Flow partitioning in the lithosphere during core complex formation: An interactive evolutionary computation approach using particle-in-cell finite elements

Klaus Gessner, Chris Wijns, Louis Moresi, Fabio Boschetti and Alison Ord

CSIRO Exploration and Mining, PO Box 437, Nedlands, WA 6009, Australia
(email: klaus@ned.dem.csiro.au, phone: +61 8 9284 8455, fax: +61 8 9389 1906)

Abstract

A combined approach of interactive evolutionary computing and the particle-in-cell finite element code *Ellipsis* is presented to model the dynamics of core complex formation in a three-layer model of the lithosphere. In this method a mathematical inversion procedure with a graphic output is used to validate the results of variable parameters against a target geometry of a field example. Preliminary results correlate well with conceptual models of core complex formation, and support the idea that pressure gradients across detachment faults are compensated largely by lower crustal flow.

Introduction

Metamorphic core complexes form when continental lithosphere stretches at high rates and the upper crust is dissected by large-scale normal fault systems (detachment faults). Extending continental lithosphere is generally assumed to be mechanically stratified with a 'weak' viscous lower crust sandwiched between two 'strong' layers: the brittle-elastic upper crust (e.g. Gans 1987) and the highly viscous upper mantle. Localisation of deformation in the brittle upper crust is likely to produce a significant pressure gradient across detachment faults which is sufficient to progressively exhume the footwall of detachment faults as an isostatic response to unloading in a rolling hinge (Buck 1988, Axen et al. 1995). It remains unclear, however, to what extent regional unloading during normal faulting and the resulting horizontal pressure gradient affect the deeper layers of the lithosphere. A weak lower crust is likely to accommodate crustal thickness contrasts by flow, thus leaving the Moho and topography flat across the detachments as observed in the Basin and Range (McKenzie et al. 2000). If, on the other hand, the lower crust is cool and strong, viscous flow may not be sufficient to compensate the lateral pressure gradient. In this case, the Moho may become deflected and passive rift may develop (Buck 1991, Huismans et al. 2001).

Several approaches have been made to model flow partitioning in extending continental lithosphere during core complex formation. Block & Royden (1990) discussed ductile flow of the lower crust versus ductile flow of the upper mantle as possible responses to unloading due to extension of the upper crust. Wdowinski & Axen (1992) calculated isostatic rebound of non-extending lower crust and mantle in response to unloading of the system by translation of a large allochton sheet along a flat-lying detachment. Lavier et al. (1999; 2000) produced a self-consistent numerical rolling hinge model for an elastic-plastic upper crust. McKenzie et al. (2000) explored the nature of lower crustal flow with respect to the viscosity contrast across the crust-mantle boundary.

In our approach we use the particle-in-cell (PIC) finite element code Ellipsis (Moresi et al. 2001) (http://www.ned.dem.csiro.au/research/solidMech/PIC/Ellipsis.htm) in combination with an interactive evolutionary computing (IEC) procedure (Takagi in press; Wijns et al. 2001) to find a suitable range of parameters which produce a cross section geometry similar to the geometry of a field example of a core complex in western Turkey (Gessner et al. 2001).

Field example: the Central Menderes metamorphic core complex (CMCC) in Turkey

The central Menderes metamorphic core complex Gessner et al. (2001) is delimited by two symmetrically arranged detachment systems, and defines a bivergent continental breakaway zone in an Alpine collision belt (Anatolide belt) in western Turkey. Structural analysis and apatite fission-track thermochronology show that a large east-trending syncline within the Alpine nappe stack in the central part of the orogen is related to late Miocene–early Pliocene (~5 Ma) to recent core-complex formation. The syncline formed as a result of two opposite-facing rolling hinges in the footwalls of each of the two detachments (Figure 1).

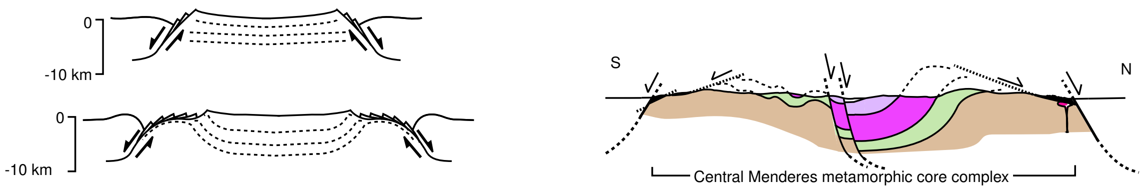

Figure 1
Conceptual model and geologic cross section across the footwall syncline of the Central Menderes metamorphic core complex after Gessner et al. (2001).

