# GEODYNAMICS: RECENT ADVANCES IN QUANTITATIVE MODELING OF COMPRESSIONAL OROGENS

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## Contents

## Summary

We report here the recent advances brought to the field of continental dynamics by the development and use of novel and complex numerical methods to solve the equations governing the deformation of crustal rocks, incorporating the effects of large and localized deformation as well as the coupling between crustal deformation and surface processes (erosion/sedimentation). Under the basic assumption that in regions of continental convergence, mantle shortening is accommodated by a subduction-like process, the model predicts that the crust behaves like a doubly-vergent critical wedge. Models also demonstrate that the dynamics of subduction-driven orogens is, in many circumstances, determined by two factors: the strength distribution within the crust (including its strong dependency on temperature) and the efficiency of surficial

processes. We report and comment on the work performed with this new generation of numerical models to show how they have led to a better understanding of the dynamical evolution of a range of past and presently active orogens.

## 1. Introduction

Much advance has been made in recent years in our understanding of the dynamics of the Earth's crust, that is the way it deforms in response to the large scale motion of the plates that form the Earth's lithosphere. The advent of large, global data sets, such as topography, gravity, geoid and magnetic anomaly, as well as better geochronological, geochemical and geophysical data are responsible for this new step forward. These new observations provide more accurate constraints on the mechanics of the Earth's crust, and the rate at which it responds to various tectonic forcings.

But the quality and quantity of this newly acquired data have driven the Earth scientist to develop new methods of analysis and interpretation. This effort has been much helped by the rapid advances in computing and has led to the development of a new discipline: quantitative modeling of Earth processes. Methods developed by engineers to quantify a range of physical processes including structural mechanics, fluid dynamics and heat transport have been used, adapted, and, in many cases, further developed for the study of Earth processes. Modeling of mantle convection and lithosphere deformation have received special attention. Complex rheologies, finite deformation, coupling to surface processes are now included in models of crustal/lithospheric deformation and permit the testing, in a quantitative manner, the plausibility of hypotheses suggested by the data. Numerical modeling provides the perfect framework to integrate a large variety of data and to test scenarios put forward by geologists. Furthermore, numerical models have evolved to the point where they can be used to suggest and/or predict complex behaviorbehaviors that arise most frequently from the non-linear nature of the many processes at play in the Earth but also their interactions. These behaviorbehaviors could hardly be derived from a simple analysis of the data. For example, the strong feedbacks that have recently been suggested between tectonics and atmospheric dynamics, not only through the strong control that topography has on precipitation, but also through the strong control that climate has on erosion, have been suggested, in many cases, by numerical models.

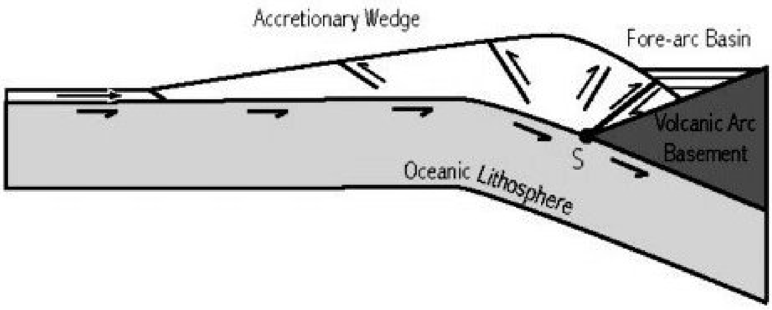
Here we present a short summary of a collection of recent works by a group of scientists that were not only responsible for developing many of the new advances in numerical methods but also for using them to develop a new framework to understand the dynamics of compressional orogens. As we will show in this review, compressional orogens offer a special challenge to the numerical modeler. On the one hand, they are regions where faulting, uplift and erosion combine to create some of the most complex structures observed at the Earth's surface. For this reason, they are difficult objects to study and many more years of painstaking data collection will be necessary to improve an already large set of observations. On the other hand, compressional orogens are where the evidence on the tectonic and deformation history of the Earth's crust is the most readily accessible; uplift and erosion bring rocks to the surface where they can be directly sampled and analyzed.

