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Dynamics of tectonic nappes: Thrusting versus intrusion or dynamic pressure versus lithostatic pressure

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Despite extensive research, the dynamics of tectonic nappes exhibiting high and ultra-high pressure ((U)HP) rocks is still debated. We classify existing models for nappe formation into two types, and refer to them as thrust and intrusion model. Thrust models approximate the orogen as wedge with a rigid buttress behind and a subducting lithospheric slab beneath. The dominant process of nappe formation is thrusting (brittle and/or ductile) that generates a dominant top-to-the-foreland shear sense. Rocks remain within crustal depth (<∼60 km). Uplift and exhumation of (U)HP rocks is explained by underplating accompanied by isostatic uplift, extension in higher levels of the wedge and erosion. Thrust models can explain the imbricate nappe stacking and first-order structural observations in the Western Alps. However, in the last decades (U)HP rocks were found in nappes, and it is usually assumed that metamorphic pressure is a good indicator of maximum burial. This assumption represents a fundamental problem for the thrust model, namely to account for the large burial depth of (U)HP rocks indicating depths >100 km. Nappe formation at such mantle depths cannot be explained by the thrust model. In intrusion models (U)HP rocks are subducted to mantle depths and return to crustal depths by buoyancy driven or tectonically forced flow. Nappes are formed during the return flow with an opposite shear sense at the bottom and top of the nappe. Intrusion models could reproduce the first-order patterns of P-T-time paths of the Western Alps. However, there are problems with intrusion models. First, the intrusion scenario requires a major extensional shear zone in the hanging wall of the exhuming (U)HP unit. However, for most (U)HP units of the Western Alps the earliest coherent structures recorded along the upper boundary are top-to-the-foreland shear zones (consistent with thrust models). Second, dynamic intrusion models are usually unable to generate an imbricate nappe stack.

The major argument against thrust models is the assumption that metamorphic pressure indicates maximum burial, and the same assumption is the major argument for intrusion models. If, however, significant tectonic overpressure existed during nappe formation, then (U)HP rocks would have formed in significantly less depth, and thrust models could be applicable to the Western Alps. We apply theoretical and numerical models to quantify possible magnitudes of tectonic overpressure during nappe formation. We show with analytical derivations and numerical simulations that lateral variations in gravitational potential energy (GPE), such as observed around continental plateaus, are a proof for the existence of tectonic overpressure, which magnitude is independent from rock rheology (viscous or elastic). Variations of GPE allow estimating a lower bound for the magnitude of tectonic overpressure in the crust. We further present synthetic P-T paths resulting from 2-D thermo-mechanical numerical simulations of tectonic nappe formation (by thrusting) during lithospheric shortening. Applications to nappe formation in the Western Alps are discussed, as well as strategies to determine whether the thrust or intrusion model better explains the formation of tectonic nappes in the Western Alps.