

THERMTEC, Thermal – Tectonic Modelling of Orogenetic Processes in the Eastern Alps

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ABSTRACT

The scope of the project THERMTEC is to model thermal-tectonic orogenetic processes in the Eastern Alps focusing on the Tauern Window. The regional geothermal regime in the study area is influenced by a series of processes like tectonically induced uplift or depression, exogene processes like erosion and sedimentation, hydrothermal convection or palaeoclimatic effects. Within this project, the aim is to study the interaction of these processes but also to gain knowledge of their individual significance on geothermal regimes. Therefore, an interdisciplinary approach was chosen. Diverse geophysical, geochronological and petrophysical investigations as well as 3D geological modelling were carried out. Numerical modelling using different state-of-the-art commercial software packages was applied implementing the previously assessed data. In order to separate the different effects influencing the thermal regime, multiple models with an increasing grade of complexity have been set up. Based on these results we can provide a quantification of the individual process-related effects on the geothermal regime.

1. INTRODUCTION

Regional geothermal regimes are influenced by tectonically induced processes in terms of uplift or depression, which in combination with exogene processes like erosion and sedimentation may lead to significant deviations from predicted pure conductive, steady state temperature distributions. The scope of the project THERMTEC is to investigate these thermal – tectonic processes in the Eastern Alps, focusing on the area of the Tauernfenster (Tauern Window).

The Tauern Window is a tectonic window, where Penninic and Subpenninic Units are exhumed due to uplift and erosion processes. These units are represented by deposits of the Penninic ocean which was subducted underneath the Adriatic plate (Tollmann, 1977) during the Alpine Orogeny in early Cretaceous (Faupl and Tollmann, 1979). The predominant Subpenninic “Zentralgneise” are described as Permo-Carboniferous intrusions into Variscan Basement Units (Schmid, 2013). Within the past about 20 – 30 Ma this high-grade metamorphic Cenozoic nappe stack has undergone extensive lateral extrusion and exhumation (summarized by Schmid, 2013).

The fast exhumation of relatively warm crustal parts in combination with erosion leads to a positive heat anomaly demonstrating a high terrestrial heat flow in this area. Other effects influencing the thermal regime in this region are topographic and palaeoclimatic effects, the radiogenic heat production rate as well as exogenous processes and deep hydrothermal circulation systems. For investigation of these complex settings, a multidisciplinary approach was chosen including geothermal, geochronological and petrophysical investigations as well as geological and numerical 3D modelling.

