MEETING REPORT

# Channel flow, ductile extrusion and exhumation of lower-mid crust in continental collision zones*

Currently, there has been a growing international interest amongst earth scientists about the world's orogenic belts to explain its exhumation in terms of the channel flow model. Recent interest in exhumation modelling in this direction has come after the discovery of partial molten mid-crustal rocks below Tibet. Interestingly, the Higher Himalayan Shear Zone (HHSZ), bounded by the Main Central Thrust (MCT) at the base and the Himalayan Detachment at the top, has been a classical study area to test the validity of this model.

The concept of 'channel flow' has its origin in fluid mechanics. In this flow mechanism, the fluid undergoes pressure gradient-induced unidirectional flow within an infinitely long parallel-walled channel. The sign of flow vorticity is opposite across a plane equidistant from, and parallel to, the two channel walls. In a conference on channel flow held by the Geological Society of London, M. P. Searle (Oxford University), R. Law (Virginia Tech) and L. Godin (Queens University) acted as technical convenors. Significant contributions related to the Himalaya–Tibet orogen were reported as follows.

Most of the participants supported the channel-flow model of exhumation of the HHSZ, or adopted it with modification. L. S. Hollister (Princeton University) reported partial melting at 35 km depth in the HHSZ, Bhutan Himalaya and visualized migmatite flow from 35 to 15 km depth, before its solidification. D. Grujic (Dalhousie University) considered the Greater Himalaya sequence to be more complex than a simple 'tooth-paste-like' extrusion of a channel, and the process of dome extrusion above the mid-crustal channel was considered as an additional mechanism for out-of sequence thrusts in the core of hot collisional orogens. P. Kapp (University of Arizona) suggested that the continued northward insertion of the Indian crust into Tibet can explain the pattern and persistence of extension and also the increasing plateau crustal thickness and elevation coeval with crustal shortening, which was possibly influenced by a northward crustal flow beneath the central and southern Tibetan plateau. Godin deciphered channel flow at the frontal part of the Greater Himalayan Slab in the Annapurna Manaslu range to get locked almost at the same time as in the Nar valley, central Nepal, and that exhumation of the Higher Himalayan gneisses was erosion-controlled.

A number of presentations assessed applicability of the channel-flow model with special reference to structural geology of the HHSZ. A. K. Jain (Indian Institute of Technology, Roorkee) proposed a two-stage exhumation model of the Higher Himalayan orogenic channel in the Zanskar section, whereby first top-to-SW sense of shearing was later superposed by Poiseuille flow to give rise to an apparent top-to-NE shearing at the top of the channel as the Zanskar Shear Zone. S. Mukherjee (IIT Roorkee) presented a three-stage numerical exhumation model of the HHSZ from the Sutlej section as follows: (i) uniform top-to-SW ductile shearing; (ii) combined simple shear and channel flow in ductile regime in shifting mode; and (iii) top-to-SW uniform brittle shearing, and presented velocity profiles for each of these cases. S. R. Wallis (Graduate School of Environmental Studies, Nagoya University) suggested that the structural history of the Himalayan Detachment needed revision on the basis of dominant top-to-N shear sense within the Malashan Granite, which has been intruded during the Himalayan orogeny. Strain analysis from deformed porphyroclasts by R. Carosi (Dipartimento di Scienze della Terra) from the Higher Himalayan Crystallines, Bhutan Himalaya revealed dominantly pure shear at the middle and simple shear at the boundaries of this extruding wedge. However, whether this information fits with channel flow or general shear mechanism, created controversy amongst the participants.

The channel flow mechanism was modelled by C. Beaumont (Dalhousie University), who described coupled thermo-mechanical numerical model of two-layered, mid-crustal channel flow and mentioned present attempts to remove its kinematic basal boundary conditions. S. Medvedev (Freie Univesität) presented the channel injection exhumation model, whereby the plateau mid-crustal channel continues in the transition zone, brings materials to the thickened transitional crust and finally widens the plateau, which is comparable to the Himalaya–Tibetan system. R. Bendick (University of Cambridge) presented an analytical solution for viscous fluid behaviour in a rigid, deformable channel under collision with a rigid indentor, which gave rise to long wavelength topographic signals similar to parts of the Tibetan plateau. Based on lubrication equations, M. K. Clark (California Institute of Technology) modelled dynamic stress associated with the obstruction of channel flow and suggested that the deep crust plays a principal role in elevating the eastern plateau by the influx of weak material from central Tibet. Searle suggested that the ductile Greater Himalayan Channel underwent sub-vertical compression during its southwestward extrusion with propagation of deformation outward with time from 20 to 16 Ma. W. S. F. Kidd (University of Albany) suggested that the strike-slip and the normal faults in the Tibetan crust are the products of horizontal velocity gradient in mid-crustal channel flow.

