Geodynamical Modeling of Collisional Orogens: From Small-Cold to Large-Hot Orogens and Applications to Lithoprobe Problems

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During the last decade we developed and used a range of finite element numerical models to gain insight into orogenesis. These models include: doubly (bi-) vergent, vise, accretionay wedge, Pyrenean and Alpine styles, and used both mechanical and thermomechanically coupled techniques applied to small-cold and large-hot orogens. Some of these model types have analogues in the orogens studied by Lithoprobe (e.g., Ellis and Beaumont, 1999).

Each of these orogen types occupies a characteristic position in an orogenic H-R diagram, just as star types plot in particular regions of the original stellar H-R diagram. The orogen H-R diagram, in which orogens are plotted according to their mass and temperature, provides a first-order classification and insight into the processes that occur in each orogen type. In addition, the evolution of orogens can be represented by paths in the H-R diagram.

Large-hot orogens are both massive and hot, leading to weak viscous regions of the crust that may contain partial melts and that may undergo gravitationally driven channel flows. Such flows can explain both the outward growth of the Tibetan plateau, as the channel tunnels outward, and the ductile extrusion of the Greater Himalayan Sequence.

Results from crustal-scale numerical models with self-generating mid-crustal channel flows and subduction-type kinematic basal boundary conditions (Beaumont et al., 2001, 2004, Jamieson et al., 2004) are certainly compatible with many first-order features of the Himalayan-Tibetan system. In these models radioactive self-heating of tectonically thickened crust leads to rheological 'melt-weakening', the development of a broad orogenic plateau, and efficient channel flows when the effective mid-crustal viscosity is 10^{19} Pa.s or less.

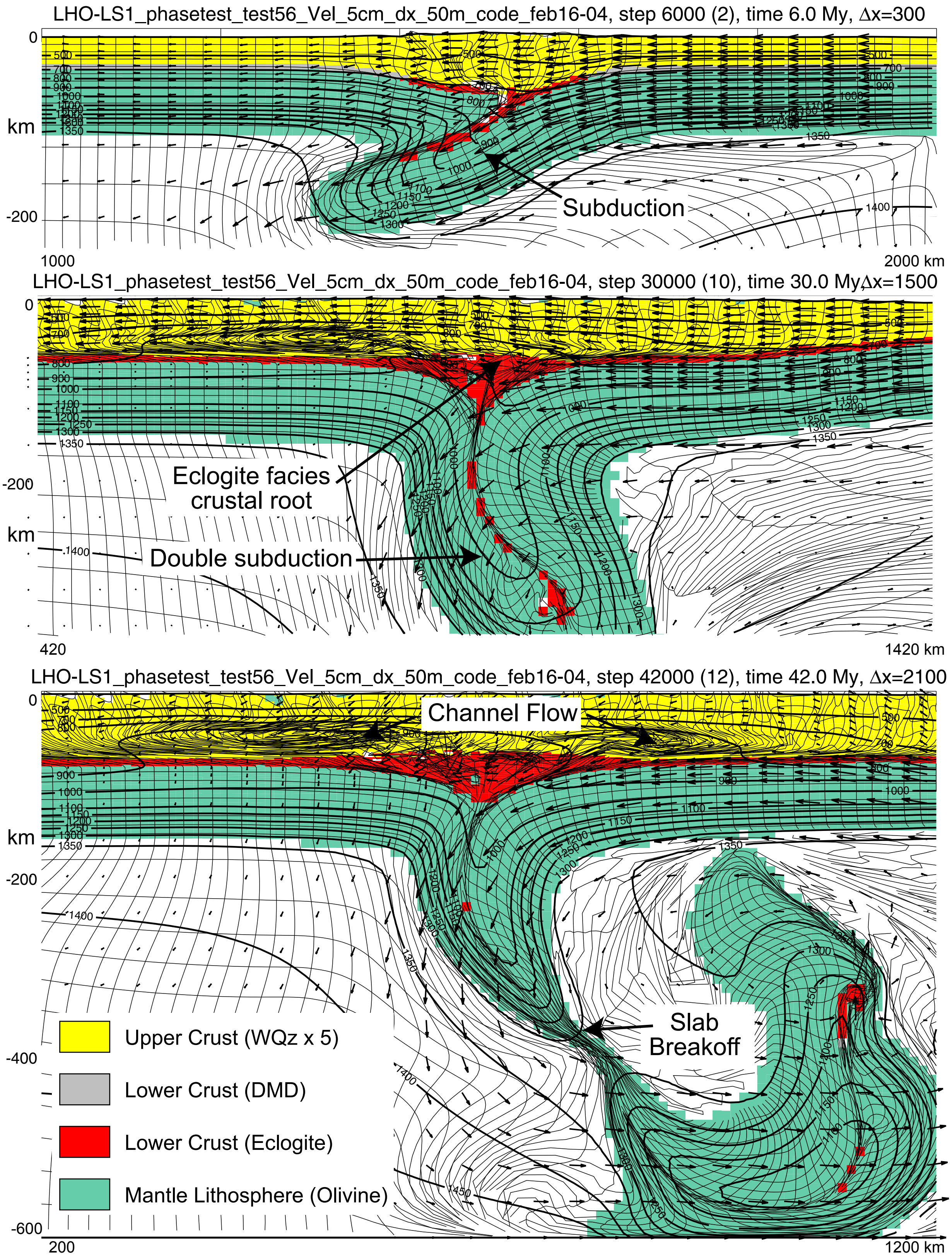
The focus of our recent research has been to broaden the investigation of large-hot orogens to models that include the lithosphere and upper mantle, thereby removing the need for the kinematic basal boundary conditions noted above. We also want to understand flow regimes in orogenic crust that is subcritical with respect to the ideal channel flows predicted by the numerical models in homogeneous melt-weakened crust. We regard the latter as an end member, which may only be possible beneath super-plateaus in giant collisional orogens, for example the Himalaya and Tibet. Such widespread channel flows may not be the best analogues for mid-crustal flows in more common situations such as cordilleran-type and other medium-sized collisional orogens.

