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CASQUS: A new simulation tool for coupled 3D finite element modeling of tectonic and surface processes based on ABAQUS™ and CASCADE

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ABSTRACT

CASQUS is a numerical simulation tool to model the feedback mechanism between surface and tectonic processes. It includes the surface processes model CASCADE into the finite element solver ABAQUS/ Standard™. The finite element method allows for geomechanical simulations of the subsurface with geometrically complex structures in 3D. Additionally, in the commercial software ABAQUS™ various types of rheological behavior are already implemented. CASCADE simulates erosion and sedimentation as the combination of fluvial transport and hillslope processes. For the integration of CASCADE into ABAQUS/Standard™ an Arbitrary Lagrangian–Eulerian modeling technique is used, which makes a coupled and automated simulation possible. Two benchmark models that are easy to reproduce demonstrate the functionality of CASQUS. Our tool aims at a better understanding of the feedback between mass redistribution at the Earth's surface and processes within a heterogeneous subsurface, and at a quantification of the involved processes.

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1. Introduction

It is well known by now that the interaction between surface processes, i.e., erosion and sedimentation, and tectonic processes provides a critical feedback mechanism. This feedback controls the evolution of landscapes as well as processes in the interior of the Earth (Molnar and England, 1990; Beaumont *et al.*, 1992; Masek *et al.*, 1994; Koons, 1995; Avouac and Burov, 1996; Willett, 1999; Snyder *et al.*, 2000; Basile and Allemand, 2002; Garcia-Castellanos, 2002; Persson *et al.*, 2004; Pysklywec, 2006; Burov and Toussaint, 2007). The transposition of eroded material by rivers over distances up to several 1000 km and the deposition of this material as sediment lead to mass redistribution on the Earth's surface. This changes the gravitational loads acting on the lithosphere, thus influencing tectonic processes. Vice versa, vertical movement of rocks by tectonic processes changes the Earth's topography, where the topography controls the pattern of channeled water flow, thus affecting river erosion as the most pervasive of erosive forces. A better understanding of this interplay and feedback mechanism between erosion/sedimentation and tectonic processes is one of the key issues in geosciences (Molnar and England, 1990; Codilean *et al.*, 2006; Bishop, 2007).

With increasing computer power over the last decades several computer models have been developed that simulate the coupling between surface processes and tectonics (Beaumont *et al.*, 1992; Masek *et al.*, 1994; Fullsack, 1995; Batt and Braun, 1997; Braun and Sambridge, 1997; Garcia-Castellanos *et al.*, 1997; Willett, 1999; Koons *et al.*, 2003; Fischer *et al.*, 2004; Simpson, 2004; Toussaint *et al.*, 2004;

Pysklywec, 2006; Burov and Toussaint, 2007; Robl *et al.*, 2008). Except for the model of Fischer *et al.* (2004) none of these coupled models is based on a commercial finite element (FE) package for the simulation of the subsurface. Commercial software packages implementing the FE method allow for the simulation of complex three-dimensional structural heterogeneities in combination with a wide range of different rheologies. The availability of corresponding preprocessing software makes a proper definition of such a complex subsurface model possible, in terms of both the geometric setup and the spatial assignment of material properties. Fischer *et al.* use the commercial FE package ABAQUS™ for their coupled model, where ABAQUS™ is combined with a surface processes model by means of auxiliary programs.¹ These additional programs iteratively exchange data between the two models to make a coupled simulation possible.

In our work we also couple surface processes modeling with truly three-dimensional FE modeling of the subsurface by using ABAQUS™. The innovation of our approach and its difference to the work of Fischer *et al.* is that we integrate a surface processes model directly within the ABAQUS™ software package. With our technique a fully automated coupled simulation is obtained; no manual user interaction is needed once the numerical model setup is defined and the computation is started.