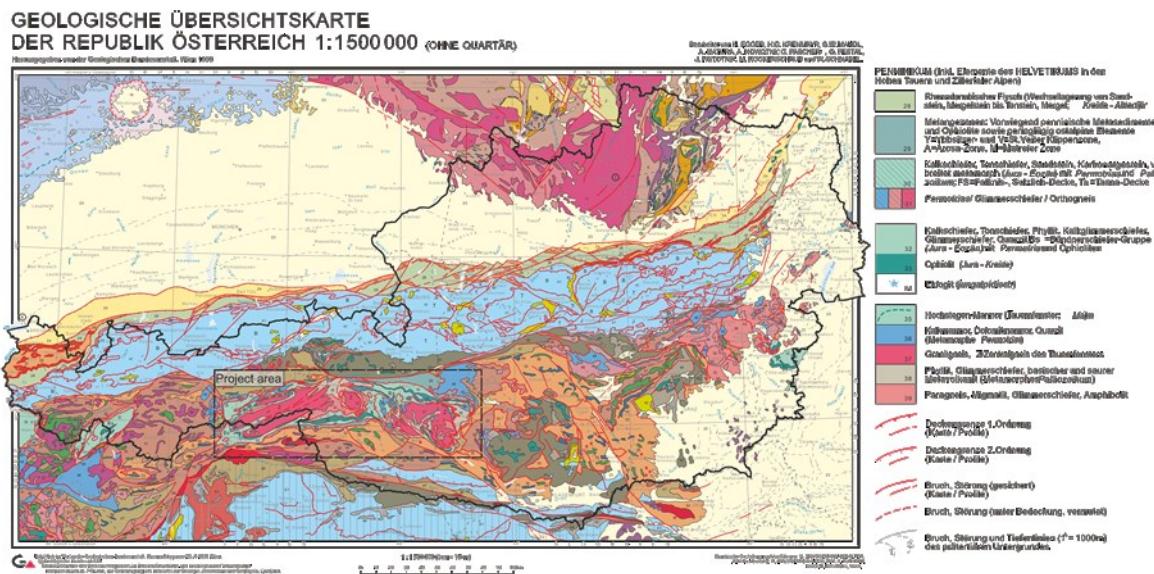


Figure 1: Geological map of Austria published by Geological Survey of Austria (original scale 1:1500000) and an overview of the investigation area of the project THERMTEC.

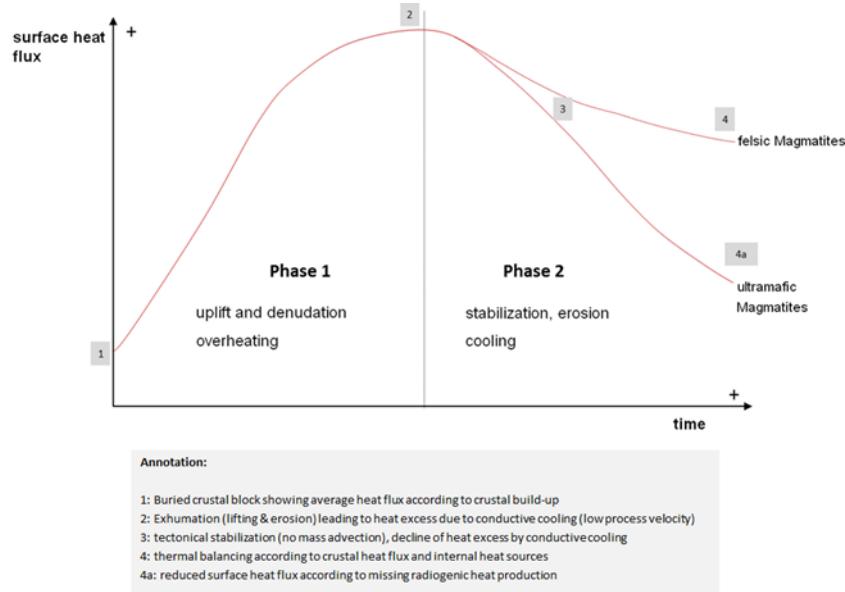


Figure 2: Schematic assumption of the time-dependent surface heat flux of uplifted crustal blocks and different radiogenic heat production (felsic and ultramafic rocks).

2. MATERIALS AND METHODS

2.1. Petrological-, petrophysical and thermal data acquisition

Approximately 160 rock samples (from outcrops as well as drillcores) were collected and analyzed in terms of thermo-physical and petrological rock properties. The sampling was done mainly with respect to the formations represented within the geological 3D model.

For general characterization of texture and mineral composition of rock samples, optical microscopy (a Leica DMLP polarizing microscope) was used, the geochemical composition was attained by XRF. The specific heat conductivity was measured by the thermal conductivity meter TK04, porosity was determined using the principle of Archimedes and the heat capacity by a calorimeter developed by the University of Leoben, petrophysics laboratory. The radiogenic heat production was measured using a scintillation spectrometer GS-256 (Co. Geofyzika Brno). Continuous borehole measurements were carried out in water filled wells using a combined temperature- and conductivity probe Cond197i (Co. WTW). Long-term temperature measurements of tunnels were recorded by the sensors iButtons DS1922L (Co. Maxim).

In order to derive rates for tectonically triggered mass movement rates for tectonic units, geochronological data was acquired from literature studies. In addition to the sampling and gathering of petrophysical data, models for the thermo-physical properties of the crust and parts of the upper mantle were estimated.