Answering the question of what initiated the channel flow, Searle suggested that channel flow was triggered by crustal melting and ductile extrusion of the Greater Himalayan Slab in the Mount Everest Massif, and that the extrusion stopped at 17–16 Ma back with the initiation of brittle deformation. D. J. Waters (Oxford University), from thermobarometric studies, concluded southwestward extrusion mechanism of the Greater Himalayan channel in the Zanskar section during early- to mid-Miocene Period, which was possibly triggered by a critical lowering of the effective viscosity of the channel accompanying melt generation. K. V. Hodges (Massachusetts Institute of Technology) worked out constraints for

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channel flow in Himalayan sections, viz. presence of partially molten crust at depth below the Tibetan plateau and coeval thrust movement of the MCT, and the extensional shearing within the Himalayan Detachment ~19 Ma back, and vigorous erosion of the Greater Himalayan slab as the force to start channel flow.

Geophysical works presented put important constraints in the channel-flow mechanism. Magnetotelluric studies of the Tibetan Plateau by A. G. Jones (Dublin Institute for Advanced Studies) revealed the Tibetan mid-crust to be highly electrically conductive, indicating its partially molten state suitable for channel-flow mode of exhumation. S. L. Klemperer (Stanford University) suggested from seismic studies complicated ductile flow of Greater Himalayan rocks within multiple thinner channels and predicted propagation of the extrusion mechanism from its place of origin within the Greater Himalayan Slab. On the basis of seismic receiver function analysis, S. S. Rai (National Geophysical Research Institute) concluded that in southern Tibet, the crust shallower than 15 km and that deeper than 60 km are seismically active, whereas the intermediate crust is seismically inactive. In my opinion, this inactive crust might be indicative of its molten state, which supports channel-flow mechanism of HHSZ exhumation.

Interestingly, a number of arguments against the channel-flow model were also put forward. T. M. Harrison (The Australian National University) opposed channel-flow mechanism in the Himalaya mainly on the basis of suspected aqueous nature of the melt phase below the Yadong–Gulu rift system and not partially molten rock, as commonly interpreted by others. In another presentation, he described the contact between Greater Himalayan Crystallines and Tethyan sediments as Kumar Sen Shear Zone (KSSZ) from Himachal Pradesh; documented three phases of deformation from the KSSZ with shear sense reversal within it, and questioned unidirectional channel-flow mechanism for the Higher Himalaya exhumation. P. J. Treloar (Kingston University) rejected channel-flow mechanism in the Himalaya due to the following reasons: (i) the absence of any thrust fault of same dimension as that of the MCT that activated coeval to extensional shearing within the Himalayan Detachment, and (ii) sections through the Indian plate thrust and stack in north Pakistan show no Miocene strain. Law worked out extrusion mechanism of the Greater Himalayan Slab in the Mount Everest region on the basis of dominantly pure shear-strain component as deduced from strain analysis and, therefore, questioned the validity of channel-flow mechanism. A. J. Martin (University of Arizona) presented a kinematic model that included several large displacement foreland breaking thrusts, a Lesser Himalayan duplex, and several large normal faults; explained structural, metamorphic, and thermochronological data from the Southern Annapurna range, Central Nepal; and pointed out that channel-flow model is not required to explain these facts. M. Caddick's (University of Cambridge) *P–T* calculation supported the concept of foreland steeping of the Himalayan thrust planes followed by their reactivation as extensional features; implied the difference between the Higher- and Lesser Himalayan sequences in terms of the lag time during which they resided at depth; and emphasized the fact that the initial exhumation of the highest grade units may not have been aided by the partial melt zone. Using geochronological data, P. G. DeCelles (University of Arizona) mentioned that the kinematic history of the Greater Himalayan Slab is not compatible with large-scale involvement of Tibetan middle crust in channel-flow, as currently articulated in the literature, and presented features to support channel-flow exhumation mode of this Himalayan unit to be more akin to critical taper models of thrust belt behaviour.

The conference ended with a discussion and revision of the presented thoughts on the following points: (i) What initiated channel flow in the Himalaya? (ii) When did the channel flow initiate in the Himalayan orogeny? (iii) When did the channel-flow stop in the Himalaya, or is it still active? All the abstracts have been encapsulated in a book.

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