1. Introduction: Motivation and Objectives

The goal of the research is to improve our understanding of lithospheric tectonic processes over a range of scales through a coherent program in which basic, underlying processes are combined in an experimental modelling framework, the sensitivity of the model results to various hypotheses is examined, and the results are compared with observations from natural systems. The anticipated significance of the research work is the provision of a testable quantitative framework that describes and predicts lithospheric geodynamics and tectonics. The framework will be based on a parsimonious set of assumptions. The predictions can then be compared and contrasted with those from approaches based on other assumptions and with observations. Frameworks incompatible with observations are then rejected. Ultimately, 'All models are wrong, but some of them are useful', because they provide insight into system behaviour and point to key data necessary to discriminate among competing hypotheses.

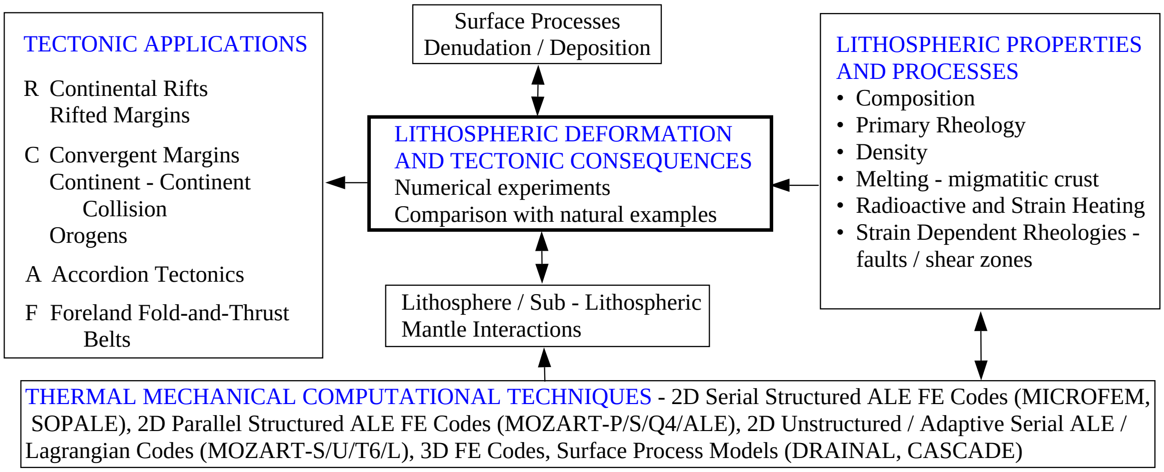

Fig. 1 Geodynamical Research Framework

2. Recent Progress in Research Activities Related to this Proposal

The framework (Fig.1) is designed to demonstrate a coherent program of related projects. This proposal builds on the successful Canada Research Chair research proposal from September 2000. Fig.1 illustrates the general approach in which lithospheric properties and processes that are considered important are incorporated in numerical models of lithospheric deformation to address specific tectonic applications, and the results of the numerical experiments are compared and contrasted with natural examples. The computational techniques are those developed by our group, or by our collaborators (e.g. CASCADE, Jean Braun).

3. Principal Results: Continent-Continent Collision (Fig.2)

3.1 Mantle Subduction Model of Orogenesis

We and our collaborators have published a series of papers on model predictions of crustal deformation in which the basal boundary condition corresponds to asymmetric subduction of the underlying mantle lithosphere. PAPER 1, Fig.3.6 shows the geometry and boundary conditions for this model and Plates 3.4a-3.6 show some specific results, including coupling between surface processes and tectonics. In other versions the subduction, or 'S', point advances or retreats kinematically as subduction progresses.

The model predictions are consistent with the large-scale crustal deformation styles of many small and medium sized orogens (e.g. Fig.2, Southern Alps, New Zealand, Beaumont *et al.*, 1996; Pyrenees, Beaumont *et al.*, 2000 (PAPER 2); European Alps, Pfiffner *et al.*, 2000). These models are both mechanical and thermal-mechanically coupled (e.g. Jamieson *et al.*, 1998).