2.2. Data Management and processing

The software package ArcGIS was used as database for geological- and tectonic maps, structural data, information on outcrops, locations of published cross-sections, etc. It is also used as the tool for the management of the newly acquired data like temperature measurements or geological samples but also for visualization aspects like publishing maps. The software package GOCAD™ was used as geometric 3D modelling tool. It represents the 3D-database from where it is possible to export horizon interpretations for further usage in numerical modelling approaches.

Numerical modelling was carried out using the software packages FEFLOW™ 3D and COMSOL Multiphysics™, depending on the considered question and grade of complexity. In order to separate the different effects influencing the thermal regime, multiple models with an increasing grade of complexity have been set up. FEFLOW™ 3D was used for pure Heat Transfer models (for assessment of the topographic and the palaeoclimatic effects). Using the software package COMSOL Multiphysics™ (full 3D FEM solver), coupled thermal-tectonic modelling is carried out during several steps focusing on 2D cross sections, representative for the whole Tauern Window. The major geological surfaces were modelled using GOCAD™ and subsequently transferred to COMSOL™ via ASCII files. The surface temperature is set as boundary condition on the top of the model as altitude dependent function. For the bottom boundary condition, a constant mantle heat flux was applied. The thermo-physical properties as functions of temperature and pressure (i.e. depth) can be implemented directly in terms of 3D interpolation functions.

Based on the summarized geochronological data, cooling paths were reconstructed and subsequently correlated with the previously established tectonic zoning of the project area. Developing time-dependent profiles for exhumation rates and palaeo-temperatures help to define convective boundary conditions for numerical simulations. Thermo-physical rock properties are essential input parameters for a coupled thermal-tectonic simulation and represent a) thermal conductivity and their anisotropy, b) specific and volumetric heat capacity, c) radiogenic heat production, d) density and porosity. The porosity and temperature dependency of the thermal conductivity and specific heat capacity is considered based on Vosteen and Schellschmidt (2003). The pressure dependence according to Kappelmeyer and Haenel (1974) was also applied to these parameters. The measured data of the radiogenic heat production were extrapolated by means of the exponential model (Čermák et al., 1991) from the surface to the deeper parts of the

geological model. Given that igneous and metamorphic rocks are predominant in the project area – the Tauern Window, a first assumption of a depth-independent porosity distribution for the numerical simulation was made.

3. RESULTS

3.1 Large-scale geological 3D model

Tectonic windows within the Central Alps, where mainly Penninic Units come to surface due to uplift and erosion are represented by the prominent Tauern- as well as the Unterengadiner- and the Gargellen Fenster (“window”). The geological 3D model represents the whole of the Tauern Window which covers an area of approximately 180 x 60 km. As the Tauern Window does not bear hydrocarbon reservoirs, hardly any deep wells or seismic surveys are existent for this area. That is why this model is to be titled as conceptual – it is based on surface geology, few wells and two large seismic projects (TRANSALP and ALPASS) focusing on the structure of the lithosphere. The publication of Schmid et al. (2013) comprising a tectonic map of the whole Tauern Window plus a series of ten cross-sections reaching a depth of 5 km was partly implemented into the model.

Necessary steps foregoing the actual modelling was the creation of a homogeneous geological map in terms of scaling and tectonic/lithological correlation. A part of the study area lies over the border in Italy resulting in a greater homogenization effort. The area is not yet fully mapped in 1:50 000 so maps in different scales, years of publication and from different editors had to be compiled. The resulting surface geological map with structural and tectonic information represents the main input for the model.

The intention of using the completed model for numerical simulations regarding subjects like vertical movement of crustal blocks, heat flux anomalies or deep hydrothermal circulation systems lead to dimensions where the MOHO represents the deepest model unit. The MOHO geometry was adopted by the study ALPASS (Behm, 2007). The decision on how to build up the model was made considering different geological aspects like tectonic and/or lithological correlations – and thus correlations of their thermal rock properties.

