental studies of the coesite aggregates show in particular, that the strength of the crustal rocks reduces from ca. 200 MPa at the mid-crustal level [16,17] to about 10 MPa at 750 ± 150 °C and $P = 3$ GPa [18–20] (corresponding to ca. 100-km depth). Such strong drop of the crustal strength 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 results. They confirm that in a low compressional regime of continental subduction, coherent slices of the subducted continental crust do rise between the plates, although both their volume and exhumation-depth are smaller than in the isothermal experiments. The crust subducted to more than 70-km depth in new experiments follows different evolution, undergoing intense plastic deformation and upward flow beneath the crustal slices exhumed in the interplate zone. A part of this deeply subducted continental crust flows up to the overriding plate base where it is underplated. The sedimentary material subducted till the overriding plate base experiences still greater deformation: it is squeezed by the thickening and moving up crust and extruded partly upwards and partly into the asthenosphere under the overriding plate.

2. Set-up of thermo-mechanical experiments

The set-up of the thermo-mechanical experiments (Fig. 1) is similar to that of the mentioned isother-
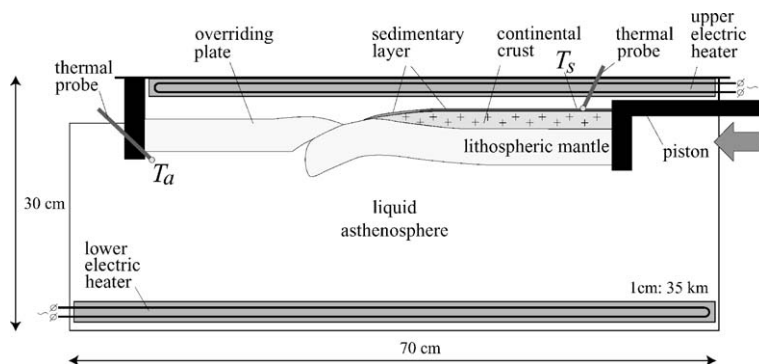

Fig. 1. Scheme of the experimental set-up. The lithospheric layers are made of the hydrocarbon compositional systems and the asthenosphere is pure water. Temperatures T_s and T_a are maintained at the model surface and the asthenosphere.

mal experiments, although in the thermo-mechanical modelling the lithospheric layers are made of new temperature sensitive materials (hydrocarbon compositional systems) and the whole model is subjected to a vertical thermal gradient (Fig. 2a). The model includes two ''lithospheric'' plates. The subducting plate contains two parts: one-layer oceanic and three-layer continental lithosphere with a passive continental margin between them. The upper layer of the continental lithosphere model corresponds to the weak sedimentary cover (Fig. 2b). The stronger continental crust layer is made of a single material in contrast to 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 natural and continues manner due to the temperature gradient. Finally, the lowest layer of the continental lithosphere model corresponds to the lithospheric mantle, made of a still stronger material which strength also reduces with depth due to the temperature increase (Fig. 2b). The overriding lithosphere is oceanic and one-layer. The lithospheric plates are underlain by low-viscosity asthenosphere, which is water (Fig. 1). The thermal gradient within the model is maintained by upper and lower electric heaters (Fig. 1) and is controlled by high precision thermal probes and auto-adaptive thermo-regulator.

Table 1
Parameter values adopted for the model and scaled to nature

Symbol	Prototype	Model
σ_s (Pa)	3.4×10^7	3
σ_c (Pa)	2.0×10^8	17.5
σ_l (Pa)	2.6×10^8	22.5
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	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
κ (m^2/s)	10^{-6}	8×10^{-8}
t	1 my	4.6 min