3.2 The Role of the Mantle Lithosphere in Orogenesis (Fig.2)

Assimilation of lithosphere by the mantle during contraction is a pivotal problem in continental dynamics, with proposed mechanisms ranging from viscous distributed deformation and Rayleigh-Taylor (RT) type 'drips', through delamination and slab breakoff, to subduction. In response to criticism that we have focussed on one mechanism (the mantle subduction model described above) and have not considered others, we have recently developed an Arbitrary Lagrangian-Eulerian (ALE) finite element model for creeping flows with viscous and Coulomb materials (SOPALE, Fig.1) capable of representing the Earth to a depth of approx. 600km at moderate resolution (see PAPER 3 Fig.1). Flows are driven by

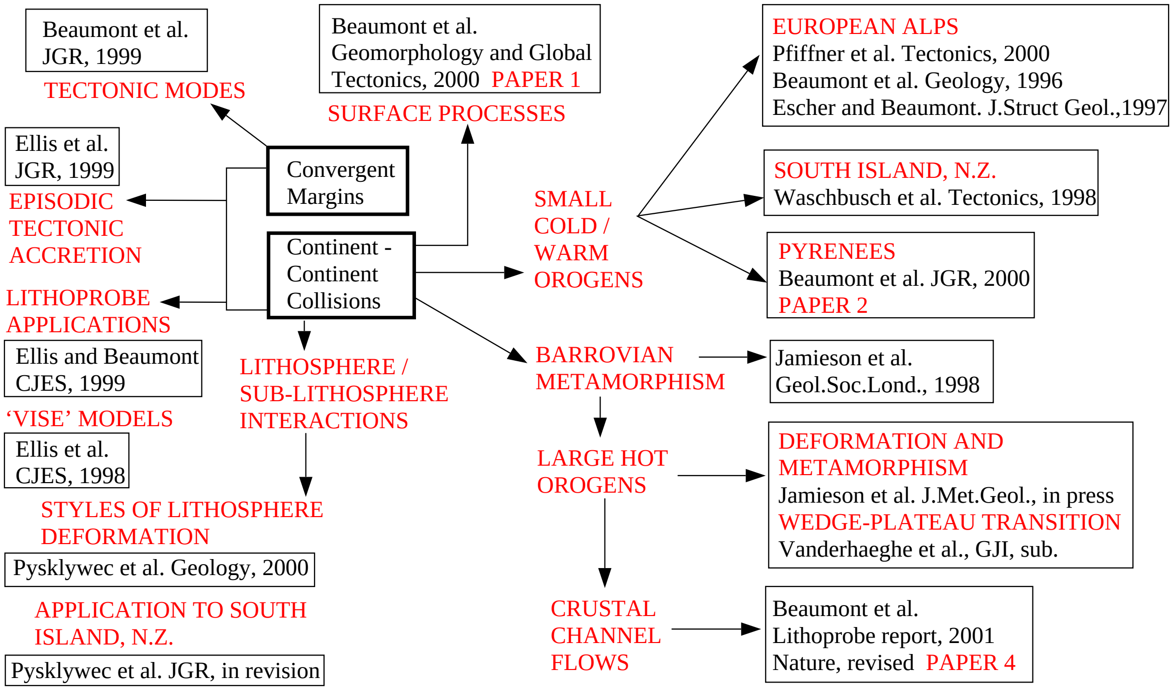

Fig. 2 Thematic Chart for Contractional Tectonics

gravitational forces and far field material fluxes through the boundaries. The importance of this approach is that the basal kinematic subduction b.c.'s are relaxed and the lithospheric deformation is determined dynamically.

Initial results (Pysklywec *et al.*, 2000) demonstrate several modes of lithospheric assimilation - subduction, double (ablative) subduction, dripping, slab breakoff and delamination. Equally important, subduction/underthrusting of the Coulomb part of the mantle lithosphere can be accompanied by viscous RT dripping of the lower lithosphere (Fig.4). These results imply that we need to consider a range of potential geodynamic interactions between the lithosphere and sub-lithospheric mantle (indicated in Figs. 1 and 2), not just subduction versus distributed viscous thickening. New seismic data combined with model experiments are poised to provide better constraints on lithosphere assimilation. For example, Pysklywec *et al.* (in revision for JGR), shows that models like that in the upper panel Fig.4 are compatible with the style of lithospheric deformation inferred beneath the South Island continental collision zone, New Zealand (e.g. Stern *et al.*, 2000).

