1st International Geoscientific Abaqus Workshop

Institute of Geology, Mineralogy and Geophysics
Ruhr-University Bochum

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This conference has been generously sponsored by CRC 526 *Rheology of the Earth - From the Upper Crust to Subduction Zones* and co-sponsored by the ILP Task Force VII - *Temporal and Spatial Change of Stress and Strain*.

Preface

The Geoscientific Abaqus User Group GEOQUS is an open user group of scientist who employ the commercial finite-element software Abaqus (Abaqus Inc.) for any geoscientific application. GEOQUS is based on an idea of Oliver Heidbach of the Geophysical Institute, University of Karlsruhe and Kasper D. Fischer Institute of Geology, Mineralogy and Geophysics, University of Bochum. For further information please contact check on the GEQUS website at http://www.ruhr-uni-bochum.de/geoqus/. The user group addresses mainly academic users of universities and other scientific research institutes around the globe.

Key objective of the first GEOQUS workshop is to foster discussion on technical aspects of modelling with the finite-element software Abaqus. Focus will be on methods and techniques to integrate typical geoscientific constraints, boundary conditions, loads, forces, and physical properties in a numerical model. These are often necessary when the modelled geoscientific processes depend for example on gravity, erosion, non-linear rheologies, or faults. Techniques discussed will be user subroutines, contact properties, implementation of gravity loading, and Abaqus scripting.

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Schedule

Wednesday, October 4th

13:00	Registration & Poster setup
14:00	Welcome
14:15	**Gabriele Morra, Philippe Chatelain** (Invited Presentation) *Geodynamics Modelling Through Coupling Abaqus with an Accelerated Boundary Element Method*
15:15	**Fabio Capitano, Gabriele Morra, Saskia Goes** *Geodynamic models of lithosphere subduction and resistive forces in the Earth's mantle*
15:45	**Daniel Kurfeß, Oliver Heidbach** *Modelling landscape evolution within ABAQUS: new user subroutines linking fluvial mass transport and the dynamics of the lithosphere*
16:15	Coffee break
16:45	Poster presentations **Susan Ellis** (Invited Presentation) *Attaining geostatic equilibrium and initial stress states: crustal faulting experiments using Abaqus* **Nikolaus Bleier, Otto Bruhns, Wolfgang Friederich, Bernhard Stöckhert** *Two-dimensional FEM simulation of the Aegean Subduction Zone* **Paola Ledermann, Oliver Heidbach** *Modelling of Coulomb Failure Stress changes (ΔCFS) from subsequent strong earthquakes in the Vrancea area, Romania* **Johannes Altmann, Oliver Heidbach, Malte Westerhaus** *3D model of tiltmeter signals of the Volcano Merapi* **Andrea Manconi, Thomas Walther, Falk Amelung** *Heterogeneous finite element simulations of surface deformation on Darwin volcano: understanding volcano unrest*
17:00	Discussion at posters
18:30	Departure for ice breaker party

Thursday, October 5th

09:00	**Hugo Schott, Bert Vermeersen, Patrick Wu** (Invited Presentation) *Shallow Low-Viscosity Zones in Flat-3D Finite-Element Models of Glacial-Isostatic Adjustment*
09:30	**Holger Steffen, Georg Kaufmann, Patrick Wu** *Investigation of the glacial isostatic adjustment in Fennoscandia with a flat three-dimensional Earth model*
10:00	**Sebastian Gac, Ritske Hiusman, Atle Austegard** *Dynamic models of lithosphere extension using ABAQUS*
10:30	Coffee break

11:00 Poster presentations

John Naliboff, Carolina Lithgow-Bertelloni
Sources of Stress in the Lithosphere

Markus Staackmann, Kasper Fischer
Load-induced stress concentration beneath islands

Holger Steffen, Georg Kaufmann
Deformation changes induced by lake-level fluctuations of the Hohenwarte reservoir, Thuringia, Germany – an estimation with numerical modelling

Tobias Hergert, Oliver Heidbach
Postseismic stress relaxation After the June 23rd 2001 Mw = 8.4 earthquake in southern Peru

Beatrice Cailleau, Antje Kellner, Nina Kukowski, Onno Oncken
Mechanisms for localising the deformation related to oblique convergence: Weak volcanic arc versus coupling at the subduction interface

Antje Kellner, Sergei Medvedev, Nina Kukowski, Onno Oncken
Deformation of the fore-arc wedge along the obliquely convergent Chilean margin

Jan Bolte, Jürgen Klotz, Volker Grund, Marcos Moreno
Three-dimensional Finite Element Modelling of the Andean Subduction Zone