The FE solver ABAQUS/Standard™ that our work is based on handles the modeling of subsurface structures with complex three-dimensional geometric shapes like tectonic faults or geological layers with topography. A wide range of rheologies is available in ABAQUS/Standard™,

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¹ For technical details, see Fischer (2001).

such as a Coulomb failure criterion for ruptures. Temperature dependent or anisotropic material properties can also be defined. Other available features include the possibility of coupled pore fluid-stress analyses, the possibility to define hydrostatic pressure simulating the gravitational effect of water masses, and more. I.e., with our approach based on ABAQUS/Standard™ it is possible to simulate a heterogeneous model of the subsurface in 3D, integrating the feedback effects of surface processes in an automated way.

In this paper we want to present the new simulation tool for this integrated coupled analysis: CASQUS - a geoscientific software extension to the commercial FE software ABAQUS™.² It integrates the erosion and sediment transport routines of the surface processes model CASCADE written by Braun and Sambridge (1997) into the powerful ABAQUS/Standard™ FE solver (ABAQUS, Inc., 2004). In our research we have implemented the original CASCADE versions into CASQUS incorporating long-range fluvial transport processes by channeled water flow and short-range hillslope processes due to gravitational mass movement. Advanced surface processes models based on (or similar to) CASCADE may be implemented by the user to replace these original routines. The characteristic feature of CASQUS is its integration into ABAQUS/Standard™ that is used in geosciences with growing popularity for geomechanical analyses of complex models of the subsurface (e.g., Buchmann and Connolly, 2007; Masterlark, 2007). The following sections will describe the flexibility and application possibilities of the FE method in 3D (Section 2), the geomorphic model underlying the CASCADE code (Section 3) and the technical concept behind CASQUS (Section 4). They are followed by the results of two benchmark models demonstrating its functionality (Section 5).

2. Finite element modeling with ABAQUS/Standard™

ABAQUS/Standard™ is an implicit FE solver package for the numerical solution of various types of mechanical and thermomechanical problems (ABAQUS, Inc., 2004). With the FE method structures of airplanes are analyzed, for example, as well as the deformation behavior of human bones or the stability of boreholes. ABAQUS/Standard™ handles these static or quasi-static mechanical problems by solving the equation that describes the equilibrium of forces in a continuous medium:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + f_i = 0, \quad i, j = 1, 2, 3 \quad (1)$$

Here σ is the stress tensor, f is the body force per unit volume, and x_1 , x_2 and x_3 are the coordinates in a Cartesian reference frame (Davis and Selvadurai, 1996).

The FE method solves this equation numerically by partitioning the model volume into smaller subvolumes, the so-called finite elements (Zienkiewicz, 1977). This discretization can be arbitrary and irregular, i.e., it is not limited to a rectangular or equidistant grid. So three-dimensional models including structures of geometrically complex shape can be analyzed. In commercial FE software packages

such as ABAQUS/Standard™ a wide range of rheologies is implemented, and they can handle inhomogeneous and anisotropic material properties and contact definitions. A contact definition is used where model bodies interact on contact with each other; for example, a contact definition between tectonic blocks can simulate a tectonic fault with Coulomb friction.

A growing number of geoscientists uses ABAQUS™ for geomechanical modeling on tectonic scales (e.g., Dyksterhuis et al., 2005; Hetzel and Hampel, 2005; Ellis et al., 2006; Hergert and Heidbach, 2006; Buchmann and Connolly, 2007; Masterlark, 2007). The CASQUS user should be familiar with geomechanical static stress/displacement analyses based on the FE method, at least on a basic level. An introduction to this type of numerical analysis as well as teaching the basics of ABAQUS/Standard™ would go far beyond the scope of this article. Here we refer to the ABAQUS™ documentation (ABAQUS, Inc., 2004).

3. CASCADE's geomorphic model

For the mathematical formulation of surface processes in CASCADE Braun and Sambridge (1997) follow an approach that Kooi and Beaumont (1994) used before: They assume that on tectonic time scales and large spatial scales landscape evolution results from the interplay between two processes, long-range sediment transport by rivers and short-range gravitational mass movement (hillslope processes).

