3D tectonic evolution of the North Island of New Zealand

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1 Introduction

It has often been postulated that the deep (mostly mantle) part of the continental lithosphere could be recycled into the mantle under conditions experienced during lithospheric thickening. This process has been proposed to explain geological and geophysical evidence such as sudden subsidence and uplift, erosion rate changes, regional volcanism, remnant gravity anomalies, and heat flow anomalies. The development of such gravitational instabilities is the result of a balance between driving buoyancy forces due to variations in relative density, and resisting viscous stresses.

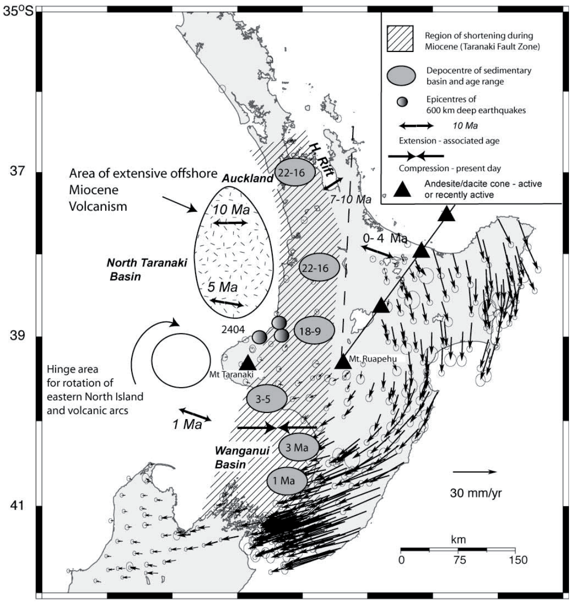

Figure 1 – Map of the N. Island New Zealand showing the region where it is thought 70-100 km of shortening has occurred. Also shown are depocentre location and ages for a series of sedimentary basins that appear to have migrated southwards with time.

We are interested in understanding the basic processes by which the lower most parts of the continental lithosphere are recycled into the deep mantle: the mechanisms involved in the removal, how much of the crust can be removed, and the observable consequences of lithospheric detachment such as regional and rapid uplift of the Earth's surface. The central and western North Island of New Zealand (Figure 1) is a favourable locality to test some of these concepts. It has been hypothesized that the mantle lithosphere of the central western North Island was thickened during a compressive phase from 35-5 Ma, and then convectively removed when the thickened lithosphere became gravitationaly unstable — a form of Rayleigh-Taylor instability. If this happened at around 5 Ma, it coincided with the onset of rifting of the Taupo Volcanic Zone — a back-arc rift that has propagated into continental lithosphere but only to approximately 39 S. Its southern limit is marked by an abrupt and substantial change of crustal and upper mantle structure in the western North Island across an east-west line between Ruapehu and Taranaki volcanoes (RT line). We speculate that the asthenosphere flow that followed the lithospheric detachment north of 39 S was instrumental in initiating rifting.

Evidence for convective removal of mantle lithosphere can come from seismic tomography, where developing instabilities are "caught in the act" (Gemmer and Houseman, 2007; Stern et al., 2000; Valera et al., 2008; Zandt et al., 2004) or from compiled geological and geophysical evidence (Garzione et al., 2006; Kay and Kay, 1993; Molnar et al., 1993). The case for a an ongoing mantle instability removal beneath the western North Island is based largely on the anomalous surface uplift record (Pulford and Stern, 2004), the missing mantle lid based on seismic observations (Horspool et al., 2006) distribution of Hi-K volcanics (Price et al., 1999) and location of 600 km deep earthquakes (Boddington et al., 2004). While any one of the forgoing observations from western North Island could be explained in a more conventional sense, its explaining the package with a single unifying process that makes the case of convectively removed mantle instability an attractive alternative (Stern et al., 2006).

2 Numerical model

When direct comparisons with geological, geochemical, and geophysical evidence are sought, numerical simulations need to include realistic thermophysical properties for all the materials composing the model. In recent years, particular attention has been given to the self-consistent combination of mineral physics and thermodynamic calculations into fluid dynamical simulations of the Earth (e.g. Li and Gerya, 2009; Tirone et al., 2009). This approach has two important advantages over other standard methods. One is that it maximizes the internal consistency of the system by intertwining all physical parameters and governing equations through a thermodynamic model. Therefore, a given change in density due for instance to a change in P-T conditions is also reflected in appropriate (thermodynamically consistent) changes in all other parameters (e.g. heat capacity, compressibility, etc). The other advantage is that it allows realistic modelling of metamorphic reactions driven by the dynamics of the system. These include not only solid state reactions but also hydration/dehydration reactions, partial melting, and melt-solid interactions. This in turn is essential when comparing real petrological and geophysical observables with simulation results (Gerya et al., 2006; Beaumont et al., 2009; Li and Gerya, 2009).

