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On the viability and style of subduction in a hotter Earth

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Intro

Was plate tectonics possible in a hotter Precambrian Earth? Geological evidence leads to devided opinions[1], and other Earth-cooling mechanisms have been proposed: magma ocean, flake tectonics or mini-subduction[2,3]. In a ΔT_{pot}=50-300 K hotter Earth, crustal thickness increases[4] (Fig. 1) and viscosity η decreases[5]. Although higher radiactive heating allowed for faster plate tectonics[2], most parameterized convection models lead to very fast subduction and very high mantle temperatures, which is called 'thermal catastrophe'[6]. Subduction has furthmore been outruled because of crustal buoyancy[7]. Here we examine the viability and thermal consequences of subduction in a hotter Earth numerically, and show that slow eclogitization kinetics and rheology play a more sophisticated role than previously assumed.

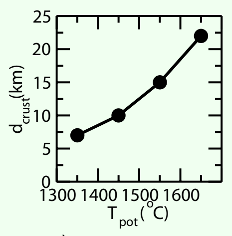

Fig. 1) Oceanic crust was thicker in a hotter Earth[4].

Model

[2-D FEM code SEPRAN: mass,momentum& energy conservation] [tracer composition] [WxH=5000x2000 km] [static fault decouples converging plates] [density: ρ_o=3300 kg/m^3; $\Delta\rho_{basalt}$=-500, $\Delta\rho_{ecl.}$=+100, $\Delta\rho_{Hz}$=-75] [phase transitions: basalt -> eclogite (b→e): at 40 km depth, equilibrium/1 Ma/5 Ma; 400-D & 660-D, equil.] [rheology: composite[5,6],yielding, Byerlee's law,$\Delta\eta_{mw}$ weaker mantle wedge]

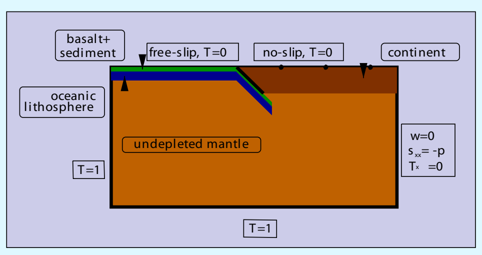

Fig. 2) Model setup

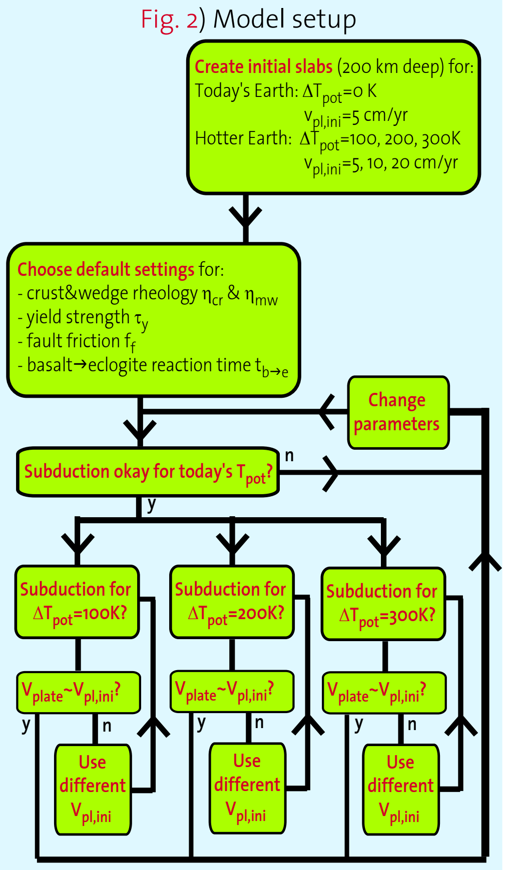

Fig. 3) Solution method

Results

We performed several calculations to examine not only the style and viability of plate tectonics throughout the Earth's history. Variation of parameter settings shows the robustness of the results. Fig. 4 shows the case with 'default' settings. Variation of fault friction (Fig. 5), type of plate decoupling (Fig. 6), depletion strengthening (Fig. 7), eclogitiation kinetics (Fig. 8), and yield strength (Fig. 9) all have significant influence. Some cases show no continuation of subduction after the initiation phase, mostly for the hottest-Earth conditions. Subduction was faster in a moderately hotter Earth (Fig. 10), but for a potential temperature increase of (ΔT_{pot}) of 200K or more, most cases show a reduction in convergence speed, mostly due to slab break-off or crustal delamination.