The resulting geological 3D-model consists of about 20 layers and represents a conceptual approach on alpine tectonics within the study area. Established large-scale tectonic features like the SEMP strike-slip fault or the Brenner normal fault were taken into account as well as discussed and controversial structures.

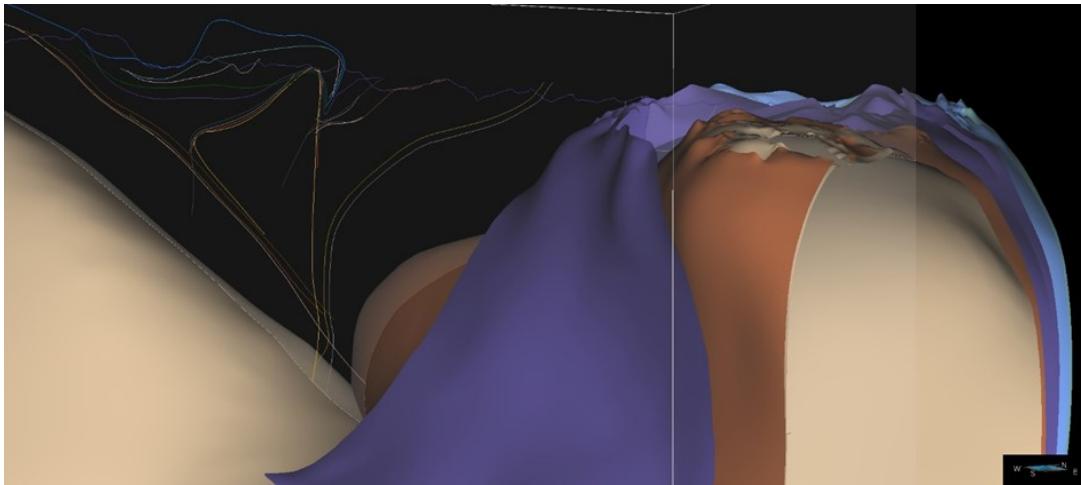


Figure 3: Screenshot from the GOCAD™ model of the central-eastern Tauern Window up to a depth of about 20 km with view to north-west: colored surfaces represent the modeled geologic horizons, lines indicate modeled surfaces as 2D-cross-section cutting through the model from east to west.

3.2. Geothermal data

To improve the state of geothermal data in the Tauern Window, subsurface and borehole temperatures were attained. Long-term measurements to collect locally predominant heat flux data were realized in several tunnels, galleries and mines using temperature data loggers. Also, newly available data (mainly thermal logging data) from the Brenner-Basis-Tunnel in Tyrol will be taken into account. Data from realized field campaigns using long-term measurements of air temperature and borehole measurements using fiber optic systems were evaluated. The calculated values for the geothermal gradient were in the range of 12 to 39 K/km. These results indicate that enhanced geothermal conditions are locally restricted.

3.3. Numerical Modelling

Initially, the topographic effect is assessed using a simple homogeneous model with the relief of the topography on top, where an altitude dependent function is used as temperature boundary condition. A strong relief causes a reduced geothermal gradient below the mountains and slightly enhanced geothermal conditions in the valleys compared to a flat topography. This effect is hard to quantify in a general way, numerical models can deliver crucial results: On the one hand, the results of this modelling step help for interpretation of measured underground temperatures. On the other hand, the resulting temperature field of this model can be used as reference for quantification of the anomalies caused by the different effects investigated in consequent models.

The palaeoclimatic effect, especially the signal of the last ice ages, is still supposed to have a major influence on the geothermal conditions. Numerical methods provide a quantification of this effect by applying an altitude corrected, time-dependent function

(Rellstab, 1982) for the temperature BC at the top of the model domain. According to 1D models, the maximum amplitude of the temperature anomaly caused by the palaeoclimate is found in about 2 km depth. Combined with the topographic effect and applied on a 3D model, the maximum anomaly can be found in about 500 meters subsea, laterally located below the major valleys.