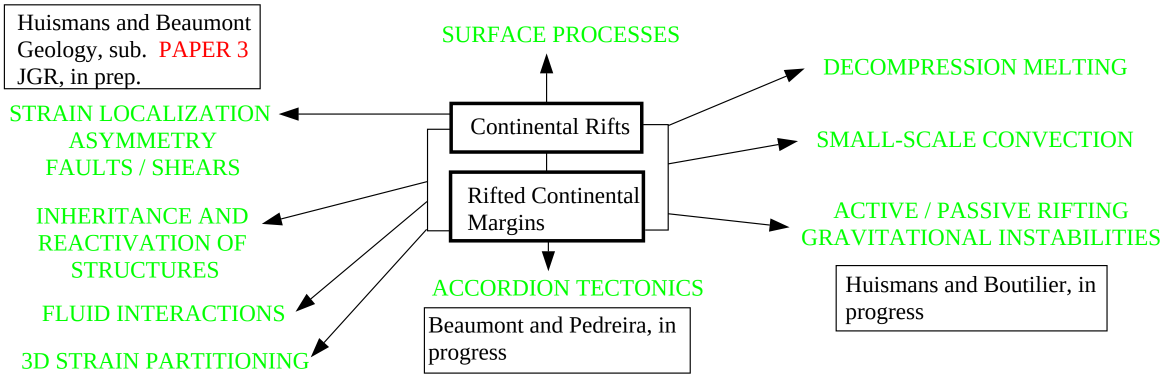

Fig. 3 Thematic Chart for Extensional Tectonics

3.3 Large Hot Orogens: Plateaus and Crustal Channel Flows (Fig.2)

We extended the mantle subduction model to investigate: 1) the orogenic wedge to plateau transition that occurs when the viscosity of thickened lower crust decreases as is becomes hotter (Vanderhaeghe *et al.*, sub.), and; 2) the relationship between deformation and metamorphism in similar thermal-mechanically coupled systems (Jamieson *et al.*, in press). Following Royden (1996), for example, we