11:30 Discussions at posters

13:00 Lunch

14:00 Break-out sesssions: a) gravity implementation
b) code coupling
c) relaxation processes
d) contact elements in 3D subduction models

17:00 Reconvene for summary from breakout sessions

18:00 End

20:00 Bowling

Friday, October 6th

09:00 **Marco Naujoks, Thomas Jahr, Gerhard Jentzsch, Jochen Horst Kurz**
Comparative geodynamic modelling about earthquake swarm areas and processes

09:30 **Oliver Heidbach, Tobias Hergert, Anne Becel, Alfred Hirn**
3D Finite Element model for the stress field evolution for the Marmara Sea r egion

10:00 **Wouter van der Zee**
Drilling Through Salt: a FE Approach to Borehole Closure and Casing Integrity

10:30 Coffee break

11:00 Summary and final discussion

12:00 End

Invited Presentation

Geodynamics Modelling Through Coupling Abaqus with an Accelerated Boundary Element Method

Gabriele Morra
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Philippe Chatelain
Computational Laboratory, ETH Zürich

Abstract
Geodynamical numerical models usually have to deal with large viscosity variations in relatively small domains, occurring from the crustal up to the planetary scale. Furthermore relevant geophysical events are often located only within a small portion of the Earth (e.g. earthquakes at plate boundaries and within the core of subducting slabs, exhumation and volcanism at back-arc areas). It is therefore highly desirable to model separately at high resolution the zone interesting for the modeller, preserving the self consistent feed-back with the background dynamics.

In this lecture a hybrid approach is presented for coupling solid and fluid within the Stokes flow approximation (negligible inertia). The technique combines Fast Multipole BEM and Lagrangian Mechanical FEM (Abaqus implicit): the first calculates the drag due to Stokes flow in bounded and unbounded domains, the second solves the fine and eventually complex thermo-mechanical dynamics of the area of interest. Tests are performed for large strain 3-D Rayleigh Taylor Instability in a box and viscosity variations of several orders of magnitude, for a rising plume in the mantle and for modelling first order interaction between close and far subduction systems.

In general the evolving boundary between a solid and a fluid is characterized by a discontinuity in stress (e.g. due to viscosity change or visco to visco-elastic transition), but continuity in velocity. Coupling FEM and the BEM allow reproducing such interaction after the choice of the proper strategy for exchanging both velocity and stress between the two domains. Coupling modality on the domains boundary can be either implicit or explicit and includes velocity, stress or both. In this lecture a specific innovative technique based on "drag tensors" for the stress-velocity feedback is proposed and explained in details, showing advantages and limitations, through several examples and verification tests. Validation benchmarks show that the method is especially suitable for very large viscosity variations at the BEM-FEM boundary. Performances tests indicate that the BEM solver scales linearly with the problem size, O(N), while the FEM scales between O(N*sqrt(N)) and O(N^2), where N is the number of elements.

The integration of the method in Abaqus is done employing the external subroutines DLOAD and UTRACLOAD for imposing the adaptive drag tensors and the routine URDFIL for extracting and elaborating the results at each increment and for calling the external BEM code. The implementation is based on coupling brick type Finite Elements with triangular Boundary Elements. The local drag tensors at each element side are passed from URDFIL to UTRACLOAD through commonly allocated arrays. The entire implementation is pre-processed using a python script that creates the combined BEM and FEM meshes, the input files for Abaqus, the one for the BEM code and takes care of the staggered model evolution. Some didactical examples of subroutines will be available for download.

Geodynamic models of lithosphere subduction and resistive forces in the Earth's mantle

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Gabriele Morra
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Saskia Goes
Dept. of Earth Science and Engineering, Imperial College London, U.K

Abstract

Lithospheric aging and consequent cooling leads to subduction of slabs in the Earth's mantle where viscous forces contrast their descending motion. The interaction between slabs and resisting mantle accounts for the dissipation of the largest part of energy of plate tectonics, thus controlling lithosphere deformation, subduction kinematics, plate motion as well as mantle flow and shear heating.

The key role of such an interaction requires a joint effort of solid and fluid mechanical modelling. Furthermore dynamic and energetic consistency is essential for the proper assessment of the model. In order to do so, I will first review a set of body and surface forces defining the system. Second, lithosphere's rheology and inherent characteristics will be discussed and, third, relevant mantle response is illustrated in its implementation. The set up described allows to investigate the role of lithospheric rheology, represented by a viscoelastic Maxwell model with constant viscosity or layered viscosity. In subsequent set ups, resisting dissipative forces arising from the viscous resistance are modelled, including the depth-dependence of mantle viscosity, of which the asthenosphere and a jump at the upper-lower mantle boundary are the most important expressions. Other resisting forces in the mantle are related to the hydrodynamic pressure on the slab that results from the slab-induced flow (suction), which is exerted by the corner flow in the wedge above the slab and by the overriding plate.

