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Grain-scale equilibrium reactions guide fluid-driven eclogitization of dry crustal rocks

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When a fluid is introduced into dry rocks at high-pressure conditions, it acts as a catalyst and facilitates re-equilibration. This often promotes weakening and subsequent ductile deformation. Here, we present a detailed micro-structural and mineral chemical study of eclogitization of initially dry continental crustal rocks in the absence of ductile deformation. The studied sample features an incomplete (fluid-induced) transition from lower crustal granulite to eclogite, and the transition is fully preserved. None of the mineral phases show any signs of ductile deformation, indicating that the transformation was entirely static. Material transport during the reaction was limited to the availability of fluids. Detailed analysis of the local assemblages along the transect reveals that the reaction occurs in three distinct steps: The plagioclase-plagioclase grain boundaries were the first to re-equilibrate followed by clinopyroxene-plagioclase and garnet-plagioclase grain boundaries. Lastly, the grain boundaries that included only garnet and/or clinopyroxene are involved in the transformation. Thermodynamic modelling of local equilibria at dry conditions and with H₂O in excess reveals that this stepwise transformation is caused by the varying reactivity of the local assemblages at the prevailing P-T conditions. Those reactions that result in the largest decrease of the Gibbs free energy from the dry case to the case with H₂O in excess occur first. Once the reaction is facilitated, this effect is amplified because the density increase is largest at those grains boundaries that have reacted first, creating new fluid pathways through volume reduction. The calculated stable local mineral assemblages are consistent with those present in the sample indicating that element transport is limited, also supported by the observation that the fabric of the granulite is preserved in the eclogite. Our results demonstrate that reactive fluid flow is guided by the local energy budget along the grain boundaries, and that element transport during static re-equilibration is limited to the extent where it is thermodynamically advantageous.