In this review, we report on the development of new concepts and ideas that were either suggested or confirmed by the numerical models. We show how the numerical models have helped to make sense of complex, sometimes apparently conflicting pieces of evidence. We also describe how the models have been applied to particular orogens.

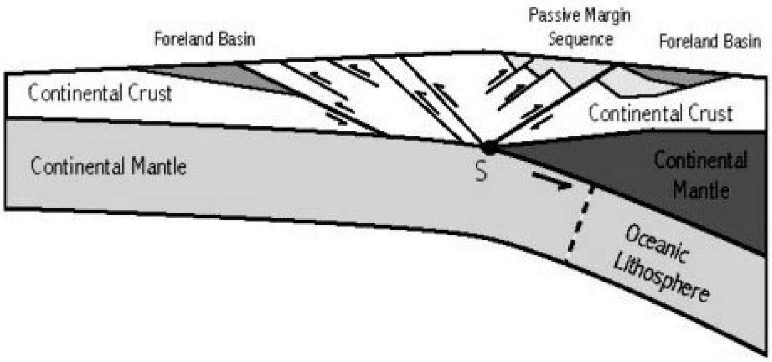
## 2. 'S-point' dynamics

### 2.1. Introduction

a) Active Margin



b) Continent-continent Collision



c) Geodynamic Model

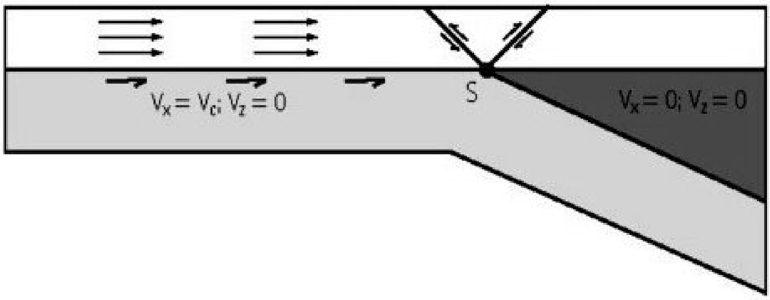


Figure 1. Generalization of the concept of (a) an accretionary wedge at an ocean continent plate boundary to (b) a continent-continent collision driven by subduction of the underlying mantle lithosphere. (c) Boundary conditions used in the geodynamic model to represent the process of mantle subduction.

The basic assumption behind the large body of work that is presented in this review is that crustal deformation in compressional orogenic belts is driven by basal shortening driven by a velocity discontinuity, or strain singularity (the so-called 'S-point'), that represents subduction of the underlying mantle. This type of continental collision is assumed to represent the next step in the evolution of an oceanic subduction zone when a second continent, or continental fragment, becomes involved along the plate boundary (Figure 1).