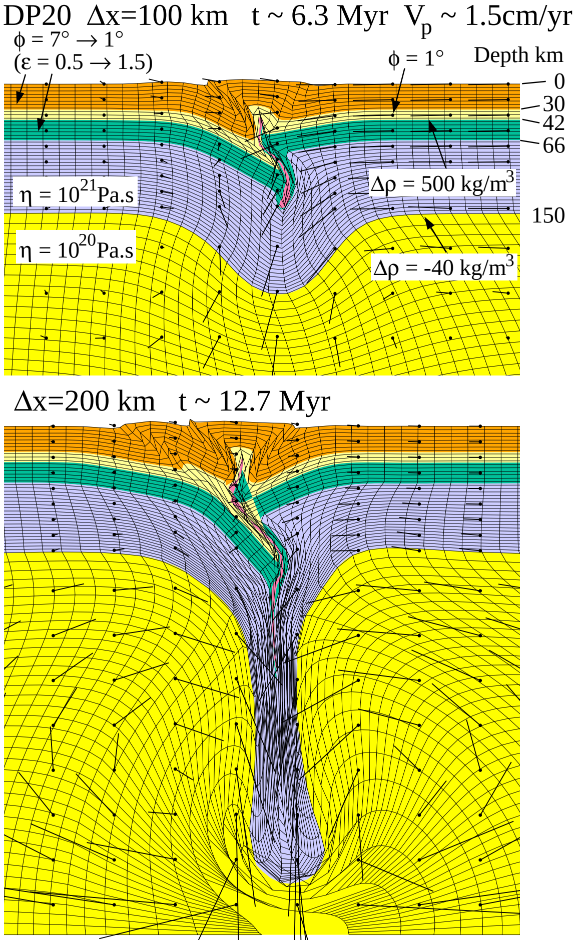

Figure 4. Small convergence (Δx=100, 200 km) ALE finite element model experiment showing underthrusting of Coulomb plastic upper mantle lithosphere (green) and viscous RT (dripping) of lower mantle lithosphere (mauve). η's are linear viscosities, Δρ's are density changes at base of crust and between mantle lithosphere and lower viscosity upper mantle (yellow). Crust has two layers, both frictional (Coulomb) plastic with internal angles of friction, ϕ, that decrease with strain softening. Mesh is deformed Lagrangian grid. Lines show velocities. Only the central 600 km of the total 2400 km of the model domain is shown. Scale is 1:1.

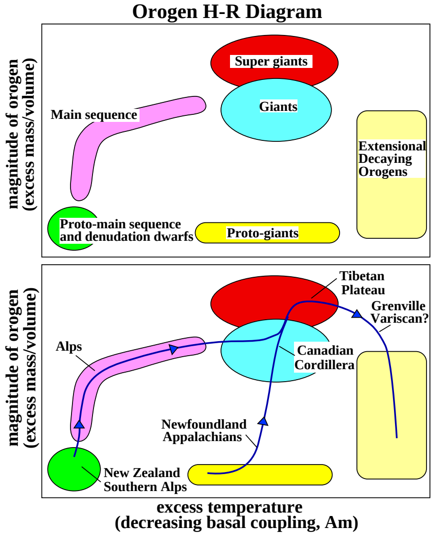

Fig.5 Proposed classification scheme for orogens, based on processes used to describe stellar evolution in the Herzsprung-Russell diagram.

have shown that gravitationally driven tectonic channel flows develop in thickened low viscosity crust (Jamieson *et al.*, in press; Beaumont *et al.*, 2001). PAPER 4 considers the exhumation and extrusion of such tectonic channels caused by denudation of plateau margins and proposes that this coupled system explains many tectonic, structural and metamorphic characteristics of the Himalaya and adjacent Tibetan Plateau.

3.4 Continental Rifts and Rifted Margins (Fig.3)

Huismans and Beaumont (in revision for Geology, PAPER 3) uses the thermal-mechanically coupled version of SOPALE to demonstrate that strain softening of the Coulomb regions of the crust naturally leads to asymmetry during rifting. These results indicate the potential importance of all processes that weaken specific parts of the lithosphere. The implications are discussed below.

4. Proposed Research

4.1 New Directions and Opportunities for Innovation

The convergence of several factors makes this an opportune time to investigate the role of weak faults and shear zones, melts and other weak materials, such as salt and shale, in lithospheric deformation. 1) Persistent weak faults and shears have long been considered to have a significant influence on the architecture and patterns of strain partitioning within the crust (e.g. Sibson, 1977; Handy, 1989; Holdsworth *et al.*, 1997 and many others). Although arguments exist against weak faults (e.g. Scholz, 2000; Townend and Zoback, 2000) recent research has begun to point to specific weakening mechanisms based on field (e.g. Holdsworth *et al.*,2001) and laboratory (e.g. Bos, 2001) data, and theory (e.g. Bos, 2001; Braun *et al.*, 1999). 2) These results lead to microphysically based rheological deformation 'laws' that predict how the crust may strain soften. For example, for polymineralic fault/shear zones phyllosilicates may determine the frictional-viscous behaviour where cataclasis and pressure solution dominate over dislocation creep and can lead to strain- and strain-rate weakening of a fault zone by factors of four, and possibly much more (Bos, 2001). 3) Improved finite element calculations on unstructured self-refining/coarsening meshes allow the effects of localized weakening on deformation to be computed accurately. 4) Melts reduce the effective bulk viscosity of the crust and PAPER 4 demonstrates the potential importance of this reduction on tectonic processes. 5) In sedimentary basins and thin-skinned fold-and-thrust belts, salt and shale subject to high fluid pressures are special weak materials that profoundly alter the deformation style. These 'weakening' effects will be investigated as part of the specific projects outlined below.