Temperature T_s is imposed at the model surface and the asthenosphere is maintained at temperature T_a. Lithosphere strength envelopes shown in Fig. 2b were obtained from the shear tests of model materials conducted at various temperatures. In the experiment presented in this paper T_s is 38 °C and T_a is 42 °C. Subduction is driven by a piston moving at a constant rate and by the pull force generated by both subducted oceanic lithosphere and the continental lithospheric mantle, which are slightly denser than the asthenosphere (see Table 1 for the parameter values).
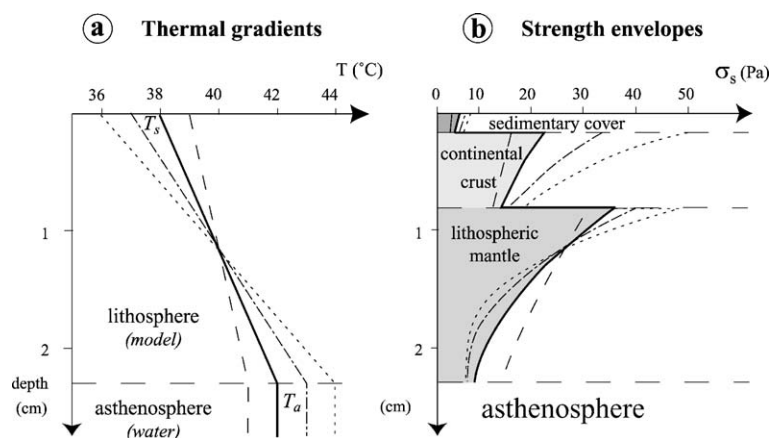

Fig. 2. Initial (before deformation) thermal gradients within the model (a) and corresponding strength envelopes for the continental lithosphere model (b) derived from the shear-type rheological tests under different temperatures. In the experiment presented in this paper $T_s = 38$ °C and $T_a = 42$ °C (solid lines).
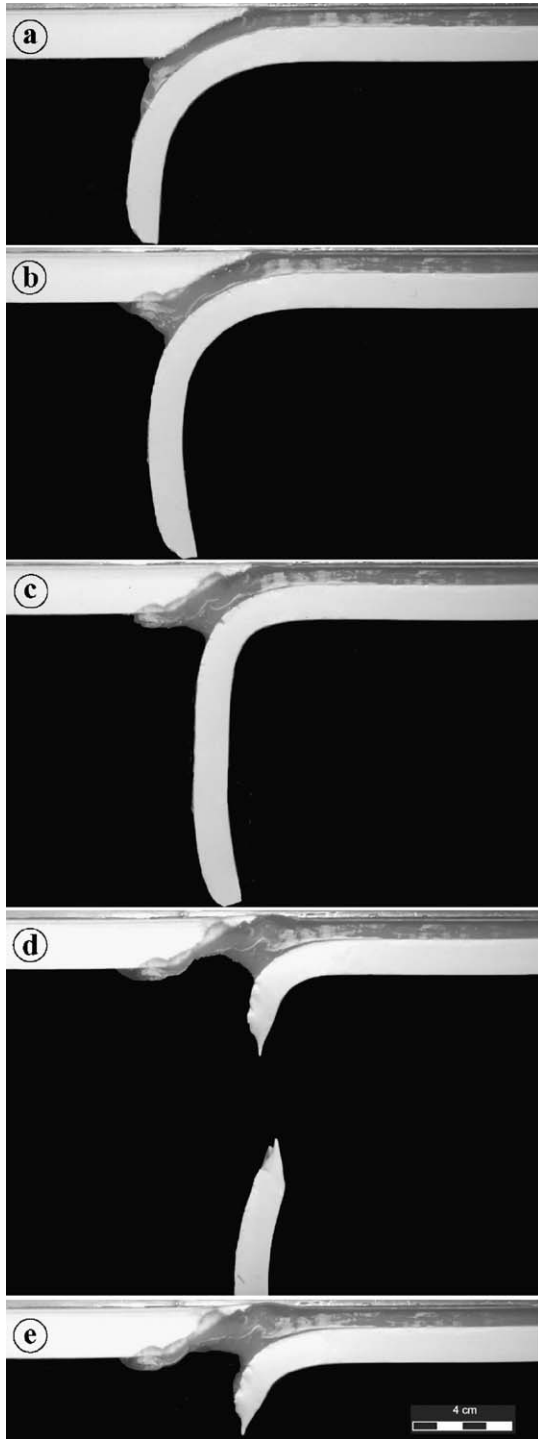
Fig. 3. Successive stages of the experiment in cross-section (model parameter values in Table 1).
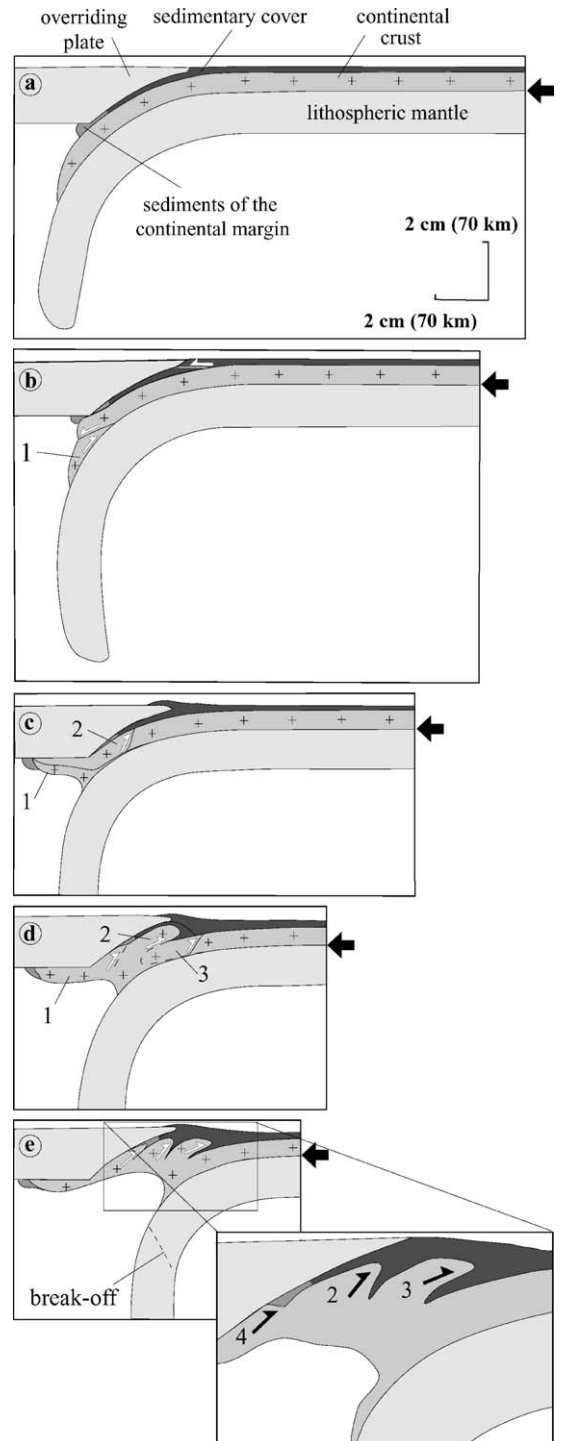

