Crust-mantle interactions beneath the Hangai Mountains in western Mongolia. Insights from 3D magnetotelluric studies and 4D thermo-mechanical modelling

Summary

The dome-shaped Hangai Mountain range in western Mongolia is an ideal natural laboratory for studying on-going and past intra-continental orogenic and magmatic processes resulting from crust-mantle interactions in space and time. While such intra-continental uplift and subsidence have long been recognized as an important part of continental tectonics, their origin remains enigmatic. The explanations are diverse and controversial and include uplift above a hot upwelling mantle, small-scale asthenospheric upwelling, magmatic underplating, crustal delamination and lower crustal flow. Thermo-mechanical modelling, when constrained by geophysical and geological data and models, can nowadays simulate realistic tectonic processes and test for different geodynamic hypotheses. While past and on-going geophysical studies have focused on gravity and seismology, magnetotelluric (MT) data are missing from the Hangai. MT data are particularly important, however, as these are the sole means of estimating crustal and upper mantle electrical conductivity, which is very sensitive to fluids and partial melt. Hydrous phases and melt, on the other hand, provide critical parameters for calibrating thermo-mechanical models. In this project, we propose to image crustal and upper mantle electrical conductivity beneath Hangai Mountains using 3D MT and to derive constraints for 4D high-resolution thermo-mechanical modelling studies. We expect to derive estimates on fluid/melt volumes and to identify regions of rheological weakness from the MT data, if present. The study aims to understand the processes responsible for developing dynamic topography in the Hangai Mountains and to place them within the larger framework of crust-mantle interactions and dynamic topography. The key components of the project are to 1) acquire, process, and invert MT data in western Mongolia in terms of 3D conductivity models; 2) to guide 4D thermo-mechanical modelling with constraints that derive from laboratory-based electrical conductivity models; 3) to perform 4D thermo-mechanical modelling. The proposed project is a collaboration between ETH Zurich (ETHZ, Switzerland) and the University of Münster (UoM; Germany) in the framework of the joint German-Austrian-Swiss (DACH) program and will be carried out in cooperation with the Research Center of Astronomy and Geophysics (RCAG) of the Mongolian Academy of Sciences. The project partners combine expertise in the fields of MT data acquisition, MT data processing, MT forward and inverse modelling, and geophysically-constrained 4D forward thermo-mechanical modelling. Funding is requested for three PhD students: two of whom will be located at ETHZ covering MT and geodynamics and one at UoM in the field of MT. Requested funding also includes organization of two MT field campaigns. Expenses for the field campaigns will be equally shared between ETHZ and UoM. The main expected outputs from the project are 1) the first 3D geo-electrical model beneath the Hangai dome in Mongolia and 2) a geomorphological-thermo-mechanical model of intra-continental lithospheric deformation, magmatic activity, and evolution of dynamic topography that is consistent with the geophysical and geological observations.

2. Research plan

2.1 Current state of research

2.1.1 Intra-continental uplift and magmatism are still enigmatic

There is consensus that plate tectonics explains many observations of dynamic processes within the lithosphere and on Earth’s surface, including the distribution of earthquakes, volcanoes, mountain belts, and the transfer of material at subduction zones and rifts. These manifestations of plate tectonics are bound to lithospheric re-organisation at active plate boundaries; they, however, cannot predict intra-continental uplifts far away from plate boundaries that occur in many regions of the world. These intra-continental plateaus are characterized by high elevation with relatively low relief and spatial wavelengths of hundreds of kilometers. End member explanations for intra-continental uplift or subsidence include 1) an upwelling hot mantle plume (e.g. Windley and Allen, 1993); 2) convective delamination at the base of the lithosphere (Foulger at al., 2011) or plate-boundary enforced lithospheric extension, associated with an upwelling and melting of shallow astenosphere (e.g. McKenzie and Bickle, 1988); 3) crustal thickening in response to magmatic underplating (e.g. Cox, 1993), 4) thermal shielding, where continental lithosphere is thought to prevent convective heat transfer to the surface, leading to build-up of heat and subsequent melting (e.g. Petit et al., 2002, Barry et al., 2007). All of these models, which are associated with melting processes in the astenosphere and lithosphere, are closely related to intra-plate magmatism but originate from distinct crust-mantle interactions. In addition, 5) channelized flow of a weak lower crust in response to lateral pressure gradients (e.g. Clark et al., 2005) has been proposed as a mechanism for dynamic topography.

