Subduction initiation: Weak fault by water?

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Subduction initiation remains one of the unresolved challenges of plate tectonics. Up to now fluid-dynamical approaches have been used in which the yield strength of the lithosphere has been assigned arbitrarily. Our analysis focuses on the solid mechanical processes prior to and during yielding; i.e. we investigate the formation of a weak zone, the proto-subduction zone. It is long known that the negatively buoyant oceanic lithosphere, once pushed down deep enough on such a weak zone can in a second finite amplitude instability overcome flexural bending and shear-resistance.

While realistic analytical, analogue and numerical models of subduction postulate the presence of a weakness, the problem of weak zone formation has not been looked into until very recently. In a first nonlinear elastic fracture mechanical approach we investigated whether thick sediment piles at passive margins on the old oceanic lithosphere can cause failure of the lithosphere. An earlier model study came to the conclusion that the old oceanic lithosphere should be strong enough to support such a weight. However, the oceanic lithosphere strength envelope since have been revised to much lower strength values.

Following our studies based on fracture mechanics we now present a coupled solid-fluid mechanical approach in which the laboratory creep laws are implemented directly. Our previous study focused on the effect of strain hardening, here we are able to investigate systematically the roles of creep rate sensitive, temperature, and water effects on weak zone formation. We use a finite element approach on a generic oceanic lithosphere with and without adjacent continental lithosphere. Thermal initial conditions are implemented analytically, using a cooling half space model with thermal parameters that give a statistical best fit of worldwide ocean floor topography as a function of thermal age. A skewed triangular sedimentary loading function is introduced as a nodal load on the continental margin. The peak sedimentation rate is set to 15cm/kyr over a time span of 100 Myrs. Sedimentary and water buoyancy responses to bending deformation are introduced by buoyancy forces applied to the bottom of the plane strain model where passive mantle flow mimicked by two families (z and x) of nodal nodal dashpots (10^{21} Pas) at the base.

1) Strain Rate weakening Our formulation provides a self-consistent, laboratory data based constitutive equation of a thermo-elasto-visco-plastic mechanical lithosphere (the solid layer) resting on a fluid dynamic rheological sublayer. In this

approach the boundary between the fluid and solid domains is clearly defined by the validity domain of the Peierls mechanism. In laboratory experiments the boundary was found to be about Tbase =1200K corresponding to fluid like deformation above and solid like deformation below this temperature. Geological extrapolations have been based on estimates of the thickness of the mechanical lithosphere from nonlinear flexure giving Tbase =1073 or 1173 K, respectively. 1200 K are given as an upper limit of shear localization in upper mantle peridotites. Our formulation embeds localized weakening in shear zones within the solid layer through the yield phenomenon of the Peierls mechanism. Above the yield stress the solid becomes weak and flow starts with a characteristic strain rate. Further strain-rate weakening due to enhanced shear localization results from both Peierls and power law nonlinear flow laws but not from the diffusion creep law. Weakening in the diffusion creep regime can, however, become important through grain size reduction effect after yield. Grain size reduction has not been considered here because it is an evolved weakening mechanism requiring large strain after subduction initiation.

2) Strain weakening Another weakening mechanism, which does not require an intermediate phase of power law creep for grain size reduction may however play a role. In a wet mantle free fluids can self organize into void sheets under the action of an applied shear stress. We have tested this approach and find that in a compressive environment the effect is negligible. Under global tension the weakening due to free fluids can become important. A tensile subduction initiation mechanism envisioned by refs is mechanically plausible with our rheology. An argument against a tensile mechanism is that passive continental margins are on a global scale under compression.

3) Wet versus dry lithosphere We come back to the wet versus dry rheology and investigate whether subduction initiation is possible under the combined action of sediment load and ridge push. Ridge push results from thermal expansivity and acts as a lateral push. The sediment load minus water depresses the oceanic lithosphere vertically on passive continental margins. The sediment load acts locally on the future subduction zone. Erosion on the continents furnishes a steady supply of sediments. Thus the sediment load can locally reach values, which are one order larger than ridge push. Sedimentary basins on continental margins are continuous but have varying thickness. Our model treats sediment basins as a line loads (plane strain model). We thus assume the continental margins have been uniformly filled. We first discuss the case of a lithosphere under an increasing sediment load only.

Both wet and dry lithosphere fail under the sediment load. However the style of failure is very different. In the dry lithosphere case, only the top 10 km (plus 10km which are not considered) fail in a solid mechanical manner while the lower part deforms in a diffuse way. Ultimately, the sediment load triggers a Rayleigh Taylor instability in the weak rheological sublayer which then delaminates from the mechanical lithosphere. Our cooling half space model thus develops dynamically into a cooling plate model between 10 and 100 Myrs.

The wet lithosphere case shows an entirely different behaviour. It fails on its whole mechanical thickness and subduction can initiate. The presence of water on the passive continental margin thus appears to be the first and foremost factor to control subduction initiation on the Earth.