Fig. 4. Drawings of the experimental photos with explanations.

3. Similarity criteria

The mechanical similarity criteria met in this modelling are the following [21]:

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

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 lithospheric mantle, respectively; ρ_s, ρ_c, ρ_l and ρ_a are the densities of the sedimentary cover, the crust, the lithospheric 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. The parameter values assumed for the prototype and the model which satisfy the similarity conditions (1) are given in Table 1.

4. Experimental results

A total of 37 experiments have been conducted. We present below one of the most representative experiments (Figs. 3–5) and summarise the results from the others. The experiment starts with subduction of the oceanic segment of the subducting plate followed by the subduction of the continental margin. This process first occurs without any complications, as simple oceanic subduction. Although the sedimentary layer is very weak, it subducts almost completely to the base of the overriding plate. After reaching the asthenosphere, the sedimentary material is accumulat-ed at the exit of the interplate zone (Fig. 3a and 4a,b). The continental crust subducts deeper, following the subducting lithospheric mantle and reaches ~ 4 cm-depth (equivalent to ~ 130 km in nature). Then the crust fails and its slice (unit 1 in Fig. 4b) starts to slide up, intruding the lower crust. This is the beginning of a delamination of the subducted crustal and mantle layers which propagates upward into the interplate zone. The continental crust in this zone undergoes ductile along-interplate zone shortening and thickening in the perpendicular direction, resulting in the failure of the crust at ~ 50 km-depth and formation of a second slice (unit 2 in Figs. 3b and 4c) that rises up, pushing and extruding the sedimentary material accumulated between the lithospheric plates (Fig. 4d). This is rapidly followed by the formation of a shallower third slice (unit 3 in Fig. 4d). Uplift of all slices results in progressive across-interplate zone crustal thickening. A fourth slice forms within unit 1 at ~ 50 km-depth (Fig. 4e). Along-interplate zone shortening of the crust causes considerable uplift of the crust-asthenosphere boundary in this area (Figs. 3d and 4d,e). Thickening of the interplate zone occurs simultaneously with the roll-back of the subducted lithospheric mantle, which finally breaks off (Figs. 3d and 4e). The experiment was stopped at this stage to preserve the deformed model structure for further detailed study (see Fig. 5).