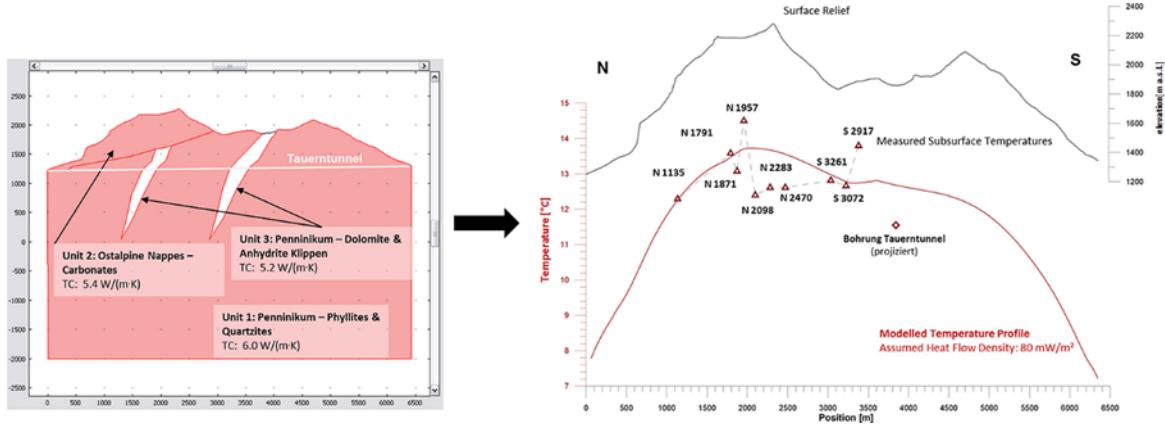


Figure 4: 2D model of the Tauern tunnel; left: 2D geometry of the Tauern tunnel and material properties; right: modelled temperature profile (red line) according to a conductive model (COMSOL) compared to measured rock temperatures (red triangles).