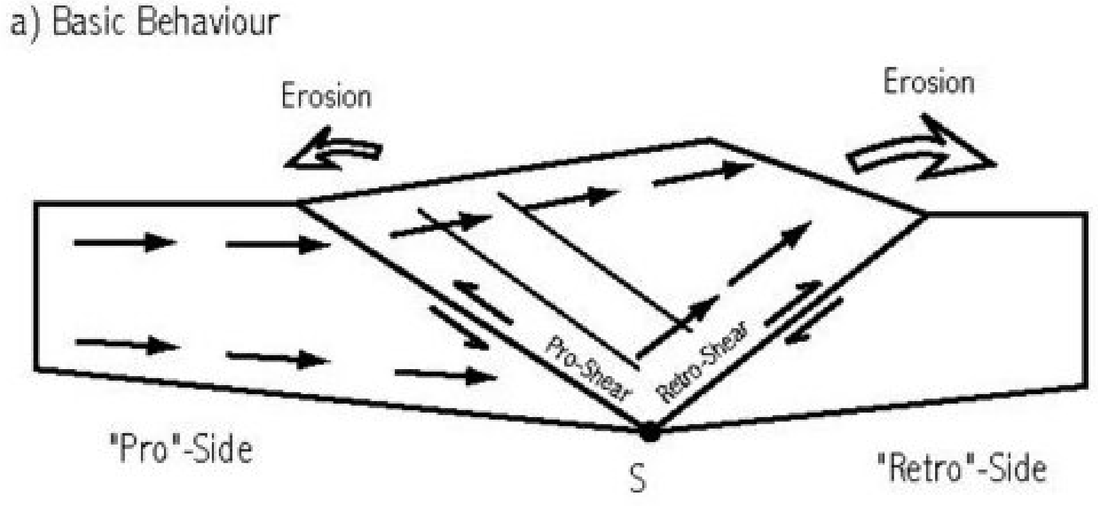
The exact nature of the mechanism responsible for mantle subduction, its initiation and evolution through time, are not addressed in these models. The response of the crust to a simple boundary condition is the focus. A large variety of responses have been evidenced which arise from a variety of assumptions on the rheology of the crust (and especially the strength of the coupling between crust and mantle), the size and location of pre-existing mechanical heterogeneities, and the efficiency of erosion and sediment transport processes to redistribute mass along the top stress-free surface.

These studies were driven by a need to understand system behavior, and by a detailed analysis of new datasets on convergent orogens. In several instances, the models contributed to defining the questions that required further data collection. It is clear, however, that the evolution of the modeling originates from improved methodology and computing power, which allowed modelers to create structures and patterns of exhumation more directly comparable to geological data and geophysical images. It followed that the application of a simple boundary condition, i.e.,, the velocity discontinuity representing mantle subduction, created large-scale structures that were very similar to observed crustal faults/shear zones in orogenic belts. This led to a re-interpretation of even the first-order, large-scale observations in orogenic belts, such as the type and geometry of structures, sedimentation patterns in the foreland, the distribution of metamorphic grades and ages for a range of thermo-barometers.

### 2.2. Basic response

The response of a layer of frictional material to shortening driven by a basal velocity discontinuity was first illustrated in sandbox experiments, and reproduced, later, in a set of numerical experiments. Following initiation of convergence between the two continental blocks, the first structure to develop is a set of opposedly-dipping or "step-up" shear zones rooting into the velocity discontinuity (a narrow slit in the base of the sandbox through which a piece of cloth/mylar is pulled from underneath one of the two halves of the model - see Figure 2a). Reverse movement on both structures leads, at first, to uplift of the triangular plug comprised between the two step-up shears. In cases where the time scale for erosion and removal of material from the orogen is smaller than the tectonic time scale, surface processes act to maintain a low-amplitude, constant surface topography. Uplift of the inner part of the orogen leads to rock exhumation at a uniform rate across the orogen.

This basic deformation pattern appears symmetrical when considered in a Lagrangian frame of reference, i.e., for an observer attached to the deforming rocks (Figure 2a). When described in an absolute or Eulerian system of reference, i.e., fixed with respect to the deforming crust or, by convention, attached to the continent that is not undergoing subduction, the "retro"-side of Willett et al. (1993), rock (or particle) paths are strongly asymmetrical. Rocks are advected into the orogen from the "pro"-side (i.e., the side attached to the subducting mantle), pass through the pro-shear and are then thrust up, along the retro-shear. Deformation along the pro-shear is thus instantaneous and affects all rocks entering the orogen; deformation along the retro-shear is long-lasting, but only affects the rocks that enter the orogen at large depth and are subsequently exhumed in the vicinity of the retro-shear.



