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Geomorphological–thermo-mechanical modeling: Application to orogenic wedge dynamics

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ABSTRACT

Coupled geomorphological–thermo-mechanical modeling is presented in a new implementation that combines two established thermo-mechanical and landscape evolution models. A finite-difference marker-in-cell technique is used to solve for the thermo-mechanical problem including complex visco-plastic rheologies in high resolution. Each timestep is synchronously solved with a fluvial landscape evolution model that includes numerical solution of fluvial incision and analytical hillslope processes for both diffusive and slope-limited processes on an adaptive grid. The implementation is successful in modeling large deformation at different scales. We demonstrate high degrees of coupling through processes such as exhumation of rocks with different erodibilities. Sensitivity of the coupled system evolution to surface parameters, and mechanical parameters, is explored for the established case of development of compressive wedges. The evolution of wedge models proves to be primarily sensitive to erodibility and the degree of river network integration. Relief follows deformation in propagating forward with wedge growth. We apply the method to a large-scale model of continental collision, in which a close relationship between deep tectonics, fluvial network evolution, and uplift and erosion can be demonstrated.

1. Introduction

The inherent interaction between surface processes and crustal and lithospheric dynamics has gained increasing recognition as quantitative approaches to both geomorphology and geodynamics have advanced (e.g., Bishop, 2007; Braun, 2006, 2010; Burov and Gerya, 2014; Coulthard, 2001; Gerya, 2010; Gerya and Yuen, 2007; Goren et al., 2014a; Perron et al., 2008; Simpson, 2006; Tucker and Hancock, 2010; Willett, 1999; Willett et al., 2014; Wobus et al., 2006 and references therein). Surface metrics such as topography, river longitudinal profiles, but also geological exposures and erosional exhumation can be linked to underlying crustal or deep tectonics (e.g., Beaumont et al., 2001; Braun and Yamato, 2010; Burov and Cloetingh, 1997; Clark et al., 2004; Cloetingh and Willett, 2013; Gerya et al., 2008; Goren et al., 2014b; Koons et al., 2002; Willett, 1999; Willett et al., 2014). Deforming fluvial patterns potentially testify to tectonic forcing (Castelltort et al., 2012; Hallet and Molnar, 2001; Wobus et al., 2006).

Conversely, the dynamic importance of surface processes on tectonics, by means of mass redistribution along the surface, local stress changes, localization of deformation, or altering of the plate coupling in collision zones, has been recognized at different scales within both the context of divergent (e.g., Burov and Cloetingh, 1997; Kooi and Beaumont, 1994; Sacek et al., 2012) and convergent settings (e.g., Avouac and Burov, 1996; Willett, 1999; Beaumont et al., 2001; Koons et al., 2002; Finnegan et al., 2008; Gerya et al., 2008; Gray and Pysklywec, 2012). In particular, the relative conceptual ease and availability of formal descriptions (e.g., Dahlen, 1984) have fostered a series of studies on wedges and critical orogens, where changes in compressive wedge dynamics can be related to surface processes (e.g., Willett, 1999; Hilley and Strecker, 2004; Simpson, 2006; Stolar et al., 2006; Roe et al., 2008; Simpson, 2010; Braun and Yamato, 2010; Fillon et al., 2013; Ruh et al., 2014).

The numerical tools which have been developed to model tectonics–surface process coupling (e.g., Braun and Sambridge, 1997; Braun and Yamato, 2010; Burov and Poliakov, 2001; Collignon et al., 2014; Garcia-Castellanos et al., 1997; Maniatis et al., 2009; Refice et al., 2012; Simpson, 2006; Stolar et al., 2006; Stüwe et al., 2008; Thieulot et al., 2014; Willett, 1999) employ a range of (thermo-) mechanical implementations, different surface process models from simple linear diffusion to fully-developed landscape evolution codes; vary in dimensionality from 2D, 2.5D to 3D (e.g., Beaumont et al., 1992; Braun and Yamato, 2010; Stolar et al., 2006); are constrained by contemporary computational efficiency limitations (i.e. resolution, spatial extent); and thus are generally suited for a particular tectonic situation. As a result, existing coupled models are difficult to compare, and the dependence of results on model choices and input parameters should be examined carefully.

It can be argued that tectonically active regions are marked by the formation of regional topographic slopes, and that fluvially dominated

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surface evolution is a reasonable simplification. Fluvial networks are inherently two-dimensional, and surface process models applied to a two-dimensional surface provide a natural boundary condition for a three-dimensional tectonic problem (Braun and Yamato, 2010). In addition, natural tectonic deformation shows spatial heterogeneity that is inherently three-dimensional, such as the formation of limited-length double-plunging folds in fold-and-thrust belts (FTBs). Recent advances in numerical methods (e.g., Gerya, 2010, 2011; Gerya and Yuen, 2007), using efficient parallel iterative multigrid solvers, allow thermo-mechanical 3D modeling that employs phase changes, melting, and potentially complex combined, non-linear, self-localizing rock rheologies in high numerical resolution (e.g., Burov and Gerya, 2014; Ruh et al., 2013, 2014). High-resolution thermo-mechanical models can be used to provide complex dynamical feedback, and achieve more self-consistent coupling to a surface process model than with a kinematic prescription (e.g., Castelltort et al., 2012).