Concluding, estimates of energy dissipation partitioning as well as subduction kinematics are discussed allowing for the evaluation of the consistency of the set up.

Modelling landscape evolution within ABAQUS: new user subroutines linking fluvial mass transport and the dynamics of the lithosphere

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Abstract

Several surface process models simulating erosion/deposition on geological scales have been developed over the past years. As one of them, CASCADE (written by Jean Braun) handles gravitational mass movement and river transport; and it is based on an irregular spatial discretisation of the earth's surface. This feature makes the CASCADE code qualified to interact with a finite element grid.

On the other side, ABAQUS offers a set of user subroutines, among them the routine UMESHMOTION that allows the user to specify nodal displacements independent of the generic finite element analysis.

We present how we bring these two technical concepts together in order to provide a software extension that is capable of integrating river networks within ABAQUS models. It will allow us to simulate the interaction between long-range mass redistribution on the earth's surface and the mechanical deformation of the lithosphere. The current state of our work and preliminary results generated by this modelling technique will be illustrated.

Invited Presentation

Attaining geostatic equilibrium and initial stress states: crustal faulting experiments using Abaqus

Susan Ellis
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Abstract

Crustal-scale numerical experiments often require perturbation from an initial steady-state stress field. For example, the seismic cycle of a fault in a compressive setting may be analysed by starting from the present topographic, thermal, and stress state of the crust as determined from geophysical observations. Attaining an initial equilibrium for this type of problem can be difficult using a lagrangian elasto-plasto-viscous code such as Abaqus, especially when initial variations in density and material strength are present. Assuming that we wish to apply the full gravitational body forces in the problem, there are several tricks that can be used:

1. Prescribing an initial Andersonian stress where deviatoric stress is an approximate function of depth and frictional yield condition;
2. Using several start-up steps to attain geostatic equilibrium
3. For problems where the initial stress state is not in geostatic balance but which depend on dynamic stresses from boundary conditions, the initial geostatic steps must be neglected

Deforming the model according to some long-term stress or velocity boundary conditions to attain the initial stress state. This may be performed as a "boot-strap" process, by running the model for a long time, outputting the resulting stress state, and then applying this stress state as an initial condition on an undeformed model geometry. This bootstrap process allows a starting stress state which is close to dynamic equilibrium but which has not accumulated large amounts of deformation.

Examples of these techniques will be given. Determining which technique to use depends on whether or not the starting steady-state stress state is "dynamic" i.e. sustained by ongoing boundary processes, vs. "static" where it purely results from geostatic conditions.

Two-dimensional FEM simulation of the Aegean Subduction Zone

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Abstract

The subject of our poster falls under the heading of numerical simulation of huge spatial geophysical processes in subduciton zones with the finite element method. The aim of our study is to gain insight into the nature of effects in a subduction zone. At the present state of our investigation we restrict our attention to a two dimensional model.

Our model initiates with ABAQUS/Standard to compute the present state of the subduction zone with linear elastic material assumptions. Then we continue the calculation with ABAQUS/Explicit in a dynamic compilation with viscous effects in the mantles.

We present a few sample results of our computations and show some concepts how to model different aspects of the problem, e.g. the temperature-field and the boundary conditions, with ABAQUS.

Modelling of Coulomb Failure Stress changes (∆CFS) from subsequent strong earthquakes in the Vrancea area, Romania

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Abstract
In the last 50 years, a sequence of 5 strong earthquakes with moment magnitudes Mw between 5.8 and 7.7 took place in the Southeast Carpathians (Vrancea area). These earthquakes revealed thrust faulting mechanism and occurred in a small seismogenic volume located at intermediate depth (80 – 150km) within a high-velocity body.

In this study we use a 3D finite element model to investigate the stress transfer between subsequent earthquakes and possible earthquake triggering. The model includes elastic rheologies. The model geometry incorporates the topographies of the surface and the Moho as well as the shape of the high-velocity body. The rupture planes of the 5 earthquakes are implemented as frictional contact surfaces.

In order to simulate the thrust faulting stress regime displacement boundary conditions were applied at the model borders. At the bottom and upper boundary of the model only displacement parallel to the model boundaries are allowed. To simulate the co-seismic displacement of the rupture planes the hanging wall and footwall were displaced by half the average displacement. First results show that after each earthquake stresses on the rupture plane decrease, while the induced stresses on the plane of the subsequent earthquake are not large enough to trigger this event.