Default case

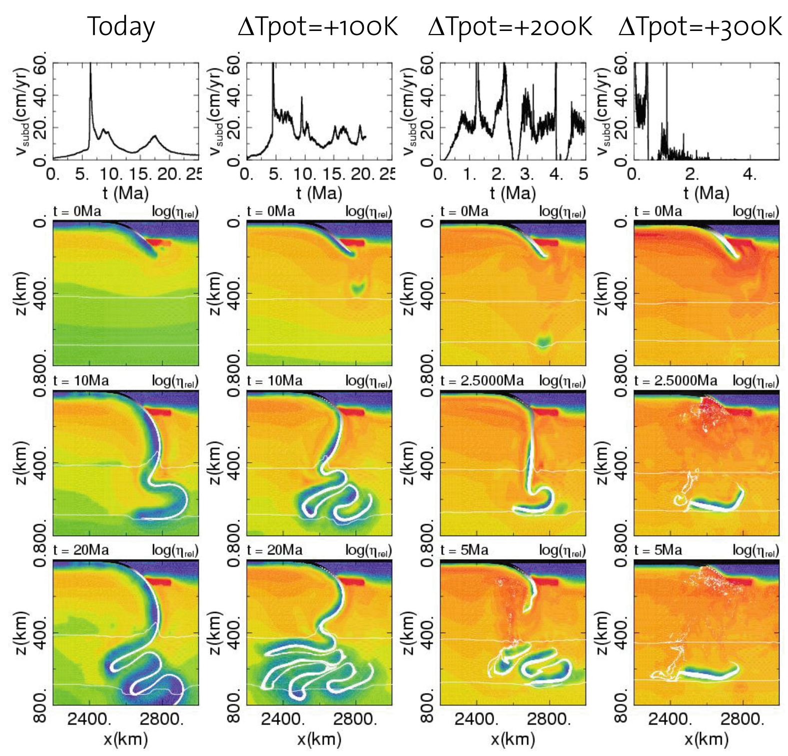

Fig. 4) Colors: viscosity, b/w: basalt/eclogite. Default settings: relatively strong crust[8], $\Delta\eta_{mw}$=0.01, f_f=0, $t_{b\rightarrow e}$=1 Ma, τ_y=2x10^8 Pa. Top row: starting situation with a 200-km deep slab. For ΔT_{pot}=+100K, subduction looks normal but for higher ΔT_{pot} frequent slab breakoff occurs, which can block subduction.