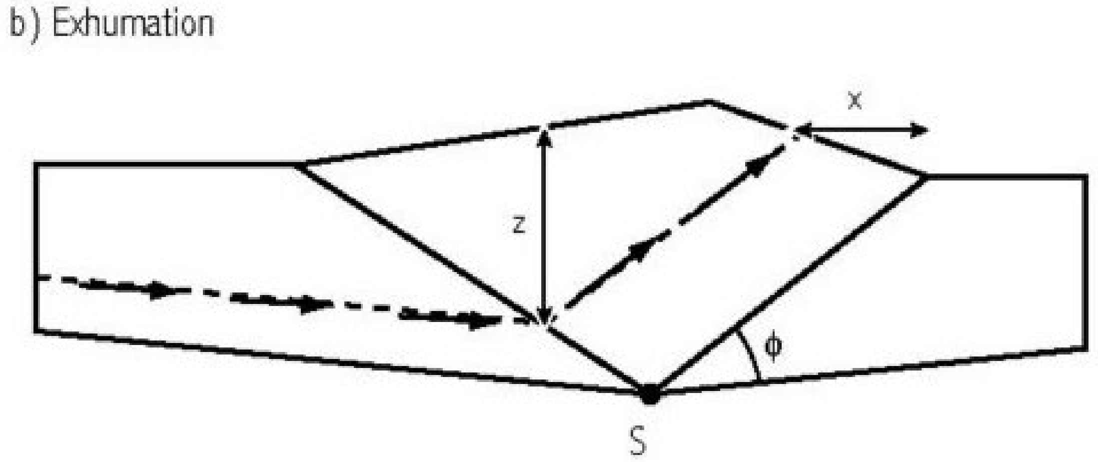


Figure 2 (a) Basic behavior of a crustal layer shortened by a basal velocity discontinuity. (b) Particle paths and exhumation depth $z$ as a function of distance from the main retro-shear $x$.

Further convergence leads to an enhancement of the asymmetry (Figure 2b), especially in the amount of total exhumation experienced by rocks that emerge at various location across the orogen: rocks that are exumed near the retro-shear come from the largest depths (i.e., the base of the deforming layer), whereas rocks that are exhumed near the pro-shear have experienced come from near surface depths. The relationship between exhumation depth ($z$) and distance from the retro shear ($x$) thus depends on the dip of the retro-shear ($\phi$): $z=x \tan \phi$.

## 2.3. A word on the numerical methods

This basic mechanical behavior was first reproduced in a series of sandbox experiments. They were later reproduced and elaborated on mainly by numerical methods. This was made possible by the development of new numerical methods that, through remeshing, allowed for large deformation and surface erosion. Several algorithms were employed, notably the ALE (Arbitrary Langrangian Eulerian) method and the DLR (Dynamic Lagrangian Remeshing) method. Combined with recent improvements in computational power, these methods led to a quantum jump in the predictive capabilities of numerical models.

The basic equation that is solved in all dynamical model of crustal/lithospheric deformation is the equation of force balance, which must be combined to a rheological law relating strain and/or strain rate to stresses. Two approaches have been used; one assumes that, on geological time scales, rocks behave like a visco-plastic material, the other assumes that rock behaves intrinsically as an elastic solid which displays a brittle (and frictional) response to large stresses and creep at elevated temperature. The first approach requires the solution of the Stokes equation adapted to take into account the non-linear nature of the rheology; the second approach requires the solution of the basic equations of structural mechanics. The main advantage of the viscous approach is that large deformations are easily handled but the tracking of material/chemical boundaries is difficult and requires the introduction of methods such as ALE. In the elastic approach, finite deformation requires the introduction of non-linear strains and the tracking of element rotation. Most elastic/solid methods are based on a Lagrangian representation of the deformation. The advection of nodes with the flow of material facilitates greatly the tracking of material particles but large deformations lead to mesh deformation and the need to frequently redefine the mesh, as is done in DLR method.

The main improvement of both approaches resides in their ability to predict the path that a rock particle follows during its transit through an orogen. By coupling the equation of force balance to the equation of advective/conductive heat transport and production, one can make accurate predictions on the pressure and temperature conditions experienced by a given rock particle through the development of the orogen. These predictions can be compared to a range of geological, metamorphic and chonological data. Coupled to a surface processes model and a flexural isostatic model, the mechanical model can also be used to predict patterns of sedimentation in foreland basins that may form on either side of the orogen.