3D model of tiltmeter signals of the Volcano Merapi

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Abstract
A prerequisite for a successful assessment of volcanic hazard is a proper discrimination of signals related to volcanic activity and non-volcanic origin. This is especially valid for volcanoes such as Merapi which are continuously active on a certain pressure level with only small fluctuations. In that case, environmental disturbances gain importance and require a thorough investigation.

The continuous tilt records obtained at four deformation stations along the hillsides of Merapi Volcano are dominated by rain- and ground water signals. Two kinds of disturbances are identified: (1) short period variations which are successfully removed from the tilt records by convolving local rain data with time functions describing loading and diffusion processes; (2) rapid, step-like drift changes which are probably not related to individual rain events. Type-2 signals, which are highly correlated between the four stations, cannot be corrected by the existing convolution approaches.

3D Finite-Element-Modelling shows that sign and relative amplitudes of type-2 signals in radial direction are compatible with a pressure source located in the central part of the volcano edifice. The model geometry includes a Digital Elevation Model with a resolution of 15 m which leads to a 3D discretisation into ~700,000 linear tetrahedral elements. Thus, the model accounts also for effects of local, small-scale topographic features on tilt measurements and can investigate pressure induced tilt signals in tangential direction. However, in contrast to the radial component, the observed type-2 signals in tangential direction are not compatible with an internal pressure variation. We conclude that externally and internally induced radial tilt disturbances along the flanks of Merapi Volcano may have similar spatial characteristics. We clearly see an influence of the local topography on the tangential tilt, but a quantification needs a further refinement of the local discretisation near the tiltmeter stations.

Heterogeneous finite element simulations of surface deformation on Darwin volcano: understanding volcano unrest

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Abstract

Magma intrusions into volcanoes may cause relevant surface deformations detectable by geodetic InSAR, GPS or tilt data. Studying the amount and the pattern of surface deformation allow locating magma intrusions, to understand the entity of the magma body, as well as to forecast a possible eruption. Inverse numerical models use geodetic data as the base of their calculations, but most of the previous modelling attempts are made in isotropic elastic half-space (e.g. using Mogi point source). However, can we neglect material heterogeneities such as piles of lava, pyroclastic deposits and sediments? How does material heterogeneities affect the surface deformations and our assessment of volcanic unrest?

In this work we use finite element models (FEM) to study the importance of mechanical heterogeneities on displacement redistribution. We use InSAR data of Darwin volcano (Galapagos Islands) and we compare inversion models based on homogeneous half-space model to heterogeneous multi layered models. We show that mechanical heterogeneities have important effects on the estimation of the magma chamber depth and on the volume of the magma inflation.

Our results suggest that the interpretation of geodetic data depends on the crust mechanical characteristics, which is influencing the correct evaluation of volcanic hazard potential.

Invited Presentation

Shallow Low-Viscosity Zones in Flat-3D Finite-Element Models of Glacial-Isostatic Adjustment

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Patrick Wu
Department of Geology and Geophysics, University of Calgary

Abstract

In recent papers (e.g. Schotman & Vermeersen 2005) we have shown the effect of crustal and asthenospheric low-viscosity zones (LVZs) on geoid heights and gravity anomalies, as predicted by models of glacial-isostatic adjustment. The governing equations were solved analytically in the spectral domain, which makes the method accurate and fast. However, it does not allow for lateral variations in earth parameters.

As the properties of shallow LVZs can be expected to vary laterally, we have developed a finite-element model based on Abaqus. Global (spherical-3D) finite-element models are currently not capable of providing high-resolution predictions, which we expect due to the shallowness of the LVZ. We therefore use a regional (flat-3D) model.

From the predicted displacements we derive geoid heights by solving Laplace's equation in the spectral domain. We compare the results with the spectral model and show that geoid heights can be computed accurately, though the accuracy deteriorates with the depth of the LVZ. We show the effect of lateral variations in the properties of the LVZ and in lithospheric thickness.

In future studies we will use this model, together with recent ice-load history reconstructions and viscosity estimates from seismic and heat-flow data, to compute geoid heights for Northern Europe, and confront these with satellite-gravity data.