Effect of fault friction

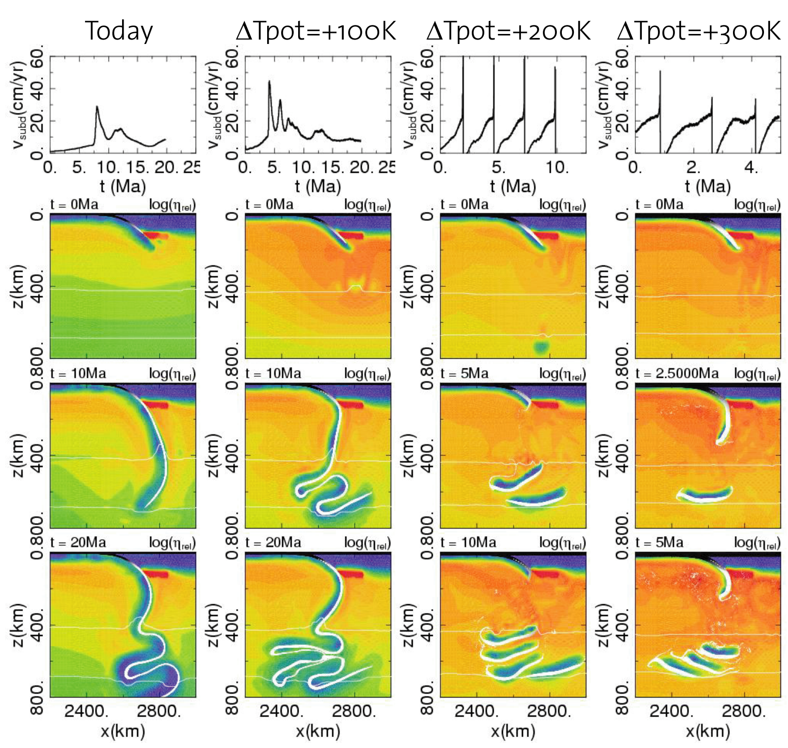

Fig. 5) Effect of a small (linear) friction of 5 MPa per cm/yr subduction. This significantly reduces the peak v_{subd} during initial 400-D penetration, and makes subduction more regular. Again, for ΔT_{pot}>+100K, slab breakoff occurs.

Effect of different type of plate decoupling

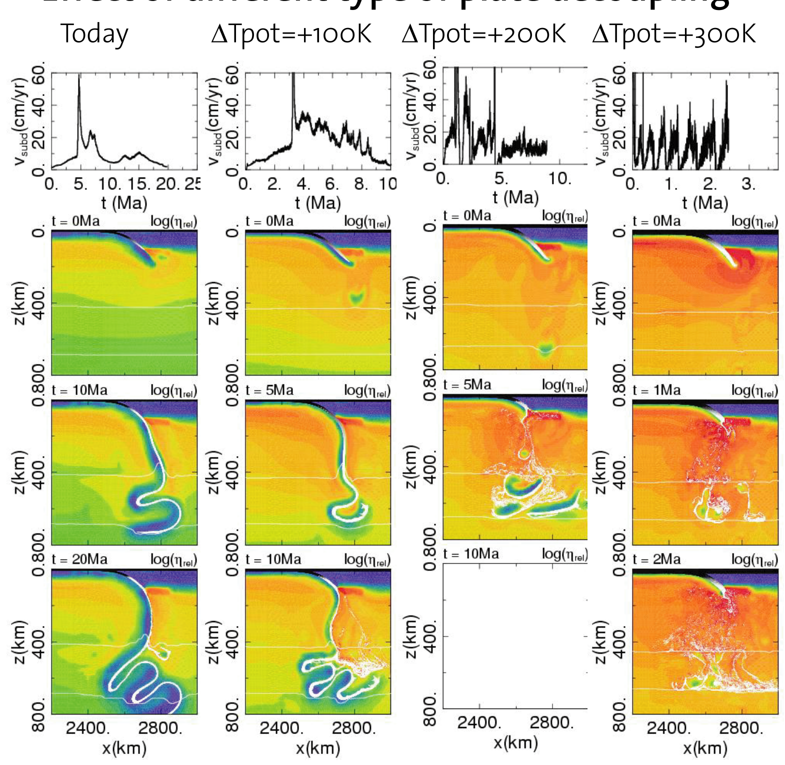

Fig. 6) Weak crust[8] and $\Delta\eta_{mw}$=0.01. Crustal delamination becomes significant for ΔT_{pot}>+100K, and blocks subduction. For ΔT_{pot}=+300K, no slab can be recognized anymore, even though plate convergence continues.

