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Subduction styles in the Precambrian insight from numerical experiments

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Plate tectonics is a self-organizing global system driven by the negative buoyancy of the thermal boundary layer resulting in subduction. Although the signature of plate tectonics is recognized with some confidence in the Phanerozoic geological record of the continents, evidence for plate tectonics earlier in the geological record becomes less certain further back in time. For this reason, to improve our understanding of tectonics on the Earth in the Precambrian time we have to combine knowledge derived from the geological record with results from well-constrained numerical modeling.

In a series of experiments using a 2D geochemical–petrological–thermomechanical numerical model of oceanic–continental subduction based on finite differences and marker-in-cell techniques we have systematically investigated the dependence of tectono-metamorphic and magmatic regimes at an active plate margin on upper mantle temperature, crustal radiogenic heat production, degree of lithospheric weakening and other parameters. Based on the results of these experiments, we identify a first-order transition from a "no-subduction" tectonic regime through a "pre-subduction" tectonic regime to the modern style of subduction. The first transition is gradual and occures at the upper-mantle temperatures between 200-250 degrees above present-day values, while the second transition is more obvious and occurs at 160-175 degrees which might correspond to the Mesoarchean-Neoarchean time (2.5-3.2 Ga). In the case of the "pre-subduction" tectonic regime (upper-mantle temperature 175–250 degrees above present), the overriding plate is strongly internally deformable because it is rheologically weakened by intense percolation of melts derived from the underlying hot sub-lithospheric partially molten mantle. Convergence of weak plates does not produce self-sustaining one-sided subduction, but rather results in shallow underthrusting of the oceanic plate under the continental plate. The oceanic plate moves far under the continental plate (up to 200 km) and causes buckling of the sub-continental lithospheric mantle, which in some cases may take the form of shallow asymmetric two-sided subduction. In contrast to the "modern subduction", this hotter "pre-subduction" regime is not associated with the formation of a pronounced mantle wedge and backarc basin. Further increase in the upper-mantle temperature (more than 250 degrees above present) causes a transition to a "no-subduction" (horizontal tectonics) regime where horizontal movements of small deformable plate fragments are accommodated by internal strain and even shallow underthrusts do not form under the imposed convergence. In the "no-subduction" regime the plates are extremely weak due to the continuous emplacement of large volumes of sub-lithospheric melts.

Thus, based on the results of our numerical modeling, we suggest that the crucial parameter controlling the tectonic regime is the degree of lithospheric weakening induced by propagation of sub-lithospheric melts. A lower degree of melt-related weakening (at upper-mantle temperatures less than 175 degrees) results in stronger plates and stabilizes modern style subduction even at high mantle temperatures.