4.2 Development of Numerical Techniques

(Philippe Fullsack, Lykke Gemmer, Ritske Huismans, in collaboration with Jean Braun, ANU) (Persons involved in 'training' are discussed in the budget justification.)

The success of the research will be critically dependent on the development and use of improved numerical strategies/ techniques. Development of these techniques is a core

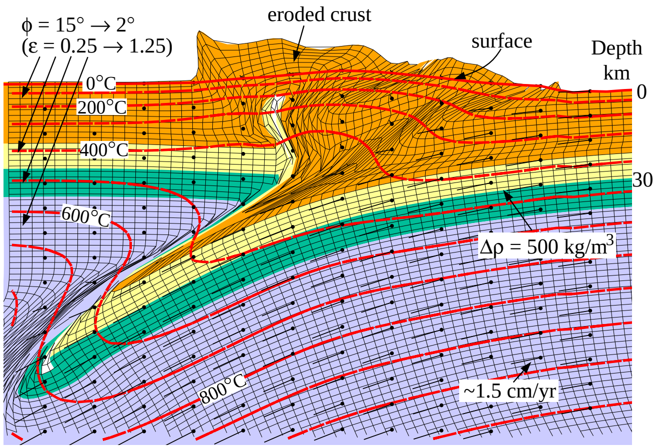

Fig.6 SOPALE prototype ‘Alps’ thermal-mechanical finite element model experiment showing bivergent crustal deformation and formation of upper crustal (orange) external basement massif above subducting/underthrusting lower crust (sand) and upper mantle (green) after convergence of 150km. Lower lithosphere (mauve) has distributed viscous deformation (similar to upper panel Fig.4). In Coulomb regime all materials strain soften from an internal angle of friction ϕ 15-2 ° over strain range ε 0.25-1.25. Ductile properties taken from laboratory data correspond to wet quartzite (upper crust), granulite (lower crust), and wet Aheim dunite (all mantle). Thermal expansivity is 2.5x10^{-5}. Upper crust has radioactive heating 2x10^{-6} μW/m^3. Surface denudation rate is proportional to local slope. 0° C isotherm is the surface. Material above has been eroded but is kept for illustration. Mesh is deformed Lagrangian grid (shown at low resolution). Lines show velocities and the lithosphere enters the domain at right boundary at approx 1.5cm/yr. Only a small part of the 1200x600km model domain is shown. Scale is 1:1.

research activity and we attribute past success to this ‘in house’ approach. Philippe Fullsack's developments of the MOZART platform (Fig.1) place us on the threshold of success in 2D and we are optimistic that medium resolution calculations on unstructured self-refining/ coarsening meshes can also be achieved in 3D. The thermal-mechanical version of SOPALE provides medium resolution (approx 150x400 meshes), structured, single processor, large convergence models. MOZART-P/S/Q4/ALE is the parallel equivalent of SOPALE and can achieve a single linear solve of a 600x800 2D f.e. system with 2 degrees of freedom per node in 12secs on 16 processors of the Dalhousie IBM SP6000. MOZART-S/U/T6/L is a near-complete serial unstructured/ adaptive code based on six-noded triangular elements. The next steps are to develop a 2D parallel version MOZART-P/U/T6/L and then work on strategies for efficient 3D codes. These strategies are discussed on the Geodynamics website and in the SUR Proposal to IBM.

5. Large Scale Lithospheric Processes

5.1 Toward a Unified Model of Orogenesis

(Chris Beaumont, Becky Jamieson, Mai Nguyen, Sergei Medvedev, Bonny Lee, Ritske Huismans, PhD graduate student, in collaboration with Russ Pysklywec, U of Toronto)

A general question concerns the development of a unified model of orogenesis. Which processes are key to orogenesis? Fig.5 (from Beaumont *et al.*, 2001) provides a conceptual classification of orogens that is based on the relative effects of orogen size and temperature. Although simple, it allows the progression from Small Cold states along the Main Sequence to Giants/Super Giants to be recognized as a series of related states. Our proposed research on Large Scale Contractional Lithospheric Processes seeks to develop a unified model for the evolution through each of these states of the Orogen H-R diagram, initially in 2D but ultimately in 3D.