Effect of slow eclogitization

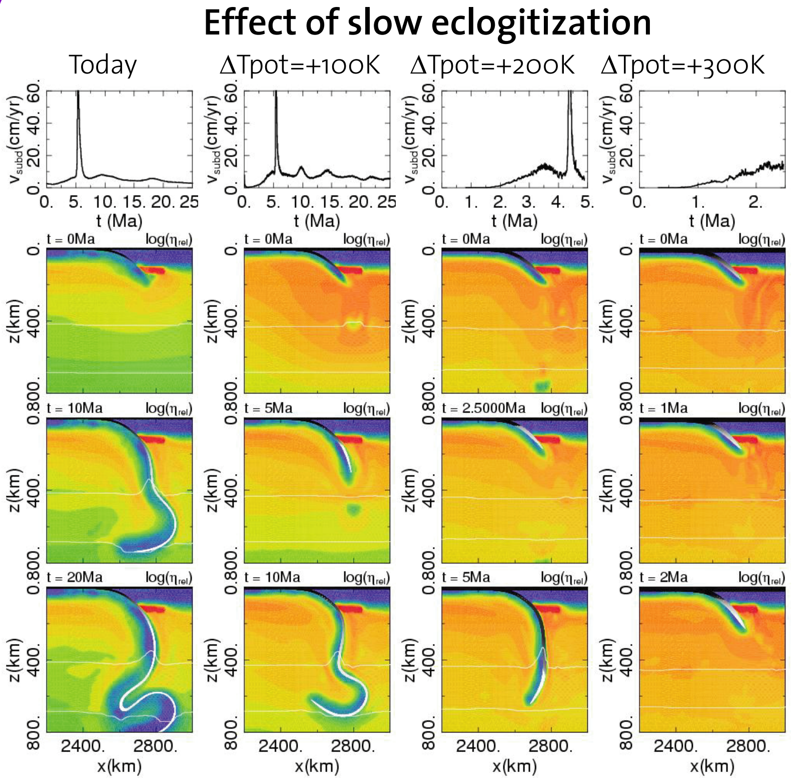

Fig. 8) As Fig. 4, but with $t_{b\rightarrow e}$=5 Ma. The resulting decrease in slab pull reduces the subduction velocity significantly, but subduction remains possible even for ΔT_{pot}=300K. Note the difference in model time span.

Effect of yielding

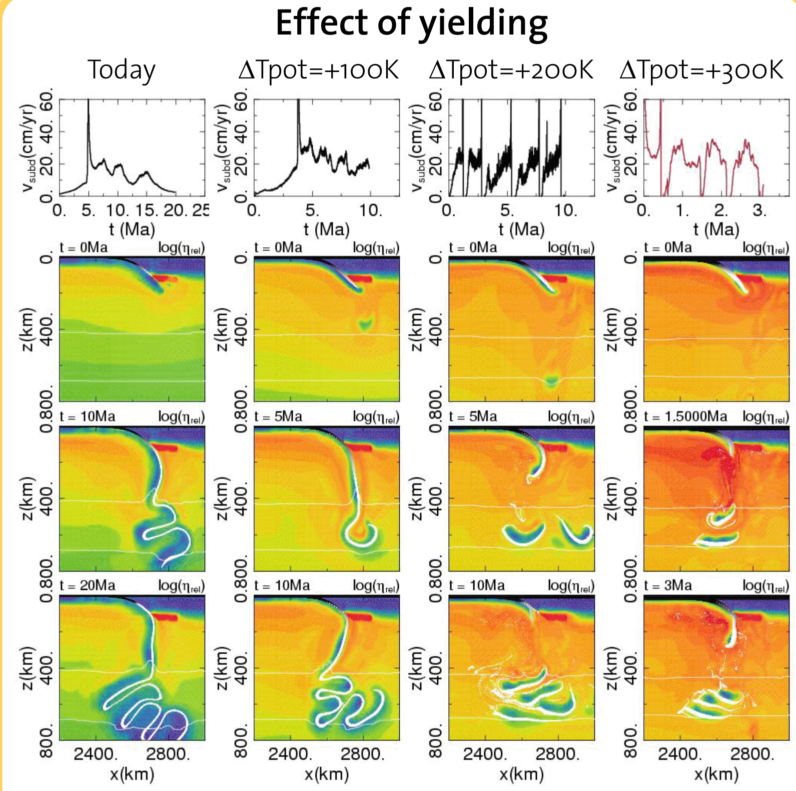

Fig. 9) Effect of a lower yield stress τ_y=10^8 Pa. Up to ΔT_{pot}=+100K slabs subduct slightly faster due to reduced strength of the slab. For ΔT_{pot}>+100K more frequent breakoff occurs. Higher yield stress (1 GPa, results not shown, but see Fig. 10) shows slower subduction (low ΔT_{pot}), less breakoff & faster subduction (high ΔT_{pot}).