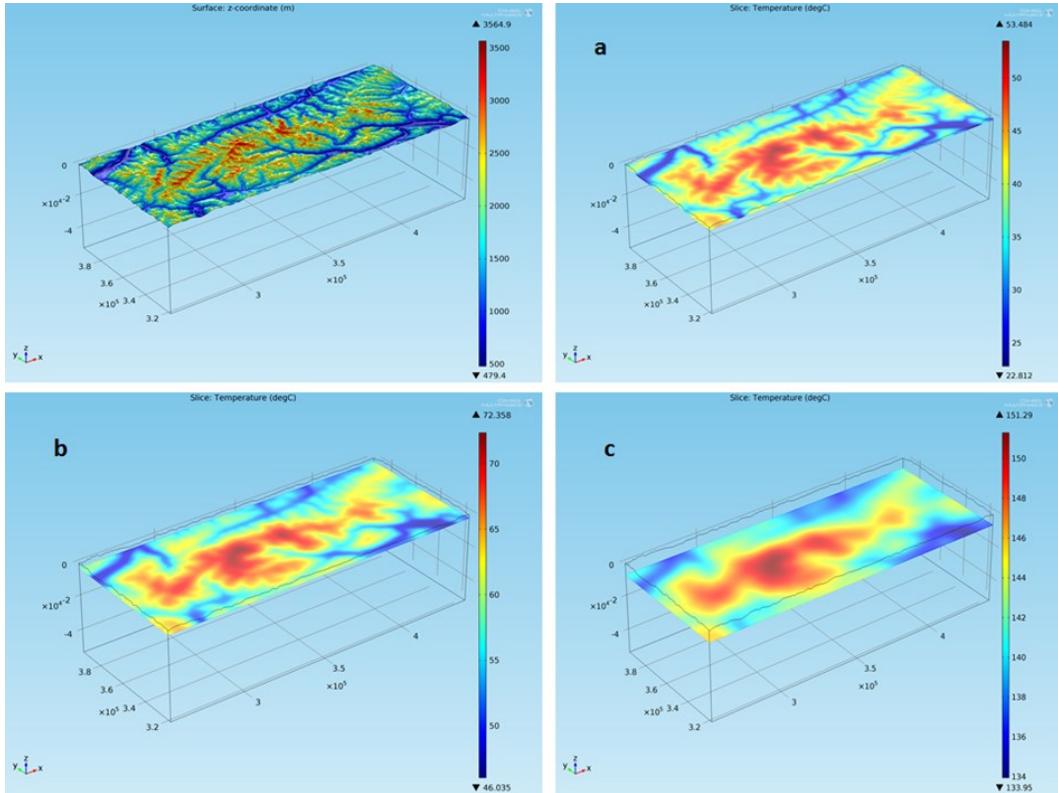


Figure 5: Steady-state solutions for three depths. Top left: topography of the Tauern Window, a: temperature at sea level, b: temperature at 1000 mbsl, c: temperature at 5000 mbsl. Even in large depth the shape of the topography has a prominent influence on the thermal regime.

Coupled thermal tectonic modelling is the most complex problem carried out in this study. For development of a suitable workflow a representative N-S cross section (Schmid et al., 2013) was chosen for setting up a 2D model (Figure 7). The results are obtained in multiple steps: First, a thermal steady state solution of the undeformed geometry is calculated as initial model. The second step is a transient solution of the heat equation under deformation – elastic deformation is assumed as a first approximation. That is the actual thermal tectonic model. The third and last step is again a thermal steady state solution of the deformed geometry without any further deformation. Finally, the difference between solution 2 and solution 3 yields the temperature anomaly caused by tectonic deformation. The results lead to a better understanding of the underlying processes and their effect on the thermal regime, especially concerning the spatial distribution of the geothermal anomalies. Subduction as well as tectonic uplift can be identified in the resulting temperature field as negative and positive anomaly respectively (Figure 7c). First results of coupled thermal tectonic

models lead to the assumption that tectonic processes are the biggest factor for large scale geothermal anomalies in the area of the Tauern Window.

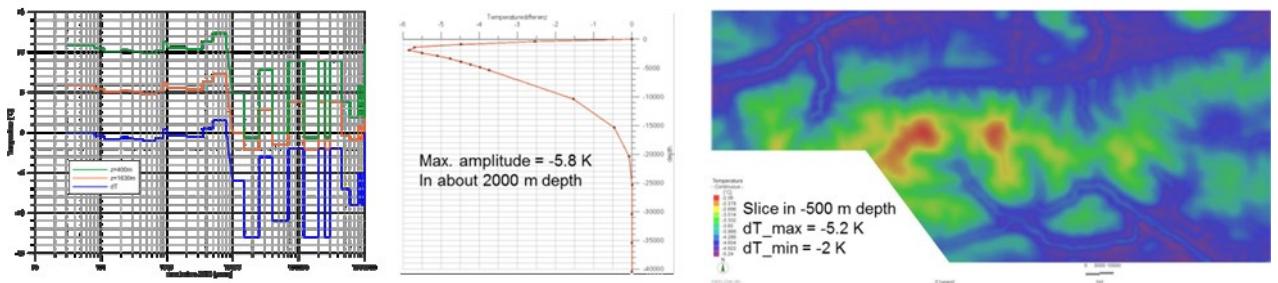


Figure 6: Evolution of the palaeoclimatic temperature after Rellstab, 1982 (left) and its temperature perturbation on a flat model (middle) and on the topographic model (right). The highest amplitude of -5.2 Kelvin is therefore at about 500 mbsl meaning approx. 1500 m below the topographic surface.