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## Bibliography

Allegre, C. (1882). Structure and evolution of the Himalaya-Tibet orogenic belt. *Nature* **307**, 17-22.

Batt, G. E. & Braun, J. (1997). On the thermomechanical evolution of compressional orogens. *Geophysical Journal International* **128**, 364-382.

Batt, G. E. & Braun, J. (1999). The tectonic evolution of the Southern Alps, New Zealand: insights from fully thermally coupled dynamical modeling. *Geophysical Journal International* **136**, 403-420.

Batt, G. E., Braun, J., Kohn, B. P. & McDougall, I. (2000). Thermochronological analysis of the dynamics of the Southern Alps, New Zealand. *Geological Society of America Bulletin* **112**, 250-266.

Beaumont, C., Ellis, S., Hamilton, J. & Fullsack, P. (1996a). Mechanical models for subduction-collision tectonics of Alpine-type compressional orogens. *Geology* **24**, 675-678.

Beaumont, C., Ellis, S. & Pfiffner, A. (1999a). Dynamics of sediment subdurction-accretion at convergent margins: short-term modes, long-term deformation, and tectonic implications. *Journal of Geophysical Research* **104**, 17,573-17601.

Beaumont, C., Fullsack, P. & Hamilton, J. (1992). Erosional control of active compressional orogens. In McClay, K.R., editor, Thrust Tectonics, p. 1-18, New York. Chapman and Hall.

Beaumont, C., Fullsack, P. & Hamilton, J. (1994). Styles of crustal deformation in compressional orogens caused by subduction of the underlying lithosphere. *Tectonophysics* **232**, 119-132.

Beaumont, C., Jamieson, R. A., Nguyen, M. H. & Lee, B. (in press). Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. *Nature*.

Beaumont, C., Kamp., P. J. J., Hamliton, J. and Fullsack, P. (1996b). The continental collision zone, South Island, New Zealand: comparison of geodynamical models and observations. *Journal of Geophysical Research* **101**, 3333-3359.

Beaumont, C., Kooi, H. and Willett, S. (1999b). Coupled tectonic-surface process models with applications to rifted margins and collisional orogens. In Summerfield, M., editor, Geomorphology and Global Tectonics, pp. 29-55, New York, John Wiley and Sons Ltd.

Beaumont, C., Munoz, J. A., Hamilton, J. & Fullsack, P. (2000) Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models. *Journal of Geophysical Research* **105**, 8121-8145.

Beaumont, C. & Quinlan, G. (1994). A geodynamic framework for interpreting crustal scale reflectivity patterns in compressional orogens. *Geophysical Journal International* **116**, 754-783.

Braun, J. (1993). Three-dimensional numerical modeling of compressional orogens: thrust geometry and oblique convergence. *Geology* **21**, 153-156.

Braun, J. (1994). Three-dimensional numerical simulations of crustal-scale wrenching using a non-linear failure criterion. *Journal of Structural Geology* **16**, 1173-1186.

Braun, J. & Beaumont, C. (1995). Three dimensional numerical experiments of strain partitioning at oblique plate boundaries: implications for contrasting tectonic styles in the southern Coast Ranges, California and central South Island, New Zealand. *Journal of Geophysical Research* **100**, 18,059-18,074.

Braun, J., Chéry, J., Poliakov, A., Mainprice, D., Vauchez, A., Tomassi, A. & Daignieres, M. (1999). A simple parameterization of strain localization in the ductile regime due to grain-size reduction: a case study for olivine. *Journal of Geophysical Research* **104**, 25,167-25-181.

Braun, J. & Sambridge, M. (1994). Dynamical Lagrangian Remeshing (DLR): A new algorithm for solving large strain deformation problems and its application to fault-propagation folding. *Earth and Planetary Science Letters* **124**, 211-220.

Braun, J. & Sambridge, M. (1997). Modeling landscape evolution on geological time scales: a new method based on irregular spatial discretization. *Basin Research* **9**, 27-52.