Investigation of the glacial isostatic adjustment in Fennoscandia with a flat three-dimensional Earth model

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Abstract

During the last ice age cycles, large ice sheets have covered North America, Northern Eurasia, Greenland and Antarctica. The Earth's crust and mantle has been depressed by the weight of these ice sheets by several hundreds of meters. At the end of the last ice-age cycle, the ice sheets have vanished around 6000 years ago, and the Earth's surface rebounded. However, due to the time-dependent viscoelastic relaxation of the Earth's mantle, the rebound, also termed glacial isostatic adjustment (GIA), is still observable today. In Fennoscandia, a key region of GIA, numerous observations such as paleo-strandlines, present-day crustal deformations monitored by GPS observations, and present-day changes in the gravity field seen by satellite missions, provide a detailed picture of the past and ongoing deformation.

We model the GIA process in Fennoscandia with ABAQUS. We employ a three-dimensional (3D) viscosity structure in the Earth's mantle derived from seismic shear-wave tomography models, and we use thermodynamic considerations to convert the shear-wave perturbations into viscosity variations. We then compare the results based on the 3D Earth's structure with a simpler earth model, where viscosity depends on the vertical direction only. Our results indicate significant differences between 3D and 1D modelling:

The vertical crustal velocities reveal differences up to 7 mm/yr, and horizontal crustal velocities are effected even stronger. The typical divergent motions of the latter observed for 1D earth models is no longer present for 3D viscosity models. Instead, a regional velocity field with movements away from the Norwegian coast towards the old Baltic Shield is observed. In a sensitivity analysis we show that the dramatic change in the horizontal flow pattern has its origin deeper in the upper mantle, between 450 and 670 km depth. We also confirm that the observed GIA process in Fennoscandia is not very sensitive to the viscosity structure in the lower mantle. However, a comparison with BIFROST data reveals a best-fit with the simple, 1D model, which requires a revision of our 3D models in a future analysis.

Dynamic models of lithosphere extension using ABAQUS

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Abstract
Recently we have started using ABAQUS for lithosphere extension problems. We are testing ABAQUS for our purposes which require large deformation using non linear and temperature dependent elastic-viscous-plastic depth dependent rheologies. The selected test problem involves a 4 layer lithosphere that consists of a 15 km thick frictional-plastic upper crust, a 20 km thick constant viscosity lower crust, a 20 km thick frictional-plastic upper mantle lithosphere, and a 65 km thick constant viscosity lower mantle lithosphere. The base of the model is fixed vertically with free slip in the horizontal direction. Horizontal velocities are applied on both vertical sides of the model in order to simulate extension. A weak plastic seed focuses initial deformation. Several models were run characterized by different depths for the weak seed and different viscosities of the lower crustal layer. The style of necking of the crust depends on brittle-ductile coupling in the system where high lower crustal viscosities result in distributed and, low lower crustal viscosities result in narrow crustal necking. More complex models are implemented characterized by temperature dependent power law viscous rheologies. For these models the brittle-ductile transition is not predefined and is fully determined by local temperature and stress conditions.

In future work we will asses differences between kinematic and forward dynamic models of lithosphere extension. Kinematic models are used to reconstruct the rift history. In kinematic modelling, the deformation does not result from rheology and applied boundary conditions but is purely geometric and depends on assumptions on the style of deformation. Pure shear deformation is commonly assumed in these approaches. Deformation in natural systems may, however, depart from pure shear at small and large scales. Dynamic modelling approaches allow self consistent computation of deformation and provide insight in the factors controlling variations in the style of deformation.

Sources of Stress in the Lithosphere

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Abstract
The state of stress in the Earth's lithosphere reflects the contributions of multiple sources, including mantle flow and lithospheric heterogeneity. In an ongoing study, the contributions of both mantle flow and variations in lithospheric thickness and density to the lithospheric stress field are computed in an effort to determine the relative importance of these two sources of stress. Our calculation of the global lithospheric stress field is two-fold: the tractions at the base of the lithosphere produced by mantle flow are calculated using a method developed by Lithgow-Bertelloni and Richards (1998) or CitcomS (Conrad and Lithgow-Bertelloni, 2006), while the stresses due to variations in lithospheric thickness and density are calculated as in Lithgow-Bertelloni and Guynn (2004). The resulting stress field from these two contributions is computed using ABAQUS, which requires a highly detailed mesh geometry to accurately compute the stresses.

The main portion of the mesh in ABAQUS contains 8 node quadratic elements, which contain roughly equal areas on their top and bottom surfaces. The thickness of these elements remains constant throughout the models. In models that include mantle shear tractions a layer of thin elements (< 1km) is placed beneath the lithospheric elements where mantle tractions are applied as a body force. Beneath the layer of thin elements we place a layer of elements with pinned basal nodes and a low Young's modulus. By connecting the top nodes of this layer to the lithosphere and pinning the basal layer, the stresses are evenly distributed across the base of the model as a result of the element's low Young's modulus, thus avoiding numerical precision errors and high stress concentrations associated with pinned nodes. In models that consider only stresses resulting from lithospheric heterogeneity, it is not necessary to apply the layer of thin shell elements, but the layer of basal elements with the low Young's modulus are still required.

