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Formation and stability of ridge-ridge-ridge triple junctions in rheologically realistic lithosphere model

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Triple junctions are probably the most remarkable features of plate boundaries since their presence constitutes one of the major demonstrations of plate tectonics theory. Divergent (R-R-R) triple junctions (at 120° and T junctions) are particular ones since their stability depends on the exact values of the relative velocities of plate divergence and hence is strongly affected by plate rheology and processes of crustal accretion. The mechanisms of their formation and long-term steadiness are not well understood even though it is commonly accepted, generally based on common sense, that the geometry and stability of triple junctions should be related to the intuitively acceptable geometric considerations that 3-branch configurations should be "stable" over the time on a 3D Earth surface. That said, most plate boundaries are in fact 2D in terms that they involve only two plates, while junctions with 3 and more branches, if even mechanically not excluded, are generally short-lived and hence rarely observed at tectonic scale. Indeed, it has been long-time suggested that triple junctions result from evolution of short-lived quadruple junctions, yet, without providing a consistent mechanical explanation or experimental demonstration of this process, due to the rheological complexity of the lithosphere and that of strain localization and crustal accretion processes. For example, it is supposed that R-R-R junctions form as result of axisymmetric mantle upwellings. However, impingement of buoyant fluid on a non-pre-stressed lithosphere should result in multiple radial cracks, as is well known from previous analog and numerical experiments. In case of uni-directionally pre-stressed lithosphere, it has also shown that linear 2D rift structures should be formed. Therefore, a complete 3D thermos-mechanically consistent approach is needed to understand the processes of formation of multi-branch junctions. With this goal we here reproduce and study the processes of multi-branch junction formation and evolution by using high-resolution 3D numerical mechanical experiments that take into account realistic thermo-rheological structure and rheology of the lithosphere. We find that two major types of quadruple and triple junctions are formed under bi-directional or multidirectional far-field stress field: (i) plate rifting junctions are formed by the initial plate fragmentation and can be subsequently re-arranged into (ii) oceanic spreading junctions controlled by the new oceanic crust accretion. In particular, we document initial formation and destabilization of quadruple R-R-R-R junctions as initial plate rifting structures under bi-directional extension. In most cases, quadruple plate rifting junctions rapidly (typically within 1-2 Myr) evolve towards formation of two diverging triple oceanic spreading junctions connected by a linear spreading center lengthening with time. This configuration remains stable over long time scales. However, under certain conditions, quadruple junctions may also remain relatively stable. Asymmetric stretching results in various configurations, for example formation of "T-junctions" with trans-extensional components and combination of fast and slow spreading ridges. Combined with plume impingement, this scenario evolves in realistic patterns closely resembling observed plate dynamics. In particular, opening of the Red Sea and of the Afar rift system find a logical explanation within a single model. Numerical experiments also suggest that several existing oceanic spreading junctions form as the result of plate motions rearrangements after which only one of two plates spreading along the ridge become subjected to bi-directional spreading.