Braun, J. & Shaw, R. D. (1998a). Contrasting styles of lithospreic deformation along the northern margin of the Amadeus Basin, central Australia. In Braun, J., Dooley, J., Goleby, B., Klootwijk, C. and van der Hilst, R., editors, The Structure and Evolution of the Australian Lithosphere, pp. 139-156, Washington, D.C. AGU Geodynamic Series.

Braun, J. & Shaw, R. D. (1998b). Extension of the Fitzroy Trough: an example of reactivation tectonics by intra-lithospheric delamination. In Braun, J., Dooley, J., Goleby, B., Klootwijk, C. and van der Hilst, R., editors, The Structure and Evolution of the Australian Lithosphere, pp. 157-174, Washington, D.C. AGU Geodynamic Series.

Braun, J. & Shaw, R. D. (2001). A thin-plate model of Paleozoic deformation of the Australian lithosphere: implications for understanding the dynamics of intracratonic deformation. In Miller, J., Holdsworth, R., Buick, I. & Hand, M., editors, Continental Reactivation and Reworking. *London. Geological Society, Special Publication* **184**.

Buck, W.R. & Sokoutis, D. (1994). Analogue model of gravitational collapse and surface extension during continental convergence. *Nature* **369**, 737-740.

Burbridge, D. & Braun, J. (1998). Analog modeling of obliquely convergent continental plate boundaries. *Journal of Geophysical Research* **103**, 15,221-15,237.

Byrne, D. E., Davis, D. M., & Sykes, L. R. (1988). Loci and maximum size of thrust earthquakes and the mechanics of the shallow region of subduction zones. *Tectonics* **7**, 833-857.

Chemenda, A. I., Mattauer, M., Malavieille, J. & Bokun, A. N. (1995). A mechanism for syn-collisional rock exhumation and associated normal faulting: results from physical modeling. *Earth and Planetary Science Letters* **132**, 225-232.

Chéry, J., Vilotte, J.-P. & Daignières, M. (1991). Thermomechanical evolution of a thinned continental lithosphere under compression: implications for the Pyrenees. *Journal of Geophysical Research* **96**, 4385-4412.

Choukroune, P. & Team, E. (1989). The ECORS Prynenean deep seismic profile reflection data and the overall structure of an orogenic belt. *Tectonics* **8**, 23-39.

Crespi, J. M., Chan, Y.-C. & Swain, M. (1996). Synorogenic extension and exhumation of the Taiwan hinterland. *Geology* **24**, 247-250.

Dahlen, F. A. (1984). Noncohesive critical coulomb wedges: an exact solution. *Journal of Geophysical Research* **89**, 10,125-10,133.

Dahlen, F. A., Suppe, J. & Davis, D. (1984). Mechanics of fold-and-thrust belts and accretionary wedges: cohesive coulomb theory. *Journal of Geophysical Research* **89**, 10,087-10,101.

Davis, D., Suppe, J. & Dahlen, F. A.. (1983). ). Mechanics of fold-and-thrust belts and accretionary wedges. *Journal of Geophysical Research* **88**, 1153-1172.

Ellis, S. (1995). Continental convergens: length scales, aspect ratios, and styles of crustal deformation. PhD thesis, Dalhousie University, Halifax, N.S. Canada.

Ellis, S. (1996). Forces driving continental collision: reconciling indentation and mantle subduction tectonics. *Geology* **24**, 699-702.

Ellis, S., Beaumont, C., Jamieson, R. A. & Quinlan, G. (1998). Continental collision including a weak zone: the vise model and its application to the Newfoundland Appalachians. *Canadian Journal of Earth Sciences* **35**, 1323-1346.

Ellis, S., Beaumont, C. & Pfiffner, O. A. (1999). Geodynamic models of crustal-scale episodic tectonic accretion and underplating in subduction zones. *Journal of Geophysical Research* **104**, 15, 169-15,190.

England, P. & Houseman, G. A. (1989). Extension during continental convergense, with application to the Tibetian Plateau. *Journal of Geophysical Research* **94**, 17,561-17,579.