It is proposed to develop the Small Convergence Lithospheric Scale thermal-mechanical models further to consider progressively longer timescales and larger amounts of convergence and to carry out the calculations at greater numerical resolution so that processes that manifest at the crustal scale (e.g. channel flows) can be accurately calculated. For the first stage, Small Convergence, initial results are published (Pysklywec *et al.*, 2000). Prototypes for Medium Convergence (e.g. Fig.6) show that low resolution models corresponding to the European Alps, for example, are tractable. The rheology of the prototype (Fig.6) has strain softening during Coulomb deformation, and ductile flow laws based on laboratory measurements. Slope-dependent surface denudation is included. Processes including strain-dependence of ductile flow, strain heating, and bulk viscosity reduction on crustal melting have yet to be included.

The purpose of these models in the context of the Alps will be to investigate: 1) the oceanic subduction to continental collision transition; 2) the relative roles of strain-dependent material properties and variable crustal composition in creating thrust/fold nappes, characteristic of the Penninic nappe stack, and external basement massifs; 3) the evolving metamorphism (do the models predict early HP-LT conditions followed by Barrovian metamorphism in the model equivalent of the Lepontine Dome, and what are the relative effects of strain-rate and radioactive heating?); 4) the development of dynamical overpressure as a possible cause for UHP metamorphism; 5) the styles of mantle lithosphere resorption (does slab breakoff occur, and if so what are the metamorphic and morphogenic consequences?).

Equivalent models will be used to investigate the sensitivity of orogenesis to important controls - convergence velocity, efficiency of surface denudation/deposition, and the properties/processes listed in

Fig.1. Model results will also be compared with observations from other small and medium sized natural orogens.

Large convergence models will be developed for comparison with Giant (e.g. Himalayan-Tibetan type) orogens and will be used to expand the investigations of channel flows and coupling with surface and sub-lithospheric processes. Other potential applications include the Andes, the Grenvillian Orogen and the Canadian Cordillera.

5.2 Continental Rifts and Rifted Continental Margins

(Ritske Huismans, Lykke Gemmer, Chris Beaumont, PhD graduate student, in collaboration with Ross Boutilier, GSC-A, and Jean Braun, ANU)

The current focus (Huismans and Beaumont, sub., PAPER 3 and in prep.) is on the effect of strain-dependent material properties on the geometry of rifts and, in particular, their asymmetry. By using the same approach of increased numerical resolution provided by improved numerical techniques outlined in 4.1 and 4.2 we will investigate: 1) proposed mechanisms for lithospheric strain softening (high fluid pressures, phyllosilicates and pressure solution, and transitions in deformation mechanisms, for example accompanying grain size reduction) on mesoscale strain partitioning, shear zone development, and faulting. The intent is to understand how localization occurs dynamically and how/when weak zones are abandoned as loci of deformation when they lose geometrical compliance. In addition, the other processes listed in Fig. 3 (green, upper case) and core complexes will be investigated.

5.3 Accordion Tectonics

(David Pedreira, Chris Beaumont, Lykke Gemmer, Ritske Huismans)

'Accordion tectonics' is our terminology for superimposed phases of extensional/contractional tectonics. It follows naturally from 5.1 and 5.2 to investigate the effects of superposition.

Among other projects, including rift inversion and rifting of collisional orogens, the Alpine evolution of the Pyrenees is a particularly good example of inversion tectonics. It is proposed to investigate the correlation between the tectonic characteristics of the Cretaceous rift and the tectonic style of the superimposed Pyrenean orogen as a function of position along the Iberian/European plate boundary. This research, and associated modelling, will constitute David Pedreira's postdoctoral project which will be part of a collaboration among the Spanish Universities of Oviedo and Barcelona and the Geodynamics Group at Dalhousie (see budget for explanation).