2.1.2 Hangai Mountains as a natural laboratory to study intracontinental crust-mantle interactions

One of the clearest appearances of intra-continental uplift is the Hangai Dome in western Mongolia at the perimeter of the India-Eurasia collision zone in the south and in the far-field of the western Pacific subduction zones to the east (see Fig. 1a). Western Mongolia and adjacent parts of central Asia currently show ~10 mm/yr of northward-directed shortening related to the India-Asia collision (Yin, 2010). The Hangai Mountains take place in a transition between principally north-south oriented compressional deformation to the south and east-west extensional deformation to the north (Yin, 2010). The northern margin of the plateau and neighboring parts of the Siberian Craton are dominated by the active Baikal and Hovsogol intra-continental rifts.

The Hangai block is located between right- and left-slip faults in a V-shaped disposition (cf. Fig. 1a). Some of the largest intra-continental earthquakes with magnitudes Mw > 8 have occurred along these faults during the last century (e.g. Schlupp and Cisternas, 2007). These include the 1905 Bolnay, 1931 Fuyun and 1957 Gobi Altai earthquakes. Situated in the junction between regions of active shortening and extension, the Hangai Mountains and trans-Hovsogol ranges occupy a large domal highland (~ 425,000 km^2) and contain the Hangai Dome (~ 200,000 km^2). The interior of the dome is at elevations ~ 1.5 km above the regional trend and locally reaches elevations of up to 4 km. To the southwest, the Mongolian Depression and the Great Lakes Valley lie between the Hangai uplift and the Altai ranges (cf. Fig. 1a).

Although the high topography of the Hangai Dome was initially related to mantle plume activities (e.g. Windley and Allen, 1993), geochemical and geophysical investigations indicate that the thermal anomaly is shallow and that the late Cenozoic volcanism was largely related to partial melting of the upper mantle (Petit et al., 2002, Barry et al., 2007). Previous seismological studies proposed a 50 km thick crust beneath Hangai, a lithospheric thickness of ~70-

80 km, anomalously low shear velocities within the lower crust and upper mantle and fast velocities at greater asthenospheric depths (Priestley et al., 2006, cf. Fig. 1b in this document). These observations do not support a deeply rooted mantle plume, although a plume-like heat pulse or mantle convection originating from the deep interior cannot be completely ruled out. Magmatic activity in Mongolia has focused since 12 Ma before present on the uplifted Hangai. Recent isotope studies on erupted lavas and mantle xenoliths explain melting beneath the Hangai Dome with lithospheric delamination or small-scale mantle upwelling (Hunt el al., 2012), both representing progressing melting processes that are initiated by decompression melting of the astenosphere and subsequent heating and melting at the base of the lithosphere. Both processes may also account for regional uplift and outward progression of melting following the thermal erosion of the lithosphere.