To date, two studies have examined the stress field using the methods described above. Lithgow-Bertelloni and Guynn (2004) compute the stresses resulting from both lithospheric and mantle tractions, while de Koker and Lithgow-Bertelloni (2004) examine the stresses arising from only lithospheric sources of stresses. Lithgow-Bertelloni and Guynn (2004), however, only consider a lithosphere with constant thickness, while de Koker and Lithgow-Bertelloni (2004) allow for variations in lithospheric thickness. Future work will examine the effects of varying lithospheric thickness combined with mantle tractions computed in CitcomS that also include the effects of varying lithospheric thickness (Conrad and Lithgow-Bertelloni, 2006). In addition, we plan to implement more realistic visco-elastic rheologies in these models. Additional active research projects involving ABAQUS include determining the stress field on Mars resulting from variations in crustal and lithospheric thickness.

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Load-induced stress concentration beneath islands

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Abstract
Since 2002 the seismicity of the Hellenic Volcanic Arc is observed by the CYClades seismic NETwork (CYCNET). The localisation of these events shows that the seismicity beneath the islands focus on a shallow area of a few kilometres depth. The distribution of seismicity depends on the stress distribution of the underground. The island as a load makes an important contribution to this stress distribution. This stress situation caused by the load can be modelled with the Finite-Element-Method (FEM). To investigate the resultant stress in the vicinity of the island, several models are created with the programme ABAQUS. The ratio of maximum shear stress and normal stress acts as an indicator for potential area with increased seismicity. If this ratio exceeds a certain threshold rocks do not longer resist the current stress and break down.

Starting point of the investigation is a model of an elastic half space and an island with a triangular profile. In several steps the model is adapted to more realistic proportion. Firstly the half space is divided into two layers. The selected depth of the layer boundary is consistent with the average depth of the Moho in this area. Elastic material does not correspond with the results of observations in this area. Rocks show a viscous behaviour. In the next step the model is computed with viscous mantle material. The layer boundary still remains in the average Moho depth. In a further step the crust gets a ductile rheology to approach the natural behaviour of rocks. The layer boundary also still remains in a constant depth. At this point changes are only made to petrophysical parameters. Among these parameters a realistic model has to contain a real run of the Moho and real topography and bathymetry respectively. In a last step the model is modified in that way, that the run of the Moho, the topography of the island and the bathymetry of the sea bottom is adapted to realistic proportion.

For the elastic half space the computation of the ratio of maximum shear stress and normal stress shows that critical values are obtained in shallow areas at the edge of the island. This indicates seismicity at the coastline which is supported by the observations of the CYCNET.

Deformation changes induced by lake-level fluctuations of the Hohenwarte reservoir, Thuringia, Germany — an estimation with numerical modelling

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Abstract

The Hohenwarte reservoir in southeast Thuringia (Germany) is a medium-sized artificial reservoir, holding on average 180 Mill. m^3 of water. It was constructed between 1936-43 and is operational since then. The water load impounded induces stress and deformations of the underlying crust and upper mantle.

The Geodynamic Observatory Moxa is located around 4 km to the north. The data of the installed seismometers and strainmeters at Moxa are successfully used for studies of the Earth's interior structure and properties. It is possible to observe tilt changes in the nrad range and displacement changes in the nstrain range.

We explore the deformation effects caused by the water load of the Hohenwarte reservoir, both on a short-term seasonal time scale and a long-term decadal time scale. A Finite Element model in ABAQUS is used to calculate deformations in vicinity of the Hohenwarte reservoir. The seasonal effect, mainly induced by elastic deformation, results in tilt and strain deformation in the 4 µrad and 1 µstrain ranges, respectively. Long-term decadal variations, however, are unlikely to be significant, if a realistic viscoelastic structure of the underlying upper mantle is used. We also show that the influence of lake-level fluctuations of up to 30% to tilt and strain registrations at the observatory is larger than the resolution of the instruments at the observatory, with differences of at most 48 nrad for the tilt and 6 nstrain for the strain. Thus, at the location of Moxa, the influence of lake-level changes on the registrations is significant.