Both processes are simulated based on numerical solutions of differential equations. These are basically mass balance equations, shortly introduced in the subsections below and described in detail by Beaumont et al. (1992) and Kooi and Beaumont (1994). In CASCADE the governing differential equations behind the two types of surface processes are numerically implemented on irregular grids, computing elevation changes as the result of the difference between influx and outflux of sediment at a grid point. Internal redistribution of sediment material within the model is possible, i.e., erosion and local deposition. Though, CASCADE needs some grid points where the water that rained onto the model surface is allowed to leave the grid, and where sediment load possibly transported by rivers reaching these grid points is removed from the model. So in CASCADE, the sum of rock plus sediment mass is generally not conserved. Braun and Sambridge (1997) explain the technical design of their code in detail, especially the relevance of the irregular grids that they use for discretizing the surface.

3.1. Fluvial transport

Rivers incise the landscape and transport sediments from higher to lower ground where they are deposited. One can define a local equilibrium sediment carrying capacity q_f^{eqb} as a measure of how much sediment a river is able to transport maximally given a point on the landscape. In CASCADE its value depends proportionally on the river discharge per unit width q_r and on the slope in the direction of river drainage dh/dl ,

$$q_f^{eqb} = -K_f q_r \frac{dh}{dl}. \quad (2)$$

² CASQUS is available by sending an email to the corresponding author.

Figure 1. Sketch illustrating basic layout of a CASQUS FE model. Surface nodes (some are shown as black dots) form upper face of uppermost layer of elements that act as an adaptive mesh domain (white). These nodes are defined by ABAQUS™ input file; they are also used by CASCADE routines as discretization of Earth's surface to calculate vertical changes in topography due to surface processes. Some of surface nodes need to be defined as 'fixed' (black stars): Their height coordinate is not changed by CASCADE due to erosion or sedimentation; but it can still be changed by ABAQUS/Standard™ due to tectonic processes. All sediment load of simulated rivers that reach these fixed surface nodes is transported out of model. Inset: In a CASQUS model geomechanical stress/displacement analysis by ABAQUS/Standard™ simulates uplift (or subsidence) of rock, and CASCADE routines mimic exhumation (or burial), according to relation "surface uplift = uplift of rock-exhumation" (England and Molnar, 1990).

Here K_f is a non-dimensional empirical transport coefficient, giving consistent dimensions (volume per unit width per unit time) for the fluxes q . The fluvial discharge q_r depends on climate, it results from conservation of water over the upstream catchment area A_c , $q_r \propto \int_{A_c} v_R dA$, where v_R is the mean precipitation rate. The approach of Kooi and Beaumont (1994) includes a formulation for fluvial mass removal that is not a priori transport-limited like in some previous surface processes models (e.g., Willgoose *et al.*, 1991a, b), which means rivers are not forced to always carry at capacity. Instead, the disequilibrium between the actual sediment flux q_f of a river and its sediment transport capacity q_f^{eqb} controls the rate of erosion (where $q_f < q_f^{eqb}$) or sedimentation (where $q_f > q_f^{eqb}$). Then the temporal height change of a point of the landscape is given by

$$\frac{\partial h}{\partial t} = -\frac{1}{l_f} (q_f^{eqb} - q_f) \quad (3)$$

where $1/l_f$ is an empirical constant. It depends on lithology and is a measure of how easily the river substrate can be eroded or how fast sediments are deposited, thus affecting how fast the river locally tends towards equilibrium. In CASCADE streams never carry more load than their carrying capacity, i.e., the model of Braun and Sambridge (1997) is transport-limited in the sense that q_f^{eqb} is the upper bound for q_f .

3.2. Hillslope processes

Observable fluvial transport only occurs where a significant amount of water drains off. Additionally, hillslope processes that are mainly driven only by gravity can feed the rivers from their flanking slopes. In the CASCADE model the cumulative effect of the different types of these processes (such as weathering, slope wash, rain splash, mass wasting and soil creep) is implemented as a linear diffusion equation:

$$\frac{\partial h}{\partial t} = K_s \nabla^2 h, \quad (4)$$

where K_s as the diffusion constant depends on both climate and lithology, controlling the rate of the short-range processes.

Typical estimates for CASCADE's empirical constants are $K_f \cdot v_R = 0.01$ m/a, $l_f = 100$ km, and $K_s = 0.1$ m²/a (van der Beek and Braun, 1998). However, as precipitation rates in different regions vary by some order of magnitude, $K_f \cdot v$ varies accordingly, and l_f and K_s may also vary by a few orders of magnitude depending on the local lithology.