In addition to: 1) the ideal homogeneous channel flow mode, we also recognize from the numerical model results; 2) the heterogenous channel flow mode, in which even relatively large scale blocks of refractory, non-fertile lower crust are detached and incorporated into the channel flow, and; 3) the hot fold-nappe mode, in which mid- and lower crust, which is forcibly expelled outward from the interior of the orogen, flows up and over stronger lower-crustal blocks that resist detachment and are therefore not incorporated into the flow. In the third flow regime the flow over stronger blocks creates large-scale highly ductile fold-nappes with overall strong flattening and extensional bulk strain and attenuated lower limbs. This last style of flow may be characteristic of crust that is subcritical in regard to ideal channel flow. That is, the crust fails to attain the necessary low bulk effective viscosity for efficient gravitationally-driven large-scale homogeneous channel flow. Under these circumstances the process that creates the hot fold-nappes is likely related to the tectonic boundary conditions. For example, the collision with the orogen of a relatively strong crustal block, which acts as a plunger or indentor, can initiate the outward flow over the block to form the expelled fold nappes. This process is particularly favoured when older cratonic, or oceanic, crust collides and cannot be assimilated by the orogen by the normal weakening processes (see Jamieson et al. abstract this volume).

There is also considerable debate concerning the mechanisms by which continental mantle lithosphere and perhaps lower crust are resorbed by the sublithospheric mantle during collisonal orogenesis, with subduction, ablative subduction, viscous dripping, delamination, and slab breakoff among the candidate mechanisms. The results of our recent upper mantle scale models exhibit a range of mantle-lithosphere interactions beneath large-hot orogens that depend on the mantle lithosphere rheology and temperature. The results (an example of which is shown in figure 1) are particularly sensitive to the bulk density contrast between the lithopheric mantle and the underlying mantle, with small variations leading to behaviours that range among advancing subduction with shortening and thickening of the retro-mantle lithosphere, advancing double subduction, normal asymmetric subduction, breakoff of the subucted slab, and delamination and rollback of the subducting mantle lithosphere. Combinations of these processes are also observed in the models with transient behaviours apparently related to the mass excess of the subducted lithophere and its strength. The sensitivity of the model behaviours to mantle density contrasts and other factors will be shown and the implications for the crustal flow regimes examined.

References: Beaumont, Jamieson, Nguyen & Lee (2001) Nature 414, 738-742; Beaumont, Jamieson, Nguyen & Medvedev (2004) J. Geophys. Res. 109, B06406,doi:1029/2003JB002809; Jamieson, Beaumont, Medvedev & Nguyen (2004) J. Geophys. Res. 109, B06407,doi:10.1029/2003/JB002811; Ellis & Beaumont (1999) Can. J. Earth Sci. 36, 1711-1741.

Figure 1: Three stages, 6, 30 and 42My, in the evolution of an upper mantle scale continental collision finite element model (2000x600km) for which convergence at 5cm/y equals 300, 1500 and 2100km. Arrows indicate velocity, fine lines are deformed Lagrangian mesh, and medium lines are isotherms (^{o}C). No surface erosion. A crustal channel develops above the eclogitic lower crust. Mantle lithosphere initially subducts then evolves to advancing double subduction and finally breaks off.



LHO-LS1_phasetest_test56_Vel_5cm_dx_50m_code_feb16-04, step 6000 (2), time 6.0 My, Δx=300
0
km
-200
1000
2000 km
Subduction
LHO-LS1_phasetest_test56_Vel_5cm_dx_50m_code_feb16-04, step 30000 (10), time 30.0 MyΔx=1500
0
-200
km
420
1420 km
Eclogite facies
crustal root
Double subduction
LHO-LS1_phasetest_test56_Vel_5cm_dx_50m_code_feb16-04, step 42000 (12), time 42.0 My, Δx=2100
0
km
-200
-400
-600
200
1200 km
Channel Flow
Slab
Breakoff
Upper Crust (WQz x 5)
Lower Crust (DMD)
Lower Crust (Eclogite)
Mantle Lithosphere (Olivine)