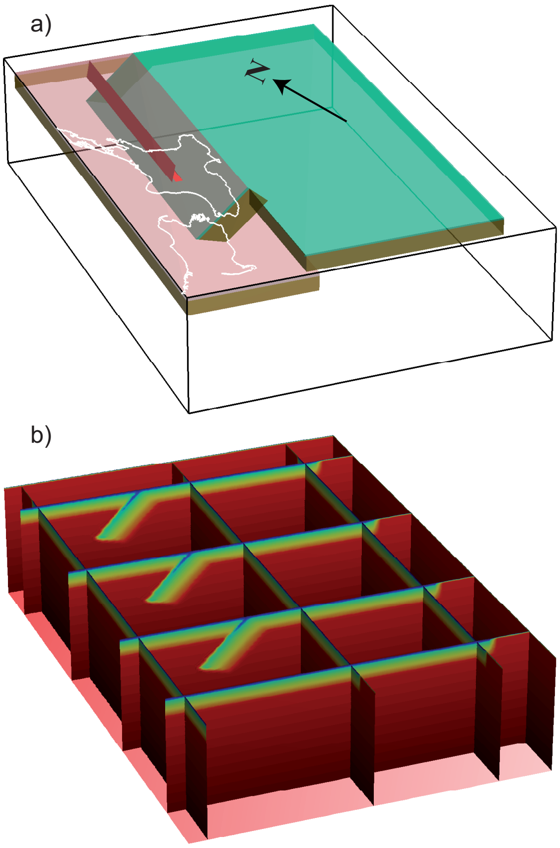

Figure 2 – Initial setup of materials (a) and temperatures(b).

Melting of the mantle is modelled as batch melting (Katz et al., 2003), including the extraction of water from partially molten rocks through an appropriate bulk partition coefficient. The amount of melt extracted from mantle parcels is tracked through the simulation and used to compute depletion effects on the bulk density and solidus temperature of the residue.

The usual conservation equations (mass, momentum and energy) are solved using the Underworld computational framework (`www.underworldproject.org`) (Moresi et al., 2003), which has been modified accordingly to account for the coupling with the petrophysical code perplex (Connolly, 2005).

Our numerical models have both plastic (brittle) and viscous (Newtonian and non-Newtonian) rheologies. The brittle behaviour of rocks is assumed to follow a von Mises criterion and the viscous behaviour follows one or two power-laws to acount for both diffusion and dislocation

Table 1 – Bulk rock compositions[wt%].

Composition	Cont. UC[a]	Oce. UC[b]	Mantle[c]
SiO_2	65.81	48.99	45.34
TiO_2	0.66	1.27	0.0
Al_2O_3	15.31	14.89	4.53
FeO	5.34	9.86	8.16
MgO	2.82	7.56	38.08
CaO	4.10	11.26	3.53
Na_2O	3.31	2.70	0.36
K_2O	2.65	0.49	0.03
H_2O	0*	2.96	0.0

[a] Estimated using 70% of upper crust composition and 30% of middle crust composition from Rudnick and Gao (2003); [b] recast from the normal MORB composition in Schilling et al. (1983); [c] Recast from McDonough and Sun (1995).

deformation mechanisms.

3 Initial setup and boundary conditions

The domain of the computational model is a box with size 1000×1500×660km in the x, y, z directions respectively. The mechanical boundary condition are free-slip on the entire boundary. Because we do not impose velocity to either force or stop plate motion, the movement of the materials and the stress field emerge self-consistently from the balance between buoyancy, pressure and viscous forces. The initial setup of the model (shown in Fig. 2) includes a "free" subducting plate and an upper plate, each one with the corresponding layer of crust. The chemical compositions for mantle and crust is shown in Table **??**. The upper plate has an weak zone representing the current back-arc of the Kermadec subduction zone, where we expect the deformation to be concentrated.

4 Summary

We present a work-in-progress to study lithospheric delamination processes. We want to study the onset and dynamical evolution of such a process and the consequent geological and geophysical observables.

It has been proposed that a delamination has recently formed in the North Island of New Zealand (Stern et al., 2006). This locations provides unusually complete geological and geophysical record that can be used to test this hypotesis.

We have developed a coupled numerical scheme between a thermomechanical code (Underworld) and a petro-physical model, that allows to reproduce an accurate density field and also gives information on the metamorphic reactions happening. Our model includes not only solid-state mineral reactions but also hydration and melting, providing in accurate density estimations. These, together with up-to-date rheological laws, gie us the best conditions to reproduce gravitational instabilities.

Finally we presented the basic setup of a model in which we have been working lately. This model does not intend to reproduce the exact configuration of the North Island, but to include the main tectonic features involved. Using that model we will study the general deformation pattern, see if it is enough to reproduce observables and current deformation and finally, see if a superimposed delamination mechanism helps to reconcile observables.