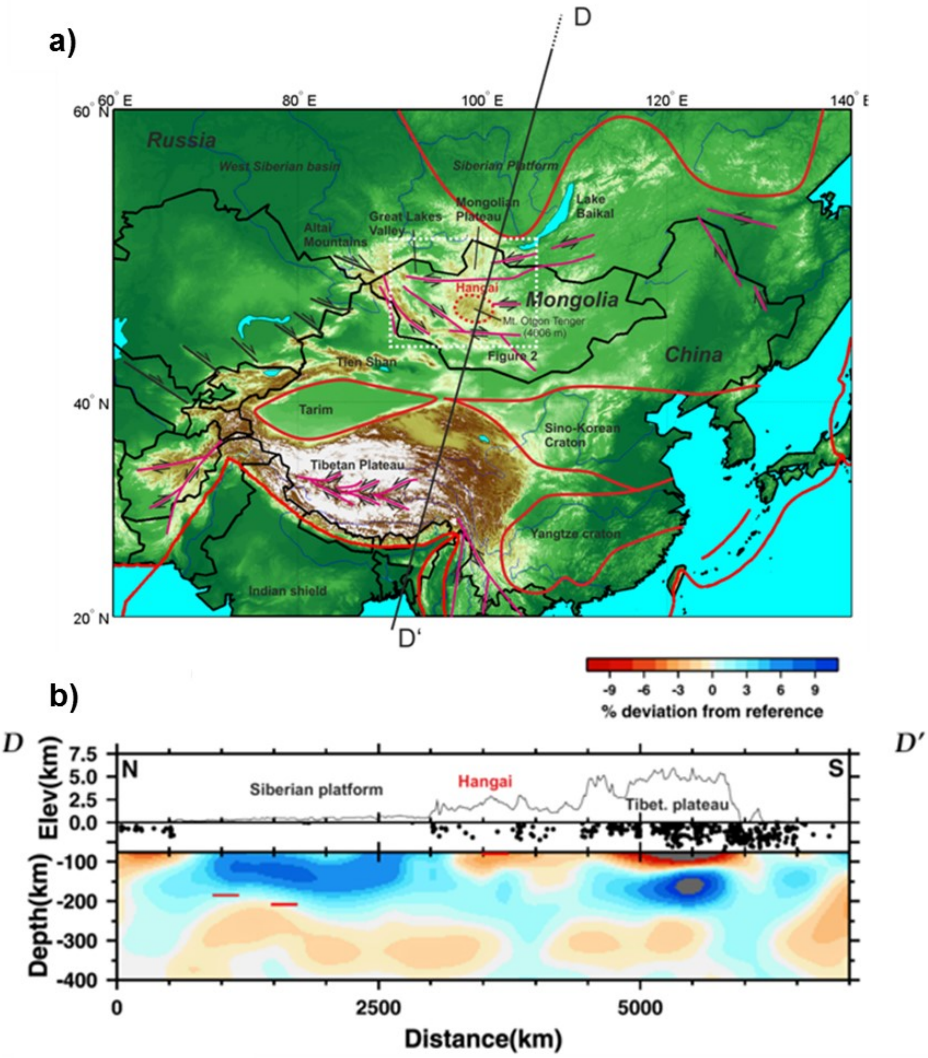


Figure 1. a) General context of morphological and tectonic division of central Asia, modified after Yin (2010) and Priestley et al., (2006). Only strike-slip faults in V-shaped arrangement are shown. Red lines mark platform and plate boundaries. White dashed rectangle outlines the study area (Figure 2). **b)** Cross-section showing the depth variation of the Sv wave speed heterogeneity along profile D'D (Priestley et al., 2006). Red lines superimposed on the cross-section show lithosphere thickness, which is probably less than 90 km beneath Hangai. Note the low velocity structure beneath Hangai, which appears to be confined to the uppermost mantle. Black dots are magnitude 5 and greater earthquakes; topography is plotted in right panel (from Priestley et al., 2006).

In summary, at least four geodynamic hypotheses have been proposed for the origin of the dome and associated magmatism, which include: 1) an upwelling mantle plume (Windley and Allen, 1993), 2) removal of the base of the Hangai lithosphere as a result of lithospheric instability (e.g. Hunt et al., 2012), 3) small-scale asthenospheric upwelling under the Hangai Dome associated with thermal erosion of the lithosphere (e.g., Hunt et al., 2012), 4) magmatic underplating of the lower crust by cumulates or mafic granulates (Petit et al., 2012). In addition, it has been demonstrated that this apparently aseismic region is tectonically active and deforms along the system of normal and strike-slip faults (Walker et al., 2007, 2008). This ongoing complex three-dimensional lithospheric deformation can strongly modify mantle-lithosphere interactions beneath Hangai and its topographic response. To model this most realistically, high-resolution 4D geomorphological-thermo-mechanical numerical modelling efforts are required (Burov and Gerya, 2014).