4. CASQUS' architecture

In order to study the feedback mechanism between surface and tectonic processes we have developed the simulation tool CASQUS, which integrates the surface processes model CASCADE into the FE software ABAQUS/Standard™. These two programs communicate with each other via the topography of the Earth's surface. In the three-dimensional geomechanical FE model this topography is discretized by the surface nodes. They define the top side of the FE mesh of the subsurface (see Fig. 1). The same surface nodes also make up the vertices of the irregular grid that CASCADE uses (Braun and Sambridge, 1997). That means, though the finite element solver runs separately from the (non-FE) surface processes computation, the discretization that is used for both computation parts is identical.

The morphology defined by the spatial coordinates of the surface nodes controls erosion and sedimentation rates, as these rates strongly depend on quantities like slope and drainage area (Eqs. (2)–(4)). CASCADE changes the topography as it shifts the vertical position of the surface nodes due to erosion and sedimentation. These node movements lead to volume changes in the FE mesh and thus to changes in the gravitationally induced body forces (Fig. 1). In return, ABAQUS™ calculates a new equilibrium of forces (Eq. (1)), simulating the tectonic response to the changed gravitational load distribution.³ This response in general leads to vertical movement of rock, which again modifies the surface topography. The new topography is reported to CAS-

³ ABAQUS™ moves all nodes in the 3D FE model vertically as well as horizontally, whereas the CASCADE routines only compute vertical shifts of the surface nodes.

Figure 2. Flow of information in CASQUS. During a first step surface processes routines compute vertical changes of surface topography simulating mass redistribution. A technique called Advection maps mechanical stresses to new FE mesh that is generated by surface processes computation. So stress state of model is preserved by ABAQUS™ despite Eulerian-type mesh geometry changes from CASCADE. Afterwards, ABAQUS/Standard™ performs a geomechanical stress/displacement FE analysis, simulating tectonic processes. During this second step FE model mechanically responds to changed gravitational loads. These two model steps are repeatedly computed to achieve a realistic feedback. Simulated time span is identical for both steps. As model is in a synchronized state only after second step, this synchronization time controls coupling between surface and tectonic processes.

CADE in order to simulate surface processes on the basis of the present, tectonically changed morphology. These computation steps are continuously and automatically repeated by CASQUS.

The technical difficulty with this integrated approach is that the surface nodes must not be fixed to the subsurface material while they undergo vertical movements due to erosion and sedimentation. But by default static stress/displacement analyses in ABAQUS/Standard™ use a Lagrangian formulation: The FE mesh as the discretization of the subsurface is attached to the material and, thus, deforms with the material. I.e., by default node movements are equivalent to deformations, and they may change the stress state of the subsurface due to straining. Hence, for the particular problem of transferring vertical nodal displacements from CASCADE to ABAQUS/Standard™, the default Lagrangian formulation is not applicable, and an Eulerian reference frame must be used in which material is allowed to flow through the mesh.

For hybrid problems of this type ABAQUS/Standard™ offers the possibility of a so-called arbitrary Lagrangian–Eulerian (ALE) analysis. This ALE technique is enabled with adaptive meshing in ABAQUS/Standard™. Our approach makes use of adaptive mesh constraints: This allows us to define mesh motion which is detached from the underlying

material, i.e., Eulerian-type node movements for the surface nodes (see ABAQUS, Inc., 2004). Via the ABAQUS/Standard™ user subroutine UMESHMOTION adaptive mesh constraints can be defined that are automatically computed dependent on other quantities like nodal coordinates and time increment. This user subroutine is the essential part of CASQUS: The CASCADE code is called from within this subroutine, and it forms the interface between ABAQUS™ and CASCADE through which the actual position of the surface nodes and other variables are exchanged. A schematic overview of the program flow of CASQUS is given in Fig. 2.

