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Evolution of the oceanic-continental subduction style since the Precambrian

Elena Sizova (1), Taras Gerya (1,2), Boris Kaus (1), Michael Brown (3), Leonid Perchuk (4,5)

(1) ETH-Zurich, Institute of Geophysics, ERDW, Switzerland (sizova@erdw.ethz.ch), (2) Adjunct Professor of Geology Department, Moscow State University, 119199 Moscow, Russia, (3) Department of Geology, University of Maryland, College Park, MD, 20742, USA, (4) Department of Petrology, Moscow State University, 119199 Moscow, Russia, (5) Visiting Professor of Faculty of Science, University of Johannesburg, South Africa

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 on continents, evidence for plate tectonics is less certain further back in time. To improve our understanding of plate tectonics on the Earth during the Precambrian, we have to combine knowledge derived from the geological record with results from realistic numerical modeling.

In a series of experiments using a 2D petrological–thermomechanical numerical model of oceanic-continental subduction we have systematically investigated the dependence of tectono-metamorphic and magmatic regimes at an active continental margin on upper-mantle temperature, crustal radiogenic heat production, degree of lithospheric weakening as well as other physical parameters. The model includes spontaneous slab bending, dehydration of subducted crust, aqueous fluid transport, mantle wedge melting, and melt extraction from the mantle resulting in crustal growth. We have identified 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 occurs at upper-mantle temperatures between 250-200 K above present-day values, whereas the second transition is more abrupt and occurs at 175-160 K. The link between geological observations and model results suggests that the transition to the modern plate tectonics regime might have occurred during the Mesoarchean–Neoarchean time (ca. 3.2–2.5 Ga). In the case of a “pre-subduction” tectonic regime (upper-mantle temperature 175–250 K above present) the plates are weakened by intense percolation of melts derived from the underlying hot melt-bearing sub-lithospheric mantle. In such cases, convergence does not produce self-sustaining one-sided subduction, but rather results in shallow underthrusting of the oceanic plate under the continental plate. A further increase in the upper-mantle temperature (> 250 K above present) induces a transition to a “no-subduction” regime where horizontal movements of small deformable plate fragments are accommodated by internal strain and even under imposed convergence shallow underthrusts do not form.

To better understand the underlying physics of these models we performed an additional series of experiments using similar 2D petrological–thermomechanical numerical model but without hydration, melting and extraction procedures. In these models, we have obtained a similarly abrupt transition from the modern style of subduction to the “no-subduction” regime at the upper-mantle temperature 160-180 K above the present-day values. This temperature is approximately the same as determined in the first set of experiments. The “no-subduction” regime is characterized by ‘dripping-off’ of the plate tips, most likely because of the small effective viscosity constrast between subducting slab and surrounding mantle. Indeed we do not observe a transitional “pre-subduction” tectonic regime with underthrusting of the oceanic plate in these sets of models. This implies critical role of rheological weakening by sublithospheric melts in defining how transition between ancient “no-subduction” stage and modern plate tectonic regime occurred in the Earth’s history.