6. Small Scale Lithospheric Processes

6.1 Foreland Thin-Skinned Fold-and-Thrust Belts (FTB's)

(Chris Beaumont, Mai Nguyen, Ph.D. graduate student, in collaboration Glen Stockmal, GSC-C)

Critical wedge theory (e.g. Dahlen, 1984) predicts the first-order geometry and state of stress of FTB's. Our interest is in the way FTB's grow dynamically, the dependence of their internal structure on the stratigraphy and rheology of the deformed sediments (including effects of weak materials like salt and shale), and their response to denudational and depositional surface processes. Fig.7 illustrates a SOPALE prototype bivergent 'sandbox-type' numerical model with, and without, slope-dependent denudation. We propose to develop high- resolution models (up to 20m vertically x 100m horizontally) using MOZART-P/S/Q4/ALE, to include the effects of fluid flow pressure and flexural compensation, and to determine the importance of material anisotropy and its strain dependence. Our intention is to understand the mechanics of particular structures (triangle zones, duplexes, imbricate stacks, etc) and the controls on their development. Comparisons will be made with natural FTB's, particularly the Foothills and Rocky Mountains of the Canadian Cordillera, for which there are extensive data and Glen Stockmal has interpretation experience.

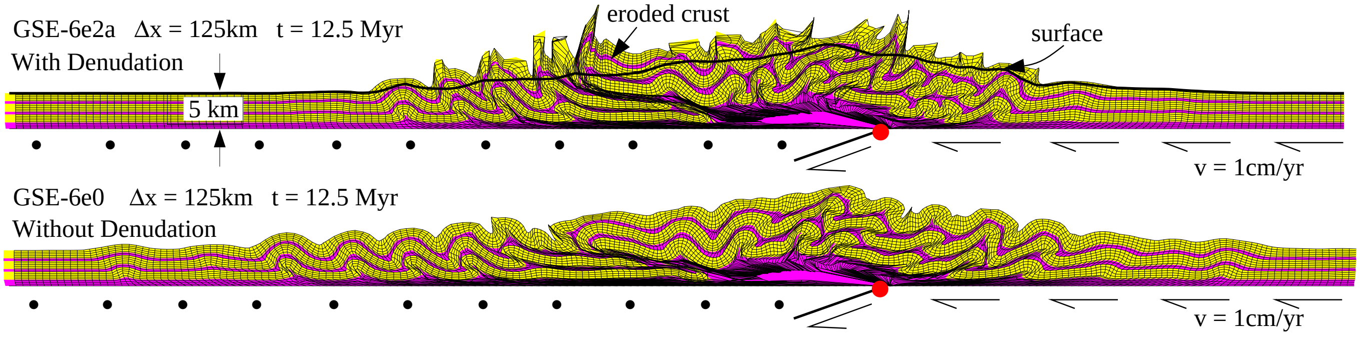

Fig.7 Effect of moderate slope-dependent denudation on FTB models. Coulomb material $\phi=30°$ (yellow), viscous material $\eta=10^{21}$ Pa.s strain softens to 2×10^{20} Pa.s over strain range ε 0.25-1.00 (magenta). Eroded crust retained for illustration. Scale = 1:1.

References

References in figures 2 and 3 are listed in the personal data form 100.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., and Lee, B., revised. Himalayan tectonics explained by extrusion of a low-viscosity channel coupled to focussed surface denudation, *Nature*.

Beaumont, C., Ellis, S., Jamieson, R.A., Pfiffner, O.A., Nguyen, M.H., and Lee, B., 2001. Contrasting geodynamics of small cold and giant hot orogens, Exploration Geodynamics, AGU Chapman Conference, Perth, Australia, Aug. 2001, http://www.ned.dem.csiro.au/research/solidMech/Geodynamics/Chapman.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., and Lee, B., 2001. Mid-crustal channel flow in large hot orogens: Results from coupled thermal-mechanical models, in: *Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) and Cordilleran Tectonics Workshop, Lithoprobe Report 79*, 112-170.