5. Benchmark models

Though CASQUS is designed to simulate the feedback between surface processes and geometrically and mechanically complex models this section will introduce two simple conceptual models that serve as benchmark examples. The first model (A) is similar to the models Braun and Sambridge (1997) used for testing CASCADE. It calculates the mechanical response of a homogenous elastic plate to mass redistribution, and the modeled change in plate deflection will be compared to the analytical solution to this problem. With the second model (B) we will concentrate on the

Figure 4. Section of model A, vertically exaggerated. Purely elastic model is composed of a 1600 km long and 34 km thick lithospheric plate that is covered by water of an ocean and an island in middle that is 80 km long at its bottom (painted in black, see inset). Model is linearly extruded to a depth of 100 km in viewing direction (along y-axis, not shown here). Rheological parameters of plate are given in figure, where E is elastic (Young's) modulus, ν is Poisson's ratio and ρ is mass density. For island $E = 10$ GPa, $\nu = 0.25$, and $\rho = 2800$ kg/m³. Plate is hydrostatically supported at bottom to take isostasy into account (simulated by spring forces), and all side faces are fixed in normal direction indicated by rollers. Note deflection of lithosphere bottom due to gravitational load of island.

Figure 4. Comparison of analytical and numerical results. Gray curve shows deflection resulting from analytical solution of flexure equation and black solid line result from numerical model. In numerical model, during 0.9 Ma island loses 9.4% of its volume due to river erosion (see inset) while maximum deflection of lithosphere decreases by 9.3% (dotted line).

feedback process itself and the appropriate synchronization time needed.

5.1. Model A (flexure)

A standard example for the flexural behavior of the lithosphere is the model of a homogenous elastic plate subjected to a line load representing an island chain in an ocean (e.g., Bodine and Watts, 1979; Turcotte and Schubert, 2002). The vertical plate deflection w as a function of the position x along a profile perpendicular to the island chain results from the solution of the differential equation

$$D \frac{d^4 w(x)}{dx^4} + (\rho_m - \rho_w) g w(x) = 0. \quad (5)$$

The first term of this equation describes the flexure of a thin elastic plate (D is flexural rigidity); the second term includes the hydrostatic buoyancy forces of a fluid mantle (ρ_m and ρ_w is density for mantle and water, respectively, and g is gravitational acceleration). The analytical solution of this equation results in a proportional relationship between the maximum deflection at the position of the line load (at $x = 0$) and the magnitude of the line load (Turcotte and Schubert, 2002).

In order to show that the FE solver ABAQUS/Standard™ responds to mass redistribution by surface processes in the correct manner we have chosen a model setup that approximates this example. Model A consists of a homogenous elastic plate of 34 km thickness and 1600 km length. In the mid-

dle of this plate an island is placed with a length of 80 km at the bottom, that means its dimension is small relative to the underlying lithospheric plate (for the shape of the island see Fig. 3). The section shown in Fig. 3 is linearly extruded by 100 km perpendicular to the viewing plane. This gives a three-dimensional model with dimensions of (1600 × 100 × 34) km for the plate and (80 × 100 × 2) km for the island. The model is discretized by 8-node linear hexahedral elements (C3D8), (1600 × 100 × 11) elements for the plate and (80 × 100 × 1) for the island. This gives a total number of 1.8×10^6 finite elements and 5.8×10^6 degrees of freedom in the model. The resulting small characteristic element length of 1.7 km in combination with the sufficient number of 22 integration points in the vertical direction assures the correct convergence of the model. As a perfectly smooth topography prevents the evolution of river networks (Braun and Sambridge, 1997) random noise in elevation is added to the island surface. The magnitude of the noise is uniformly distributed in the range (-1 mm; +1 mm). The four plane side faces of the model are fixed in normal direction. The bottom of the plate is supported by spring forces (elastic foundations in ABAQUS™). They represent that part of the lithostatic pressure that is generated by the mantle material and the water of the ocean (Turcotte and Schubert, 2002). Their stiffness per unit area is $(\rho_m - \rho_w) \cdot g = 23$ kPa/m with $\rho_m = 3300$ kg/m³ and $\rho_w = 1000$ kg/m³.