Models

Our initial configuration represents a 100 km long cross section of a three-layer continental lithosphere (Figure 2), consisiting of a pressure-dependant upper crust (10 km thick), a low-viscosity lower crust (20 km), and a highly viscous upper mantle (7.5 km). A 12.5 km thick low-density, low viscosity background layer of ‘air’ above the upper crust represents a free boundary. Strain softening properties of the upper crust allow localisation at an initial strain perturbation. For both upper and lower crustal layers, yield laws impose an upper limit to stress:

$$\text{Upper crust:} \quad \sigma_{yield} = \begin{cases} \left(B_0 + B_p p\right) f(e) & p > -B_c \\ \left(B_0 + B_p p\right) f(e) \cdot 0.001 & p > -B_c \end{cases} \tag{1}$$

$$\text{where} \quad f(\varepsilon) = 1 - (1 - E_a)(\varepsilon/\varepsilon_0)^2 \tag{2}$$

$$\text{Lower crust:} \quad \sigma_{yield} = \begin{cases} (B_0)\, f(\varepsilon) & p < -B_c \\ (B_0)\, f(\varepsilon) 0.001 & p > -B_c \end{cases} \tag{3}$$

$$\text{where} \quad f(\varepsilon) = 1 - 0.8(\varepsilon/\varepsilon_0)^2 \tag{4}$$

$$\text{Upper mantle:} \quad \sigma_{yield} = B_0 \tag{5}$$

Where B_0 is cohesion, p is pressure, B_p is the coefficient of friction, ε is accumulated strain, B_c is the tension limit, E_a an arbitrary coefficient in the yield law and ε_0 strain weakening.

The geothermal gradient is chosen to be 30 °C km^{-1}: Density is 2800 kg m^{-3} for the upper crust, 3000 kg m^{-3} for the lower crust and 3300 kg m^{-3} for the upper mantle. By using the interactive evolutionary computing (IEC) procedure as outlined in Wijns et al. (2001), it is possible to vary six parameters in the initial condition of the model in one inversion run. The parameters chosen are the (1) viscosity of the lower crust η_{LC}, (2) B_0 of the upper crust, (3) B_0 of the lower crust, (4) B_p, (5) E_a and (6) ε_0. The allowed range of the parameters is shown in Table 1.

Parameters	range	values of parameters for results shown Figure 3				
		1/0	1/6	2/2	2/6	2/7
η_{LC}	100-1000	100	100	100	100	100
B_0 upper crust	0-1000	400	200	200	0	400
B_0 lower crust	200-1000	200	200	200	900	300
B_p	0.0-1.0	0.1	0.2	0.2	0.2	0.2
E_a	0.1-0.9	0.1	0.2	0.2	0.6	0.7
ε_0	0.1-0.9	0.4	0.2	0.4	0.7	0.9

Table 1
Tabulation of the six varied parameters, the allowed range of values and the actual values used in the inversion results shown in Figure 3.

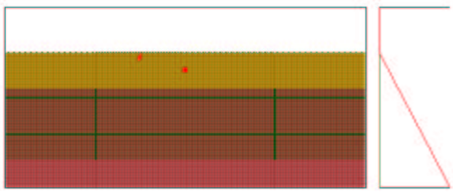

Figure 2
Initial configuration of the model as described in text. Profiles next to the images display finite strength and temperature of cross section located at the red marker. Grid lines represent passive markers in the lower crust at depths of 12.5 km and 20 km; distance between vertical markers is 50 km.

Preliminary results

The parameters chosen affect the spacing of upper crustal yield zones and the magnitude of exhumation of lower plate rocks. Some modelling results of the two first inversion runs (Figure 3) bear good resemblance to the field example; the permutation of parameters of each result are listed in Table 1. The results so far point to the conclusion that for the given boundary conditions lower crustal flow is the main process by which the lithosphere reacts to the localised unloading induced by detachment faulting. Further research of this issue however is needed to carefully assess variations of initial and boundary conditions such as magmatic underplating, overthickened crust and different strain rates. These results clearly demonstrate the potential of combining interactive evolutionary computing and *Ellipsis* to parameterise dynamics and timing of core complex formation.