The whole experiment lasts about one hour and a half, while the delamination process takes only ~ 3 min, which being scaled up to nature yields about 13 Ma. The uplift of slice 2 lasts some 45 s. The equivalent average exhumation rate is about 1 cm/year. During this process the subducted sediments are extruded upwards 5–10 times faster, i.e., at a rate of 5–10 cm/year.
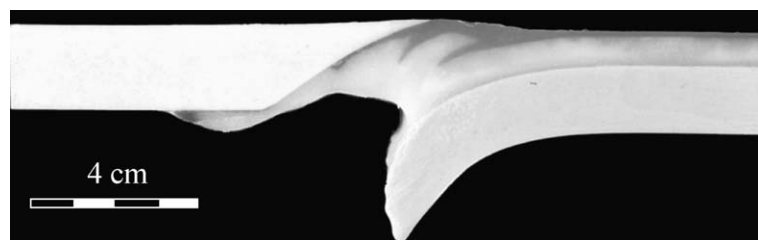

Fig. 5. Cross-section of the middle part of the model corresponding to the last stage of the experiment (e in Fig. 3) and made after model freezing.

5. Discussion and conclusion

Subduction in the presented experiment correspond to the low-compression regime [8]. As in the previously conducted purely mechanical experiments [8], starting from some depth of continental crust subduction, the crust undergoes failure and buoyancy driven uplift along the interplate zone which is followed by the lithospheric mantle break off. However, the thermo-mechanical experiments reveal new important details of this process. They show that the crustal failure and uplift are closely related with the delamination of the subducting crust and the lithospheric mantle caused by both the buoyancy force exerting the low-density continental crust and the pull force generated by the subducted oceanic lithosphere and the continental mantle. The delamination occurs via large ductile deformation of the subducted crust. This process starts in the deepest part of the interplate zone and then propagates upwards, inducing generally upward displacement of the crust. The deepest, hence, hottest crustal segment undergoes high ductile deformation which is first diffused (flow) and then localises along a narrow shear bend (ductile fault). The upper crust gripped between the overriding and subducting plates is more brittle and stronger, but it is still very weak (equivalent strength is about 100 MPa) and normally should also undergo ductile flow. Its diffused deformation however is small because it is blocked by more rigid units. Finally, this crust fails simultaneously with the delamination onset. The later allows the gripped crust to change the form and provides the room for the second crustal slice (unit 2 in Fig. 4c) that rises up between the plates. The third slice (unit 3 in Fig. 4d) forms in a similar way. Formation of the fourth slice is part of the same delamination process and widening of the interplate zone or orogen. During delamination all units undergo uplift (exhumation). The average equivalent exhumation rate was obtained to be of about 1 cm/year, which corresponds well to the available data, for example in Sezia Lanzo (Alps) and Münchberg Massif (Bohemian massif) [22]. The rate is not constant. At the end of the exhumation it approaches to zero and at the beginning should be a few to several times greater than the average value, but we cannot measure directly the rate variation. Brake off of the subducted mantle removes the driving force of delamination. Experi-

ment in Fig. 3 was stopped at this stage. In other experiments where convergence was continued, we observed a considerable shortening of the formed orogen due to the increase in horizontal compression of the lithosphere caused by the removal of the pull force. This new phase of continental subduction and orogenesis corresponds to highly compressional regime [7,8] and is not a subject of study in this work.

A new feature obtained in the thermo-mechanical experiment is the uplift of the continental crust-asthenosphere interface in the interplate zone. Such uplift of the hot asthenosphere provides heating of the surrounding crustal and mantle material. In nature, this can lead to magmatism and high-temperature metamorphism [23]. Davies and von Blanckenburg [23] have suggested that the detachment of the crust from the mantle, the asthenosphere uplift and the exhumation of the subducted crust are the consequences of the slab break off and therefore occur after it. In our experiments all these processes occur before as they are driven by the pull force. The break off removes this force and stops the delamination and rapid exhumation to the mid-crustal depth.