In the first step of the model analysis the isostatic equilibrium is computed. Fig. 3 shows the model in equilibrium at the end of this first analysis step. The profile of the bottom side of the bending plate approximates the analytical solu-

tion for the deflection of an elastic plate under a line load quite well (Eq. (5) and Fig. 4). The magnitude of the line load corresponds to the gravitational load by the island. The deviation between the analytical and the numerical result is due to three aspects: (1) The FE method solves the equation for the equilibrium of forces for a three-dimensional elastic continuum including stress heterogeneities due to gravity, and not the flexure equation approximating a two-dimensional thin plate. (2) The gravitational load of the island is distributed over a length of 80 km, so it is not a proper line load. (3) The stiffness of the island that is added on top of the bending plate reinforces the plate locally.

In the second step, the computation of surface processes is switched on. During the CASQUS analysis, rivers incise the island and transport eroded material to the ocean for a period of 0.9 Ma. Surface processes only act on that part of the island that is not covered by sea water, which also means that there is no sedimentation in the trenches adjacent to the island. River water that drains into the ocean (i.e., that reaches sealevel, see inset of Fig. 3) is removed from the model, likewise the sediment load that is transported to the sea by these rivers. So there is a net loss of material out of the model system.

Time steps of 10 ka are used for the FE analysis, which means that every 10 ka the mechanical model adjusts to the changed weight of the island. That means that the surface processes modeling and the geomechanical computation are synchronized 90 times during the complete analysis. The parameters for the computation of surface processes within the CASCADE routines are constant and uniform for the complete model region: The surface processes model is iterated with time increments of 100 a, the constant for stream erosion K_f times the net precipitation rate v_R is $K_f \cdot v_R = 0.03$ m/a, the diffusion constant $K_s = 0.3$ m²/a, the alluvial erosion length scale $l_{f,a} = 10$ km and the erosion length scale for bedrock $l_{f,b} = 100$ km. These values are taken from Braun and Sambridge (1997).

The topography of the island at the end of the analysis is shown in the inset of Fig. 4. Due to the steep slope of the two coastal regions rivers go straight to the sea. The plateau in the middle shows a local minimum in elevation due to the bending process at the beginning of the analysis and due to the unnatural initial shape of the island. Despite this artificial feature the evolution of the drainage pattern is plausible: Water that flows inland accumulates in the internal drain until it finds a way out. At this place, where one river carries all the water from the inland area, the surface is deeply incised. During the complete model time of 0.9 Ma, 9.4% of the initial rock volume of the island is transported to the sea, i.e., out of the model. Likewise, the magnitude of the maximum deflection in the middle of the plate (at $x = 0$) decreases by 9.3%, cf. Fig. 4. This corresponds very well to the analytical solution, where the maximum deflection is proportional to the magnitude of the line load (Turcotte and Schubert, 2002). It also shows that the mechanical response to surface mass redistribution gives a significant uplift signal, here of the order of 0.1 mm/a.

5.2. Model B (feedback)

Model B analyzes the influence of flexural rebound to the rate of erosion and the relevance of the synchronization

Figure 5. Sediment outflow rate $\dot{q}$ over time for different synchronization times. A synchronization time of 200 ka, e.g., means computation of surface processes and geomechanical simulation are synchronized every 200 ka. Topography is steepened while plate elastically responds to decreased loading. After synchronization, surface processes react to increased mean slope. So in general, after synchronization outflow rate $\dot{q}$ is increased. Inset: Setup of model B, vertically exaggerated. Boundary conditions are same as in model A (Fig. 3). Rheological parameters are: $E = 20$ GPa and $\rho = 2800$ kg/m³ for adaptive mesh domain (white), $E = 70$ GPa and $\rho = 3300$ kg/m³ for rest of plate (gray). $\nu = 0.25$ throughout model. Initial shape of circular symmetric mountain topography is shown at bottom.