England, P., Houseman, G. & Sonder, L. (1985). Length scales for continental deformation in convergent, divergent, and strike-slip environments: analytical and approximate solutions for a thin-viscous sheet model. *Journal of Geophysical Research* **90**. 4797-4810.

Frederiksen, S. & Braun, J. (2001). Numerical modeling of strain localisation in the mantle lithosphere. *Earth and Planetary Science Letters* **188**, 241-251.

Fullsack, P. (1995). An arbitrary lagrangian-eulerian formulation for creeping flows and its application in tectonic models. *Geophysical Journal International* **120**, 1-23.

Genser, J., Van Wees, J. D., Cloetingh, S. & Neubauer, F. (1996). Eastern alpine tectonometamorphic evolution: constrains from two-dimensional p-t-t modeling. *Tectonics* **15**, 584-604.

Goleby, B. R., Shaw, R. D., Wright, C., Kennett, B. L. N. & Lambeck, K. (1989). Geophysical evidence for 'thick-skinned' crustal deformation in central Australia. *Nature* **337**, 325-330.

Handy, M. R., Braun, J., Brown, M., Kukowski, N., Paterson, M. S., Schmid, S. M., Stöckhert, B., Stüwe, K., Thompson, A. B. & Wosnitza, E. (2001). Rheology and geodynamic modeling: the next step forward. *International Journal of Earth Sciences* **90**, 1149-1156.

Hauck, M. L., Nelson, K. D., Brown, L. D., Zhao, W. & Ross, A. R. (1998). Crustal structure of the Himalayan orogen at ≈ 90° longitude form Project INDEPTH deep reflection profiles. *Tectonics* **17**, 481-500.

Houseman, G. A., McKenzie, D. P. & Molnar, P. (1981). Convective instability of a thinckened boundary layer and its relevance for the thermal evolution of continental convergent belts. *Journal fo Geophysical Research* **86**, 6115-6132.

Houseman, G. A. & Molnar, P. (1997). Gravitational (Rayleigh-Taylor) instability of a layer with non-linear viscosity and convective thinning of continental lithosphere. *Geophysical Journal International* **128**, 125-150.

Jamieson, R. A., Beaumont, C., Hamilton, J. & Fullsack, P. (1996). Tectonic assembly of inverted metamorphic sequences. *Geology* **24**, 839-842.

Jamieson, R. A., Beaumont, C., Fullsack, P. & Lee, B. (1998). Barrovian regional metamorphism: Where's the heat? In Treloar, P. & O'Brien, P., editors, What Controls Metamorphism and Metamorphic Reactions? pp. 23-51, London. *Geological Society of London Special Publication* **138**.

Koons, P. O. (1990) Two-sided orogen: collision and erosion from the sandbox to the southern alps, new zealand. *Geology* **18**, 679-682.

Koons, P. O., Craw, D., Cox, S. C., Upton, P., Templeton, A. S. & Chamberlain, C. P. (1998). Fluid flow during active oblique convergence: a southern alps model from mechanical and geochemical observations. *Geology* **26**, 159-162.

Malavieille, J. (1984) Modélisation expérimentale des chevauchements imbriqués: applications aux chaînes des montages. *Bulletin de la Société Géologique de France* **26**, 129-138.

Molnar, P., Anderson, H. J. Audoine, E., Eberhart-Phillips, D., Gledhill, K. R., Klosko, E. R., McEvilly, T. V., Okaya, D., Kane Savagre, M. T. S. & Wu, F. (1999). Continuous deformation versus faulting through the continental lithosphere of New Zealand. *Science* **286**, 516-519.

Montgomery, D. R., Balco, G. & Willett, S. D. (2001). Climate, tectonics and the morphology of the Andes. *Geology* **29**, 579-582.

Moresi, L. & Solomatov, V. (1998). Mantle convection with a brittle lithosphere: thoughts on the global tectonics styles of the Earth and Venus. *Geophysical Journal International* **133**, 669-682.