The thermo-mechanical experiments reveal also 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. 4b). The underplated sediments remain at their place until the beginning of delamination (Fig. 4d,e). During the delamination, the coupling between the crust and the mantle reduces (as they are detaching) 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 which are very rapidly (~10 cm/year) extruded upward from ~70-km depth to about 30-km depth (Fig. 5). The increased interplate pressure (between the subducted crust and the overriding plate) makes it difficult for the new portions of the sedimentary cover to enter the interplate zone: they are scraped off and accreted in front of subduction zone (Fig. 4c–e).
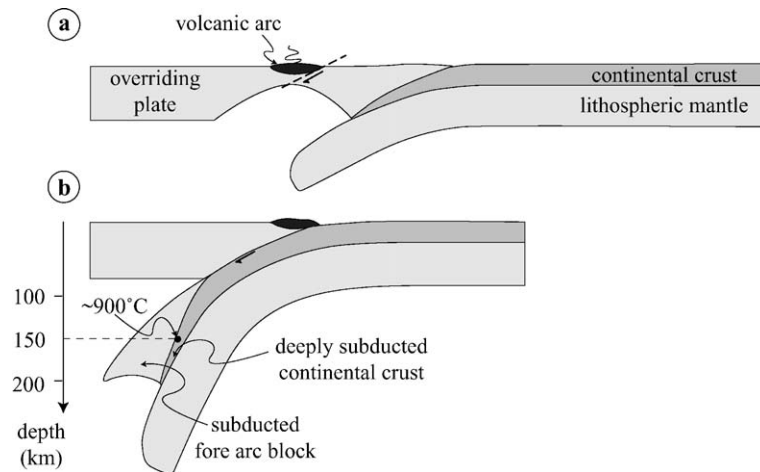
Fig. 6. Scheme of the deep continental crust and fore arc block subduction followed from a thermo-mechanical experimental modelling [28].

In the presented experiment we obtain exhumation from depths not exceeding the overriding plate thickness, i.e. 60–70 km (or, probably, maximum ~100 km), while in reality the exhumation-depth can reach ~130–150 km (or more) with temperature recorded at theses depths by metamorphic rocks being of ~ 750–950 °C [6,24,25]. With the used set up it is impossible to obtain not only the exhumation from such depths, but simply the formation of such ultra-high pressure/low-temperature (UHP/LT) material as at depth about 100 km the crust becomes too hot/weak and cannot be pushed deeper. To deliver the crustal material to ~ 150 km-depth and keep it at relatively low temperature a modification of the whole subduction scheme is necessary. Possible modification follows from the mechanical and thermo-mechanical modelling of arc-continent collision that takes into account a considerable thinning/weakening of the overriding lithosphere in the volcanic are area during oceanic subduction [26–28] as indicated in Fig. 6a. Experiments show that a large lithospheric unit, the fore arc block or the whole arc plate can be completely subducted allowing deep (~ 200 km) subduction of the continental crust (Fig. 6a). Such deep crustal subduction also occurs in the thermo-mechanical experiments [28] as the heating and weakening crust is sandwiched between "cold" and rigid units: the fore arc block and the subducted mantle. The fore arc block plays a role of thermal shield protecting the crust from overheating by the asthenosphere. Indeed,

temperature at the crust surface at 150 km-depth in the model is of ~ 40.7 °C which corresponds in nature to about 900 °C. The UHP/LT conditions were thus achieved in these models, but we did not obtain exhumation of UHP/LT material because of the same reason which provided deep crustal subduction: the crust is blocked between the rigid units. To obtain the UHP/LT rocks exhumation, a reduction of the inter-plate pressure is needed. It is difficult to imagine the mechanism of such reduction in a two-dimensional configuration. We succeeded in the required pressure reduction only locally in a specific 3-D context [29] (and paper in preparation). This implies that the exhumation of the UHP/LT rocks is essentially 3-D phenomenon that can occur only in specific locations.

Acknowledgements

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