In this study, we outline a new 3D fully coupled geomorphological–thermo-mechanical (GmTM) numerical model which can consider a range of thermal, mechanical, thermodynamic, and surface processes. We test the sensitivity of the new coupled model to the choice of surface model parameters in the relatively simple case of the dynamic development of a orogenic wedge in thin-skinned FTBs. Finally, we demonstrate the application of the implementation to large-scale geodynamic problems.

2. Method

A hybrid geomorphological–thermo-mechanical numerical tool, DAC3ELVIS, has been developed for high-resolution numerical modeling of simultaneous geodynamic and surface processes across a broad range of spatial scales and tectonic scenarios. Efficient full coupling of the finite-difference marker-in-cell thermo-mechanical code I3ELVIS (Gerya, 2010; Gerya and Yuen, 2007) with a surface process model DAC (Goren et al., 2014a) has been achieved using an intermediate software module that ensures self-consistent information exchange and shared memory between these well established stand-alone codes (Fig. 1). Simple gross-scale erosion-sedimentation functions used in previous studies with the thermo-mechanical code (e.g., Burov and Gerya, 2014; Ruh et al., 2013) are replaced by a complex surface evolution model (Goren et al., 2014a). Conversely, the kinematic component of the surface model (e.g., Castelltort et al., 2012) has been replaced by a dynamically calculated surface velocity field.

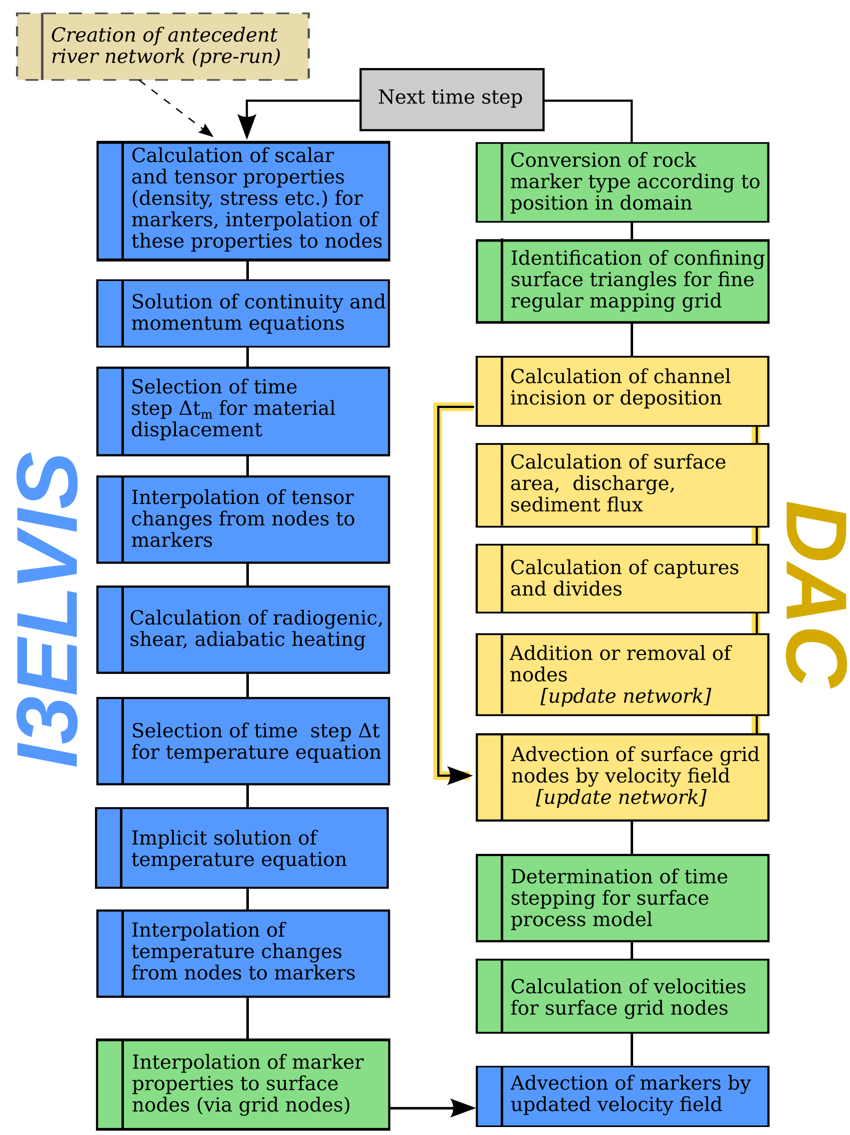

Fig. 1. Flow chart for coupled computation with synchronous stepping. Steps with blue background: thermo-mechanical calculation; yellow: surface process model calculation; green: coupling module calculation. Provisions exist to execute an arbitrary number of SPM time steps with kinematic input in a pre-run phase in order to initialize the fluvial network.