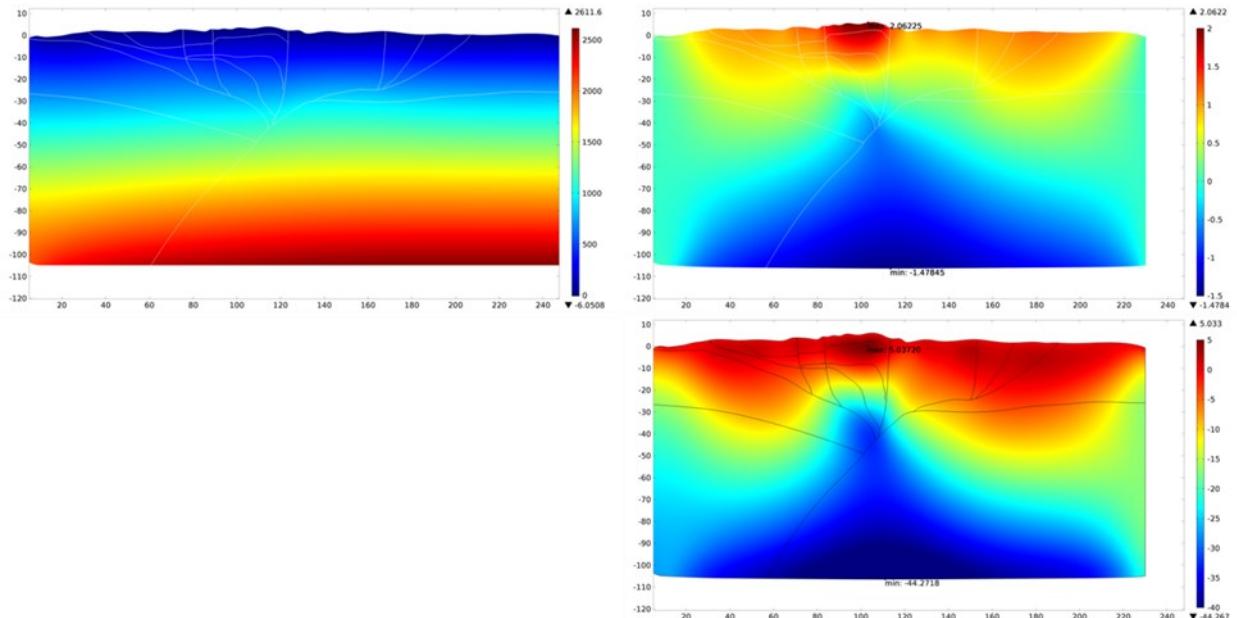


Figure 7: Preliminary results of 2D coupled thermal tectonic model. Top left (a): Steady state temperature before deformation. Top right (b): Vertical displacement after deformation. Bottom right (c): Temperature anomaly due to deformation: Difference between temperature after deformation and steady state temperature after deformation.

4. CONCLUSIONS

In terms of surface geology, the Tauern Window is a quite well-explored area. Geophysical investigations have been conducted to gather information on the deep structural levels focusing mainly on seismic surveys and gravimetric data (e.g. TRANSALP, ALP2002, ALPASS – see Behm et al, 2007). These previous studies provide good information on basic structures like the depth of the MOHO, but still there is lack of information from the interior structure of the Alpine Units. Only a couple of tunnels, mines and boreholes provide additional geological information. Hence, the produced geological model has no claim to be complete or “correct”, it represents the first approach of an illustration of the deep subsurface in this region. It was built primarily to serve as a basis for numerical simulations.

The thermal springs within the study area are presumably caused by deep water circulation within granitic units (“Zentralgneis”) and have not been taken into account for interpretation so far. Concerning geothermal modelling, no final synthesis was achieved up to date. Considered in isolation, the interpretation of the temperature measurement campaigns by itself does not indicate enhanced geothermal conditions in the project area. The calculated values for the geothermal gradient are between 12 to 39 K/km which is in the range of the global average. Still, for alpine regions with a high lithospheric thickness and strong relief the higher values can be seen as positive geothermal anomalies, possibly induced by remaining heat from the tectonic uplift.

5. ACKNOWLEDGEMENT

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