Summary

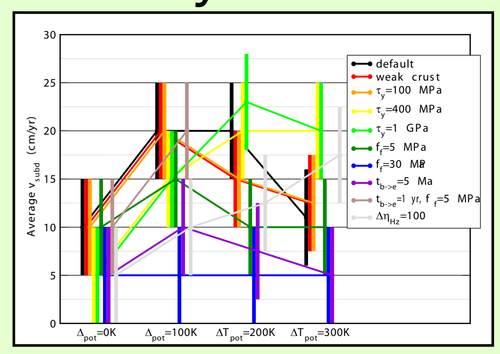

Fig. 10) Subduction velocities and variation, averaged over 20, 10, 5, & 2.5 Ma for ΔT_{pot}=0, +100, +200, &+300K, resp. Despite significant variation, all models show reasonable subduction speeds for each ΔT_{pot} below ~25 cm/yr. However, in some models slab breakoff or crustal delamination hampers continuation of subduction.

Effect of strong Harzburgite

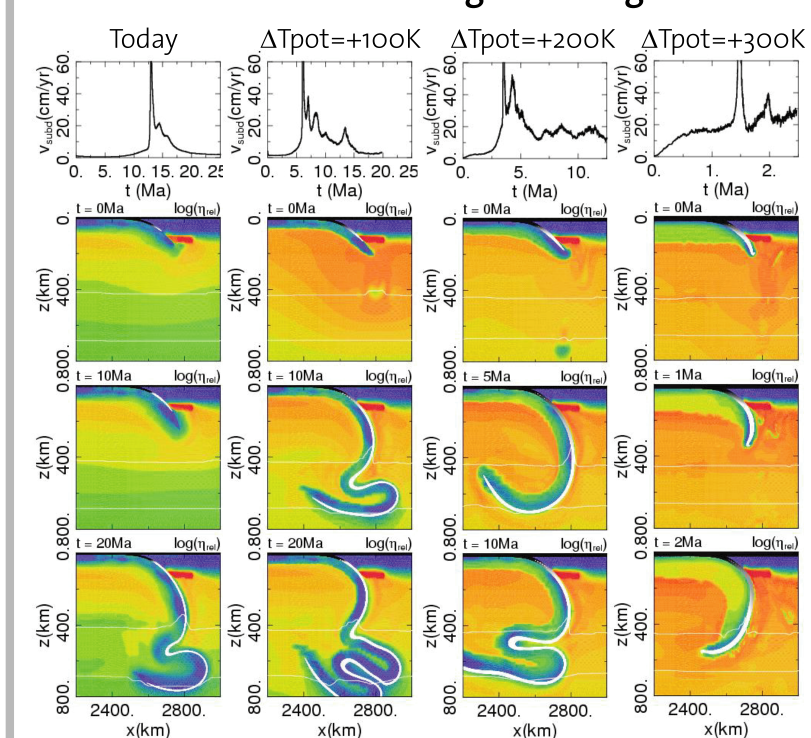

Fig. 7) Effect of a strong depleted layer: all depleted material is 100x stronger than undepleted material under the same circumstances. Since this depleted layer is increasing with mantle temperature (Fig. 1), slabs were compositionally stronger in the past. Subduction shows no break-off at higher ΔT_{pot}, but is still going faster with increasing mantle temperature.This is because the thermal weakening effect of slabs still dominates over the compositional strengthening one.

Conclusions

From modeling subduction in a hotter mantle & with a correspondingly thicker crust, we conclude that:

1) None of the models show very high subduction velocities and so 'thermal catastrophe' can easily be avoided.

2) Slab strength limits viability of subduction in the past, probably not crustal buoyancy:
- low mantle strength leads to frequent slab break-off.
- low crustal strength gives delimanation
- even very slow eclogitisation kinetics doesn't block subduction completely.

3) Low (high) yield stresses results in faster (slower) subduction at low potential temperature T_{pot}, but gives more (less) frequent breakoff at higher T_{pot}.

3) Fault friction stabilizes subduction speed, and slightly enhances subduction in a hotter Earth.

Notes and References:
1) For example (Hamilton, 1998) vs. (de Wit, 1998); 2) (Sleep, 2000);
3) (Hoffman&Ranalli, 1988, Vlaar et al., 1994, Zegers&van Keken, 2001); 4) (van Thienen et al., 2004); 5) (Karato&Wu, 1993); 6) Abbott et al., 1994; Korenaga, 2005; 7) e.g. Davies, 1992; 8) The default case uses the crustal prefactor from (Shelton&Tullis, 1981), the 'weaker crust' case uses a 6 orders lower prefactor.