Beaumont, C., Muñoz, J.A., Hamilton, J., and Fullsack, P., 2000. Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models, *Jour. Geophys. Res.*, *105*, 8121-8145.

Beaumont, C., Kamp, P.J.J., Hamilton, J., and Fullsack, P., 1996. The continental collision zone, South Island, New Zealand: Comparison of geodynamical models and observations, *Jour. Geophysical Res.*, *101*, 3333-3359.

Bos, B., 2001. *Faults, Fluids and Friction*, Ph.D Thesis, Universiteit Utrecht, Netherlands, 157pp.

Braun, J., Chéry, J., Poliakov, A., Mainprice, D., Vauchez, A., Tomassi, A., and Daignières, M., 1999. A simple parameterization of strain localization in the ductile regime due to grain size reduction: A case study for olivine, *Jour. Geophys. Res.*, *104*, 25167-25181.

Dahlen, F.A., 1984. Noncohesive critical Coulomb wedges: an exact solution, *Jour. Geophys. Res.*, *89*, 10125-10133.

Handy, M.R., 1989. Deformation regimes and the rheological evolution of fault zones in the lithosphere: the effects of pressure, temperature, grain size and time, *Tectonophysics*, *163*, 119-152.

Holdsworth, R.E., Strachan, R.A., Magloughlin, J., and Knipe, R.J., eds. 2001. *The Nature and Significance of Fault Zone Weakening*, *Geol. Soc. London Spec. Publ.*, *186*, 328pp.

Holdsworth, R.E., Butler,C.A., and Roberts, A.M., 1997. The recognition of reactivation during continental deformation, *Jour. Geol. Soc. London*, *154*, 73-78.

Huismans, R.S., and Beaumont, C., in revision. Asymmetric lithospheric extension: the role of frictional-plastic strain softening inferred from numerical experiments, *Geology*.

Jamieson, R.A., Beaumont, C., Nguyen, M.H., and Lee, B., in press. Interaction of metamorphism, deformation, and exhumation in large convergent orogens, *Jour. Metamorphic Geol*.

Jamieson, R.A., Beaumont, C., Fullsack, P., and Lee, B., 1998. Barrovian regional metamorphism: Where's the heat? in: *What Controls Metamorphism and Metamorphic Reactions?*, eds, P. Treloar and P.O'Brien, *Geol. Soc. London Spec. Publ., 138*, 23-51.

Pfiffner, O.A., Ellis, S., and Beaumont, C., 2000. Collision tectonics in the Swiss Alps: insight from geodynamical models, *Tectonics*, *19*, 1065-1094.

Pysklywec, R.N., Beaumont, C., and Fullsack, P., in revision. Lithospheric deformation during the early stages of continental collision: numerical experiments and comparison with South Island, New Zealand, sub. to *Jour. Geophysical Res.*

Pysklywec, R.N., Beaumont, C., and Fullsack, P., 2000. Modelling the behavior of the continental mantle lithosphere during plate convergence, *Geology*, *28*, 655-658.

Royden, L.H., 1996. Coupling and decoupling of crust and mantle in convergent orogens: Implications for strain partitioning in the crust, *Jour. Geophys. Res.*, *101*, 17697-17705.

Stern, T., Molnar, P., Okaya, D., Eberhart-Philips, D., 2000. Teleseismic P wave delays and modes of shortening the mantle lithosphere beneath South Island, New Zealand, *Jour. Geophys. Res.*, *105*, 21615-21631.

Townend, J., and Zoback, M.D., 2000. How faulting keeps the crust strong, *Geology*, *28*, 399-402.

Scholz, C.H., 2000. Evidence for a strong San Andreas fault, *Geology*, *28*, 163-166.

Sibson, R.H., 1977, Fault rocks and fault mechanisms, *Jour. Geol. Soc. London*, *133*, 191-213.

Vanderhaeghe, O., Medvedev, S., Fullsack, P., Beaumont, C., and Jamieson, R.A., sub. Dynamic evolution of orogenic wedges and continental plateaus: insights from thermal-mechanical modeling of convergent orogens, *Geophysical Jour. International*.