Crustal Structure Linked to Ultra-High-Pressure Rock Exhumation: A "Working" Model for the Tso Morari Complex, Ladakh Himalaya

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The distribution of ultra-high-pressure (UHP) metamorphic rocks in the Himalayan-Tibetan orogen and elsewehere demonstrates that burial (to >100 km) and rapid exhumation (>1 cm.a^{-1}) of continental crust is a normal part of early (~10 Ma) continental collision. Until recently, there has been no comprehensive model for this fundamental tectonic process that also satisfactorily explains the upper-crustal structures resulting from early collisional UHP rock exhumation. Among the characteristic features requiring explanation are: structural domes that are cored by UHP nappes; associated medium- to high-pressure nappes displaying a distinct "pressure gap"; overlying lower-grade rocks, including suture zone ophiolites; and, coeval foreland-directed thrust-faults and syn-exhumation normal faults (numbers 1-6, Figure 1).

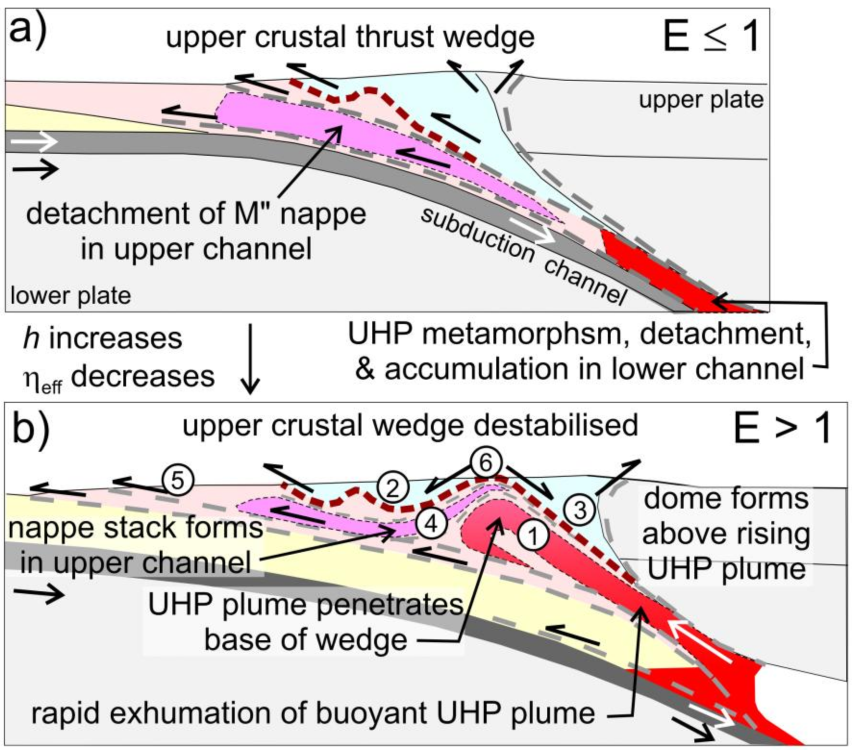

Figure 1. Processes involved in formation and exhumation of UHP metamorphic rocks, including the Tso Morari complex. a) Formation of UHP material in lower channel and detachment of M″ nappe in upper channel. Increasing channel thickness (*h*) and decreasing effective viscosity (η_{eff}), combined with inherent buoyancy of subducted crust, increase exhumation number (*E*) above critical threshold value (*E*>1). b) Formation of upper-crustal structures in response to rapid exhumation of a buoyant UHP plume (*E*>>1) that penetrates and destabilizes the overlying thrust wedge, leading to extension above the dome and coeval foreland-directed thrusting. 1) structural dome cored by UHP nappe; 2) overlying lower grade rocks; 3) suture zone ophiolites; 4) medium- to high-pressure (M") nappes; 5) foreland-directed thrust-faults; 6) syn-exhumation normal faults.

We present a geodynamical model involving crustal burial and exhumation in a subduction channel below an accretionary wedge and upper plate (e.g., Beaumont et al., 2009). Competition between down-channel shear traction and up-channel buoyancy forces, expressed as the exhumation number, *E*, controls burial and exhumation, leading to rapid up-channel flow when *E* >1 (Figure 1; e.g., Warren and others, 2008). Exhuming UHP material forms a nappe stack and structural dome as it penetrates and destabilises the overlying wedge, driving thrusting and extension. This solution is compelling because it explains both the geology and the petrology of UHP complexes, and because it demonstrates that pulse-like buoyant exhumation from deep in the subduction channel creates observed upper-crustal structures. This places constraints on the exhumation mechanism and provides a test of alternative models. Other proposed mechanisms, such as continuous circulation in a lithospheric-scale wedge or overpressured subduction channel, predict different types of upper-crustal structures and are therefore unsatisfactory explanations for early collisional exhumation of UHP terranes.

Model feasibility has been tested against observations from the Tso Morari Complex, Ladakh Himalaya (e.g., de Sigoyer and others, 2004; Leech and others, 2005; Epard and Steck, 2008, and references therein). Peak UHP metamorphic conditions have been estimated at >2.8 GPa and 600-650°C. Geochronological data suggest that UHP conditions were achieved at ca. 50-55 Ma, within 1-5 Ma of collision. UHP rocks were exhumed to crustal levels (<1.2 GPa) by ca. 48 Ma, followed by cooling to <300°C by ca. 40 Ma. The immediately overlying Tetraogal nappe, which lacks evidence for UHP metamorphism, was affected by amphibolite facies metamorphism (ca. 550-700°C, 0.8-1.2 GPa) with top-to-the-south fabrics formed at ca. 48-45 Ma. The nappe stack now occupies the core of a dome developed between 47-30 Ma, coeval with SW-directed thrusting in the frontal part of the North Himalayan nappes. The complex is separated from ophiolitic rocks of the Indus Suture Zone by a late normal fault, and dismembered ophiolitic rocks are also present at mid-structural levels within the nappe stack.

These observations are compared with Model V_P15-5, in which convergence velocity, V_P, is initially 15 $cm.a^{-1}$, representing the high convergence rate at the onset of the India-Asia collision, followed at 5.5 Ma by a decline to $V_P = 5$ $cm.a^{-1}$. Collision begins at 3.3 Ma (0 Ma-pc) and exhumation begins at 4.3 Ma-pc. The overlying accretionary wedge and M″ nappe are deformed into a structural dome above the exhuming UHP plume (Figure 1), and by 6.7 Ma-pc, UHP material lies in the core of the dome within 10 km of the model surface. The geometry of the model upper crust corresponds very well to the Tso Morari cross-section (Epard and Steck, 2008). Within uncertainties, the model is also consistent with available age constraints, and model *PTt* paths reproduce observed peak *PT* conditions, duration of UHP metamorphism (<1 Ma), and most of the exhumation path (Beaumont et al., 2009). We therefore consider this a good “working” model for the formation and exhumation of the UHP Tso Morari complex.
In addition, we consider the fate of (U)HP rocks formed during the early stages of collision that are not exhumed to the upper crust, but instead become entrained in a mid-crustal channel. Finally, we offer an explanation for the formation and exhumation of relatively young (< 20 Ma), strongly overprinted, eclogitic rocks exposed in the eastern Himalaya (e.g., Corrie and others, 2010) in terms of deep burial of a footwall ramp followed by transfer to and exhumation within the overriding channel (e.g., Jamieson and others, 2006).

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