Postseismic stress relaxation after the June 23rd 2001 Mw = 8.4 earthquake in southern Peru

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Abstract
The 2001 Mw = 8.4 southern Peru subduction earthquake marked the beginning of a transient postseismic surface motion in direction of the coseismic displacement at the permanent GPS station Arequipa. In general this motion is assigned to afterslip. Our hypothesis is that the observed transient signal can be explained by stress relaxation processes in the overriding plate. We use a 2D finite element model incorporating non-linear viscoelastic Maxwell rheology. Our model results indicate that coseismically induced stresses are relieved by viscoelastic stress relaxation in the lower crust. The trenchward directed creep motion is transferred to the upper crust due to elastic coupling leading there to an instantaneous relief of elastic stresses. In contrast to the existing conceptual models for stress relaxation, which incorporate shear stresses, we conclude that tensional elastic stresses throughout the crust and upper mantle are the main driving forces for the transient GPS signal.

The profile of our vertical 2D model geometry is oriented perpendicular to the strike of the rupture plane, which is 310° according to the Harvard CMT catalogue. It contains the GPS station Arequipa and is almost parallel to the observed displacements. The model geometry extends 300 km vertically and 600 km horizontally reaching from 100 km southwest of the Peru-Chile Trench to the Andes. The finite element mesh consists of 32,341 linear elements. We implemented three rheological units with different material properties. (1) The oceanic crust of the Nazca Plate with a thickness of 8 km dipping with 18° and below a depth of 60 km with 20°. (2) The continental crust of the South America Plate with a thickness of 45-65 km in the forearc and 65-70 km in the Andes. (3) The upper mantle.

The model also contains the rupture plane as contact surfaces with Coulomb friction, located along the boundary between the continental and oceanic crusts, dipping with 18° (Harvard CMT catalogue) and extending from 12 to 45 km depth. At the bottom and the sides of the model only displacements parallel to the model boundaries are allowed. The upper boundary of the model is a free surface. To simulate the coseismic displacement of the earthquake we displaced the nodes along the rupture plane. The slip distribution grows linearly from zero at the upper and lower edges of the rupture plane to a maximum displacement at 32 km depth. We varied the coseismic slip in order to represent the coseismic displacement at the GPS station in Arequipa. The postseismic signal is modelled with non-linear viscoelastic Maxwell rheology using dislocation creep. The coseismic stress changes cause the onset of dislocation creep with creep rates depending on the given creep parameters and the temperature distribution. The numerical problem is solved with the commercial finite element code ABAQUSTM, version 6.4-1 (Hibbitt, Karlsson and Sorensen, Inc.).

Mechanisms for localising the deformation related to oblique convergence: Weak volcanic arc versus coupling at the subduction interface

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Abstract
Under oblique convergence, the deformation of the overriding plate is partitioned into trench-normal and trench-parallel components. The first component is commonly accommodated at the trench and the second by subvertical strike-slip faults in the volcanic arc or forearc. Large scale active strike-slip faults are thought to be located along weak zones associated with the volcanic arc and/or with inherited faults in the forearc. In addition, strike-slip faults may form above the end of coupling, i.e. the end of the plate interface where stress accumulates during the interseismic period and is released during an earthquake. The study investigates these two competing mechanisms with 3D models that incorporate heterogeneous elastoplastic rheology using the finite element program Abaqus.

Deformation of the fore-arc wedge along the obliquely convergent Chilean margin

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Abstract

The forearc wedge along the Chilean margin between 37° and 42°S, which results from oblique convergence between the Nazca plate and the South American plate, is characterized by a major margin parallel strike slip fault, the Liquiñe-Ofqui-Fault-Zone (LOFZ). Field studies show a recent dextral movement along the LOFZ of approximately 1cm/a.

We present 3D numerical models that investigate the conditions in which the models develop the typical deformational pattern observed in nature. The numerical models are constrained by seismic profiles geometrically and by gravitational and seismic velocity models rheologically. The model setup includes a kinematical modelled subducting Nazca plate and a dynamically modelled South American plate, both lithospheres have an elasto-plastic rheology. The two converging plates are coupled by a frictional interface. The friction at the interface drops abruptly at the downdip end of the seismogenic zone. Parallely, the thermal field was analyzed in order to compare with available surface heat flow data.

Several parameters (e.g., coupling strength, obliquity, convergence rate, rheological properties of wedge material), which potentially govern the style of deformation, were varied in order to study their impact on forearc deformation and to most accurately match natural observations. We found that the frictional structure at the plate interface plays a key role for the segmentation of the strain in a trench normal and a trench parallel component. Without the sharply changed frictional conditions at the plate interface it would be not possible to obtain strain partitioning. This sharp transition in the strength of coupling between plates is attributed to the mainly thermally controlled updip and downdip end of the seismogenic zone. The strength of the material, which is itself highly controlled by temperature, is also an important factor controlling the style of deformation. Comparison of model results with GPS data shows a good conformity with velocities in trench parallel direction, but modelled velocities for the trench normal component are somewhat smaller than observed. In order to render the results of our modelling, we constructed a similar model for the northern part of the Chilean margin. Despite almost equal plate kinematic conditions along the entire Chilean margin, the style of deformation of the forearc wedge differs significantly between the north and the south. This comparison allows us to extract the parameters that control variations of styles of deformation along the Chilean margin.