time between the FE solver and the CASCADE routines. We use a model setup that is similar to model A. Here the lithospheric elastic plate has a square layout of 120 km side length⁴ and a thickness of 11 km. For the discretization $(120 \times 120 \times 6) = 86 \times 10^3$ 8-node linear hexahedral elements (C3D8) are used, which results in a characteristic element length of 1.3 km and 3.1×10^5 degrees of freedom. In the middle of the plate we place a circular symmetric mountain (inset of Fig. 5). All nodes of the model that are located at the upper edges of the plate (black dotted lines) are defined as ‘fixed surface nodes’ (cf. Fig. 1). These nodes are not vertically shifted due to surface processes simulated by CASCADE, because they act as outflow zone where water and sediment load leave the model. Yet they can move vertically in the geomechanical analysis performed by ABAQUS/Standard™; ‘fixed’ only refers to the surface processes computation here. The parameter values for the surface transport processes are equal to the settings used for model A, and the rheological parameters for the FE model are listed in the caption of Fig. 5. The boundary conditions are the same as in model A, with the difference that no ocean is simulated on top of the plate, so the stiffness per unit area for the elastic foundations is just $\rho_m \cdot g = 33$ kPa/m.

Just as in model A, the first step of the analysis brings model B to isostatic equilibrium. In the second analysis step, when the CASCADE routines are switched on, 1.6 Ma of coupling between surface mass denudation and isostatic rebound are simulated. The mountain is worn down and sediment is transported out of the model, while the deflected elastic plate springs back.

The synchronization time plays a crucial role in the development of the model during the simulation. After surface

⁴ As it is not the aim of this model to simulate quantitatively exact flexural behavior we can accept a laterally small-sized elastic plate in order to minimize computation time.

processes are simulated for a model time period Δt_s , tectonic processes including the mechanical response to these surface processes are computed for the same model time period Δt_s (Fig. 2). Subsequently, these two steps are repeatedly processed. I.e., after each of these passes a new synchronized model state is reached as a combination of both surface processes modeling and mechanical FE modeling, and the simulation is *not* synchronized in-between these two steps. Accordingly, the interval Δt_s is denoted as synchronization time here. It has to be chosen very carefully. The smaller the model time steps are, i.e., the smaller the synchronization time is, the more accurately the coupling between surface and tectonic processes is simulated. But for a given total model time, the number of analysis steps increases with decreasing synchronization time, and the computation time of an FE analysis generally increases with the number of analysis steps used. This has to be considered for models with a large number of finite elements where computation is time-consuming.

In order to find a reasonable compromise for the synchronization time Δt_s , the outflow rate of sediment material $\dot{q}$ is a characteristic parameter. $\dot{q}$ is the sediment volume transported to the edges of the model per unit time (cf. inset of Fig. 5). It is a measure of the mean erosion rate in the model. Fig. 5 shows this outflow rate $\dot{q}$ over time for different synchronization times: ‘800 ka’, for example, labels the curve for the model that starts in an a priori synchronized initial state and is only synchronized a second time at $t = 0.8$ Ma (within the complete model time of 1.6 Ma). Directly after synchronization at $t = 0.8$ Ma the outflow rate $\dot{q}$ rapidly increases in this model. The loads acting onto the lithospheric plate significantly decrease before this point in time as a lot of sediment material is removed from the model during 0.8 Ma, without the plate responding to this change. When the plate finally reacts to the changed loading at $t = 0.8$ Ma the maximum deflection of the plate decreases abruptly, associated with a large abrupt increase of the mean slope of the model surface. As slope and the sediment carrying capacity are directly related (cf. Eq. (2)), this explains the rapid increase of $\dot{q}$. After this abrupt change in mean slope, the rivers are far from equilibrium as far as their transport behavior is concerned (Mackin, 1948; Kooi and Beaumont, 1994), and the sediment outflow rate $\dot{q}$ exceeds the curves of the simulation runs with stronger coupling, i.e., with smaller synchronization times. A similar behavior is shown by the curves for the cumulative sediment outflow q in Fig. 6 ($q = \int \dot{q} dt$).

If we iteratively decrease the synchronization time, the curves for both $\dot{q}$ and q show an asymptotic behavior. There is no significant difference between the two models with synchronization times of 20 and 2 ka, indicating that a synchronization time of $\Delta t_s = 20$ ka is sufficient for this model example.