References

C. Beaumont, R.A. Jamieson, J.P. Butler, and C.J. Warren. Crustal structure: A key constraint on the mechanism of ultra-high-pressure rock exhumation. *Earth Planet. Sci. Lett.*, 287:116–129, 2009.

T. Boddington, C.J. Parkin, and D. Gubbins. Isolated deep earthquakes beneath the north island of new zealand. *Geophys. J. Int.*, 158

(3):972–982, 2004.

J.A.D. Connolly. Computation of phase equilibria by linear programming: A tool for geodynamic modeling and its application to subduction zone decarbonation. *Earth Planet. Sci. Lett.*, 236:524–541, 2005.

C.N. Garzione, P. Molnar, J.C. Libarkin, and B.J. MacFadden. Rapid late miocene rise of the bolivian altiplano: Evidence for removal of mantle lithosphere. *Earth Planet. Sci. Lett.*, 241(3-4):543–556, 2006.

L. Gemmer and G.A. Houseman. Convergence and extension driven by lithospheric gravitational instability: evolution of the alpine-carpathian-pannonian system. *Geophys. J. Int.*, 168(3):1276–1290, 2007.

T. Gerya, J. Connolly, D. Yuen, W. Gorczyk, and A. Capel. Seismic implications of mantle wedge plumes. *Phys. Earth Planet. Int.*, 156: 59–74, 2006.

N.A. Horspool, M.K. Savage, and S. Bannister. Implications for intraplate volcanism and back-arc deformation in north western new zealand, from joint inversion of receiver functions and surface waves. *Geophys. J. Int.*, 166 (3):1466–1483, 2006.

R.F. Katz, M. Spiegelman, and C. Langmuir. A new parameterization of hydrous mantle melting. *Geochem. Geophys. Geosys.*, 4(9), 2003. doi: 10.1029/2002GC000433.

R.W. Kay and S. Kay. Delamination and delamination magmatism. *Tectonophysics*, 219 (1-3):177–189, 1993.

Z. Li and T. Gerya. Polyphase formation and exhumation of high- to ultrahigh-pressure rocks in continental subduction zone: Numerical modeling and application to the sulu ultrahigh-pressure terrane in eastern china. *J. Geophys. Res.*, 114:59–74, 2009. doi: 10.1029/2008JB005935.

W.F. McDonough and S. Sun. The composition of the earth. *Chem. Geol.*, 120:223–253, 1995.

P. Molnar, P. England, and J. Martinod. Mantle dynamics, uplift of the tibetan plateau, and the indian monsoon. *Reviews of Geoph.*, 31(4): 357–396, 1993.

L. Moresi, F. Dufour, and H. B. Muhlhaus. A Lagrangian integration point finite element method for large deformation modeling of viscoelastic geomaterials. *Journal Of Computational Physics*, 184:476–497, 2003.

R.C. Price, R.B. Stewart, J.D. Woodhead, and I.E.M. Smith. Petrogenesis og high-k arc magmas: Evidence from egmont volcano, north island, new zealand. *Journal of Petrology*, 40 (1):167–197, 1999.

A. Pulford and T. Stern. Pliocene exhumation and landscape evolution of central north island, new zealand: The role of the upper mantle. *J. Geophys. Res.*, 109(F01016), 2004. doi: 10.1029/2003JF000046.

R.L. Rudnick and S. Gao. Composition of the continental crust. In R.L. Rudnick, H.D. Holland, and K.K. Turekian, editors, *Treatise on Geochemistry*, pages 1–64. Elsevier, 2003.

J. Schilling, M. Zajac, R. Evans, T. Johnston, W. White, J. Devine, and R. Kingsley. Petrologic and geochemical variations along the mid-atlantic ridge from 29 degrees n to 73 degrees. *N. Am. J. Sci.*, 283:510–586, 1983.

T. Stern, P. Molnar, D. Okaya, and D. Eberhart-Phillips. Teleseismic p wave delays and modes of shortening the mantle lithosphere beneath south island new zealand. *J. Geophys. Res.*, 105(21):615–621, 2000.

T.A. Stern, W.R. Stratford, and M.L. Salmon. Subduction evolution and mantle dynamics at a continental margin: Central north island, new zealand. *Reviews of Geoph.*, 44(4), 2006.

M. Tirone, J. Ganguly, and J. Morgan. Modeling petrological geodynamics in the earths mantle. *Geochem. Geophys. Geosys.*, 10:59–74, 2009. doi: 10.1029/2008GC002168.

J.L. Valera, A.M. Negredo, and A. Villase nor. Asymmetric delamination and convective removal numerical modeling: Comparison with evolutionary models for the alboran sea region. *Pure and Applied Geophysics*, 165(8):1683–1706, 2008. doi: 10.1007/s00024-008-0395-8.

G. Zandt, H. Gilbert, T.J. Owens, J. Saleeby, and C.H. Jones. Active foundering of a continental arc root beneath the southern sierra nevada in california. *Nature*, 431(7004):41–46, 2004.