Three-dimensional Finite Element Modelling of the Andean Subduction Zone

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Abstract

We present a spherical three-dimensional dynamic finite element (FEM) model of Andean subduction zone which incorporates gravitation and a static temperature field. The model results the subduction and reproduces the present-day surface deformation. Our modelling approach includes the real topography and structure of the subduction zone and uses a rheological layering, i.e. it describes the mantle as a visco-elastic material while the slab is pure elastic. Between slab and continental crust we have a low friction contact-interface. While state-of-the-art kinematic models use the plate-velocity as well as the coupling zone as input parameters for forward modelling, our model results these quantities and has only the ridge-push and slab-pull force as input. With given analytical and numerical estimates for the ridge-push and slab-pull force, realistic estimates for the friction coefficient can be given.

Comparative geodynamic modelling about earthquake swarm areas and processes

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Abstract

An earthquake swarm is a temporary and regional sequence of earthquakes with several 1000 events within a period lasting from hours to days. Usually it occurs in an area of just a few square kilometres without any prevailing single event. Earthquake swarms are observed worldwide, especially in connection with fluid movement and volcanism. To clarify possible physical mechanisms that lead to the phenomenon of earthquake swarms, two prominent regions are compared by numerical investigations using the finite element analysis software ABAQUS: The Vogtland/NW-Bohemia area situated at the border of Germany and the Czech Republic and the Magadi region in the Kenya Rift.

Geodynamic models for the two regions were constructed which take into account the regional stress field and thermal stresses as well as creep and plasticity with a porous elastic rheology. The investigations are focussed on the interaction between pore pressure variations, temperature changes, fluid movement, stress accumulation and deformations. It is suspected that these processes play an essential role in the generation of earthquake swarms. The results of the modelling for the Magadi and Vogtland areas were compared with each other and with information from other earthquake swarm areas. Conclusions were drawn to general as well as to area-specific mechanisms.

An essential result of the modelling is that the existence of the regional stress field alone neither explains the occurrence of the earthquake swarms in the Vogtland area nor in the Magadi area. It reveals that physical processes in different regions of the earth's crust are coupled. Temperature changes and periodic pore pressure variations in the earth's crust are most important for the geodynamic processes. In combination with the local geology and heterogeneous distributed material parameters these processes have a crucial influence on the generation of earthquake swarms, even though they are weighed differently in each focal area. Consequently the modelling leads to an improved understanding of the processes and interactions that contribute to the occurrence of earthquake swarms.

3D Finite Element model for the stress field evolution for the Marmara Sea region

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Abstract

During the last decades the westward propagation of large earthquakes along the North Anatolian Fault has reached the Sea of Marmara. Thus, the seismic gap along the fault crossing the Marmara Sea has the potential to generate a strong earthquake in the near future. However, the size of the gap as well as the question whether the fault will rupture in a single event or in several smaller ones due to the structural complexities is an open issue. Both informations are essential input information's for the wave propagation codes which calculate peak ground acceleration distribution and site effects in the City of Istanbul.

In order to investigate the contemporary stress state of the Marmara Sea region and its evolution during the last earthquake cycle we constructed a 3D mechanical model which incorporates the 3D structural information as well as the lithological and rheological inhomogeneities. In contrast to other work which quantify stress field changes due to instantaneous co-seismic and transient postseismic stress transfer processes, our aim is to quantify the total stress field and its evolution in time and space. Even though a wide range of numerical models have been published in the last decade, additional improvements are necessary to meet our objective:

The 3D model geometry will incorporate topography and bathymetry data, Moho variations, upper/lower crust boundary, and the complex geometry of the active fault system using contact surfaces with Coulomb friction. The constitutive law of the model is a non-linear viscoelastic rheology and boundary conditions are gravity as well as tectonic forces imposed from the indentation of the Arabian plate and the retreat of the Hellenic arc subduction zone. The numerical problem is solved with the finite element method using the commercial code ABAQUS. The resolution of the model is several hundred meters near and on the fault and has in total approximately two million linear elements. In order to control the quality of the model results we compare the model results with independent data from GPS observations (permanent stations and results from campaign measurements) and information on the tectonic regime and principal stress orientations.