6. Discussion and conclusion

CASQUS enables us to simulate the interaction and feedback mechanism between mechanical deformation within the lithosphere and erosion and sedimentation at the Earth’s surface. It allows us to numerically study the long-range redistribution of sediment masses and how the

subsurface responds to the changed loading, and - vice versa - how erosion and sedimentation changes due to processes from the interior of the Earth. CASQUS’ surface processes routines are taken (with minor modifications) from the academic modeling software CASCADE developed by Braun and Sambridge (1997). Yet these routines can be replaced by code from similar surface processes models to address particular problems. The essential part of CASQUS is the interface to the FE program ABAQUS/Standard™ that makes a simulation of surface processes within ABAQUS™ possible.

The two benchmark models presented in this paper demonstrated that CASQUS is able to appropriately simulate the coupling process. For this feedback the synchronization time between the surface processes modeling and the tectonic simulation is an important numerical parameter. We have shown a way to assess the minimum number of synchronization steps (i.e., the maximum synchronization time) needed for a particular model. This number depends on many properties of the model, including the 3D geometric setup, the geomechanical material behavior and the surface transport parameters. Generally speaking, the minimum number of synchronization steps needed will decrease for models with a stiffer behavior of the subsurface, for example due to a higher effective elastic thickness. It will also decrease if less sediment is transported, for example due to a lower precipitation rate. The opposite holds true as well.

The manner in which the mean erosion rate in a model is determined by the synchronization time also shows how sensitive the feedback between erosion/sedimentation and tectonic processes is. Both types of processes cannot be studied independently on geological time scales in a proper way; understanding their coupling is essential for understanding both surface evolution and tectonic deformations.

Due to its design and architecture our new coupled simulation tool CASQUS has some limitations, but also some advantages compared to other coupled landscape evolution models.

6.1. Limitations

It must be well considered whether using CASQUS is reasonable for the type of problem to be solved. Due to its design based on the FE method in 3D computation times are significantly longer than those of other landscape evolution models. For example, computation times for the benchmark model B are 1.3 h for a synchronization time of 800 ka and 15 h for 20 ka, on an Intel™ Pentium™ 4 CPU with 3.20 GHz. CASQUS is intrinsically designed for problems where the focus is on a proper model representation of a geometrically complex three-dimensional subsurface.

ABAQUS/Standard™ by default uses a Lagrangian formulation for the mechanical FE computation (Section 4). Therefore, by default CASQUS cannot perform simulations over very long model time scales because this will generally lead to severe distortions of the finite elements if deformation rates are not negligible. Consequently, in order to simulate an orogenesis for several million years, for example, the simulation needs to be split in several separate FE model runs to be run consecutively. The model is then remeshed in-between the model runs to maintain a suitable

FE mesh, and results are mapped from the end of one run to the initial state of the next model run. I.e., the necessary remeshing interrupts the non-interactive analysis and requires user input. Another possibility to circumvent excessive FE mesh distortions is the use of the arbitrary Lagrangian–Eulerian adaptive meshing technique for the whole subsurface model.

Another limitation is that the original CASCADE routines which are used for the provided CASQUS version model only fluvial and hillslope processes in order to simulate erosion and sedimentation. Regions where other types of surface processes prevail are not appropriately simulated without modifications. But this limitation can be overcome by replacing the CASCADE routines by code that is provided by the user and adjusted to the particular problem, for example to simulate glacial or aeolian surface processes.

6.2. Capabilities

CASQUS removes some limitations of previous landscape evolution models concerning the complexity of the subsurface. With CASQUS the ability of CASCADE to simulate surface processes on geological time scales and regional spatial scales is combined with the ability of ABAQUS/Standard™ to simulate truly three-dimensional geomechanical models with tectonic structures of complex geometry, different rheologies, distributed material properties and features like faults with Coulomb friction. Various authors have published the results of such complex 3D models analyzed by ABAQUS™ (e.g., Fischer, 2006; Morra and Regenauer-Lieb, 2006; Steffen et al., 2006; Buchmann and Connolly, 2007; Masterlark, 2007; Schotman et al., 2008; Westerhaus et al., 2008). With CASQUS more complex problems with regard to the geomechanical behavior of the subsurface can be addressed than with other existing landscape evolution models. With a view to simulating natural regions of the Earth our sequentially coupled 3D modeling technique has the potential to provide new insights into the feedback mechanism between tectonic and surface processes.

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