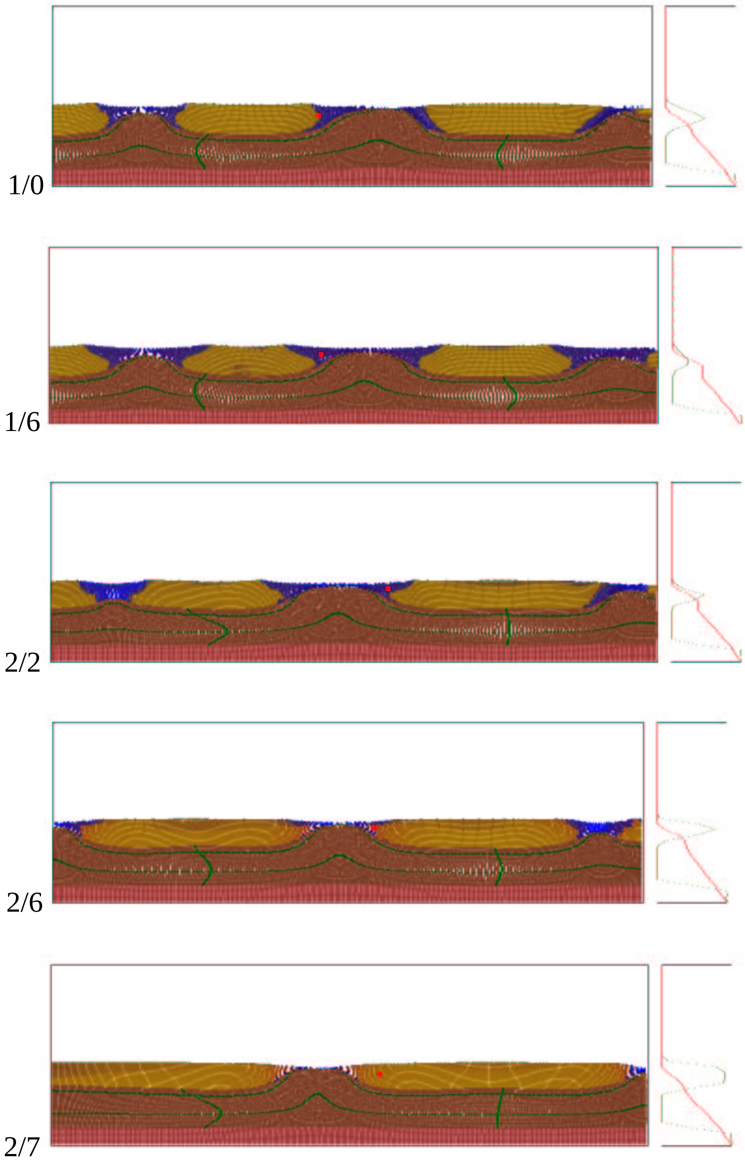

Figure 3

Five exemplary results from the first two inversion runs of the IEC procedure; figures adjacent to the images denote run and individual number of result. All of the shown results exhume metamorphic rocks from >10 km between the indiviual floating ÔraftsÕ of upper crust.

References cited

Axen, G. J., Bartley, J. M., Selverstone, J. 1995. Structural expression of a rolling hinge in the footwall of the Brenner Line normal fault, Eastern Alps. Tectonics 14, 1380-1392.

Block, L. & Royden, L. 1990. Core complex geometries and regional scale flow in the lower crust. Tectonics 9, 557-567.

Buck, W. R. 1988. Flexural rotation of normal faults. Tectonics 7, 959-973.

Buck, W. R. 1991. Modes of continental lithosperic extension. Journal of Geophysical Research 96(B 12), 20,161-20,178.

Gans, P. B. 1987. An open-system, two-layer crustal stretching model for the eastern Great Basin. Tectonics 6, 1-12.

Gessner, K., Ring, U., Johnson, C., Hetzel, R., Passchier, C. W. & Güngör, T. 2001. An active bivergent rolling-hinge detachment system: Central Menderes metamorphic core complex in western Turkey. Geology 29, 611-614.

Huismans, R. S., Podladchikov, Y. Y., Cloething, S. 2001. Transition from passive to active rifting: Relative importance of asthenospheric doming and passive extension of the lithosphere. Journal of Geophysical Research 106(B6), 11271-11291.

Lavier, L. L., Buck, W. R. & Poliakov, A. N. B. 1999. Self-consistent rolling-hinge model for the evolution of large-offset low-angle normal faults. Geology 27, 1127-1130.

Lavier, L. L., Buck, W. R. & Poliakov, A. N. B. 2000. Factors controlling normal fault offset in an ideal brittle layer. Journal of Geophysical Research 105, 23431-23442.

McKenzie, D., Nimmo, F., Jackson, J. A., Gans, P. B. & Miller, E. L. 2000. Characteristics and consequences of flow in the lower crust. Journal of Geophysical Research 105(B5), 11029-11046.

Moresi, L., Mühlhaus, H.-B. & Dufour, F. 2001. Particle in cell solution for creeping viscous flows with internal interfaces. In: 5th International Workshop on Bifurcation and Localisation (IWBL '99) (edited by Mühlhaus, H.-B., Dyskin, A. & Pasternak, E.). Balkema, Rotterdam.

Takagi, H. in press. Interactive Evolutionary Computation: Fusion of the Capabilities of EC Optimization and Human Evaluation. Proceedings of the IEEE

Wdowinski, S. & Axen, G. J. 1992. Isostatic rebound due to tectonic denudation: A viscous flow model of a layered lithosphere. Tectonics 11, 303-315.

Wijns, C., Moresi, L., Boschetti, F., Ord, A., Sorjonen-Ward, P. & Davies, B. 2001. Bringing conceptual models to life. This volume.