Pfiffner, O. A., Ellis, S. & Beaumont, C. (2000). Collision tectonics in the Swiss Alps: insight from geodynamic modeling. *Tectonics* **19**, 1065-1094.

Pope, D. C. & Willett, S. D. (1998). A thermal-mechanical model for crustal thickening in the central Andes driven by ablative subduction. *Geology* **16**, 511-514.

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

Pysklywec, R. N., Beaumont, C. & Fullsack, P. (in press). Lithospheric deformation during the early stages of continental collision: numerical experiments and comparison with South Island, New Zealand. *Journal of Geophysical Research*.

Quinlan, G., Beaumont, C. & Hall, J. (1993). Tectonic model for crustal seismic reflectivity patterns in compressional orogens. *Geology* **21**, 663-666.

Royden, L. H. (1996). Coupling and decoupling of crust and mantle in convergent orogens: implications for strain partitioning in the crust. *Journal of Geophysical Research* **101**, 17,679-17,705.

Shaw, R. D. (1991). The tectonic development of the amadeus Basin, central Australia. In Korsch, R. J., editor, Geological and Geophysical Studies in the Amadeus Basin, Central Australia, pp. 429-461, Canberra, Australia. *Bulletin of the Bureau of Mineral Resources of Australia* **236**.

Sheffels, B. M. (1995). Mountain building in the central Andes: an assessment of the contribution of crustal shortening. *International Geology Review* **37**, 128-153.

Vèrges, J. & Munoz, J. A. (1990). Thrust sequences in the southern central Pyrenees. *Bulletin de la Société Géologique de France* **8**, 256-271.

Vilotte, J.-P., Daigniéres, M. & Madariaga, R. (1982). Numerical modeling of intra-plate deformation. Simple mechanical models of continental collision. *Journal of Geophysical Research* **87 (10)**, 709-10,728.

Vissers, R. L. M., Platt, J. P. & van der Wal, D., (1995). Late orogenic extension of the Betic Cordillera and the Alboran Domain: a lithospheric view. *Tectonics* **14**, 786-803.

Waschbusch, P., Batt, G. & Beaumont, C. (1995): Subduction zone retreat and recent tectonics of the South Island of New Zealand. *Tectonics* **14**, 786-803.

Waschbusch, P. & Beaumont, C. (1996). Effect of a retreating subduction zone on deformation in simple regions of plate convergence. *Journal of Geophysical Research* **101**, 28,133-28,148.

Wellman, H. (1979). An uplift map for the South Island of New Zealand, and a model for uplift of the Southern Alps. In Walcott, R. I. & Cresswell, M. M., editors, The Origin of the Southern Alps, pp. 13-20. New Zealand, Bulletin, Royal Society.

Whipple, K. X. (2001). Geomorphic limits to climate-induced increases in topographic relief. *American Journal of Science* **301**, 313-325.

Willett, S. (1999a). Rheological dependence of extension in wedge models of convergent orogens. *Tectonophysic*s **305**, 419-435.

Willett, S. & Beaumont, C. (1994). Subduction of Asian lithospheric mantle beneath Tibet inferred from models of continental collision. *Nature* **369**, 642-645.

Willett, S. & Beaumont, C. & Fullsack, P. (1993). Mechanical model for the tectonics of doubly-vergent compressional orogens. *Geology* **21**, 371-374.

Willett, S. D. (1999b). Orogeny and orography: the effects of erosion on the structure of mountain belts. *Journal of Geophysical Research* **104**, 28,957-28,981.

Willett, S. D., Slingerland, R. & Hovius, N. (2991). Uplift, shortening, and steady state topography in active mountain belts. *American Journal of Science* **301**, 455-485.

## Biographical Sketch

**Jean Braun** is a Senior Fellow in the Research School of Earth Sciences at Australian National University in Canberra, Australia. He has been educated in physics and geophysics in Belgium and Canada and works on numerical modeling of a wide range of geodynamic problems including landscape evolution, extensional tectonics of mountain belts, fluid dynamics and rock rheology. He also has a particular interest in the development of new mathematical methods.