The Hangai mountain range also provides a window into understanding how climate influences the erosion and resulting geomorphic and sedimentary signatures of continental topography (e.g. West et al., 2013). Specifically, asymmetric erosion of the Hangai, associated with a distinct orographic precipitation gradient, offers a natural laboratory for understanding tectonic uplift, erosion, and the isostatic response to erosional unloading (West et al., 2013). Morphology of the range indicates a non-equilibrium landscape that may have persisted for millions to tens of millions of years (West et al., 2013), thus forming very slowly in response to climatic and erosional gradients as well as evolving long-term tectonic processes causing the uplift and deformation of the crustal surface (Walker et al., 2007, 2008).

2.1.3 Existing geophysical and ongoing seismological studies in the Hangai region

In 2001-2003, the University of Brest (France) in cooperation with the Russian and Mongolian Academies of Science conducted the Mongolian-Baikal Lithospheric Seismological Transect (MoBaL) experiment, which included seismic and geodetic (GPS) studies along the N-S profile crossing Hangai (https://perso-sdt.univ-brest.fr/~jacdev/mobal.htm).

In 2012, Lehigh University (USA) in cooperation with the Research Center of Astronomy and Geophysics (RCAG) of the Mongolian Academy of Sciences started a 3-year NSF-funded project aiming at understanding the processes responsible for developing high topography in the Hangai Mountains and to place these in a larger plate tectonic framework (http://www.ees.lehigh.edu/groups/mongolia/description.html). During the project geomorphological, petrological, geochemical, and seismological studies were carried out. In particular, in spring 2012, Lehigh University (USA) and RCAG deployed 72 broad-band seismometers in western Mongolia (cf. Fig. 4, open blue circles) that recorded data for a period of two years. Data interpretation is currently underway and will include receiver-function analysis, shear and compressional velocity tomography of the crust and upper mantle, and study of crustal anisotropy. We will collaborate with the seismology team from Lehigh on joint interpretation with mutual benefits for both groups (see letter of support by Prof. Anne Meltzer, Lehigh University).

2.1.4 What is missing in Hangai is the magnetotelluric (MT) component!

MT studies – by recovering the electrical conductivity distribution – provide independent and complementary information to the seismological investigations of the region. Electrical conductivity reflects the connectivity of conductive constituents such as fluids, partial melts, and volatiles and is intrinsically dependent on temperature, while seismology ascertains bulk elastic properties. Owing to the physical principles of MT, spatial resolution is low compared to seismic techniques; nonetheless, MT is very sensitive to the upper parts of any conductive zone and to lateral conductivity variations. Therefore, MT provides a firm means of testing the hypothesis of widespread heating and melting at the base of the lithosphere beneath the Hangai dome uplift, as proposed by petrological studies (Hunt el a., 2012) and suggested in seismic tomography images (e.g. Priestley et al., 2006, Fig. 1b). In addition, lower crustal conductors often thought to correspond to mechanically weak zones can be imaged. MT can also illuminate crustal pathways for magmas and fluids. We summarize some MT examples from other continental plateaus in section 2.1.5. As fluids affect rheology, electrical conductivity provides insights into the mechanical conditions within the lower crust and upper mantle (e.g. Karato and Wenk, 2002), which can be placed into the context of geodynamic models.

MT studies of the Hangai Mountains have not yet been performed. Here, we propose to image for the first time the electrical conductivity of the lithosphere beneath the Hangai dome uplift and its adjacent array with 3D MT and to use these results to guide high-resolution 4D thermo-mechanical modelling of the Hangai region. Note that establishing links between observed electrical conductivity and fluid content, viscosity, mineral content and temperature is a challenging task, which is also an important component of the project.

To tackle these issues, we have formed a team that combines expertise in 1) performing MT studies (Michael Becken and Alexey Kuvshinov), 2) integrating and converting widely different data sets (e.g. MT, seismic) to thermo-chemical parameters (Amir Khan), and 3) 4-D thermo-mechanical modelling (Taras Gerya).

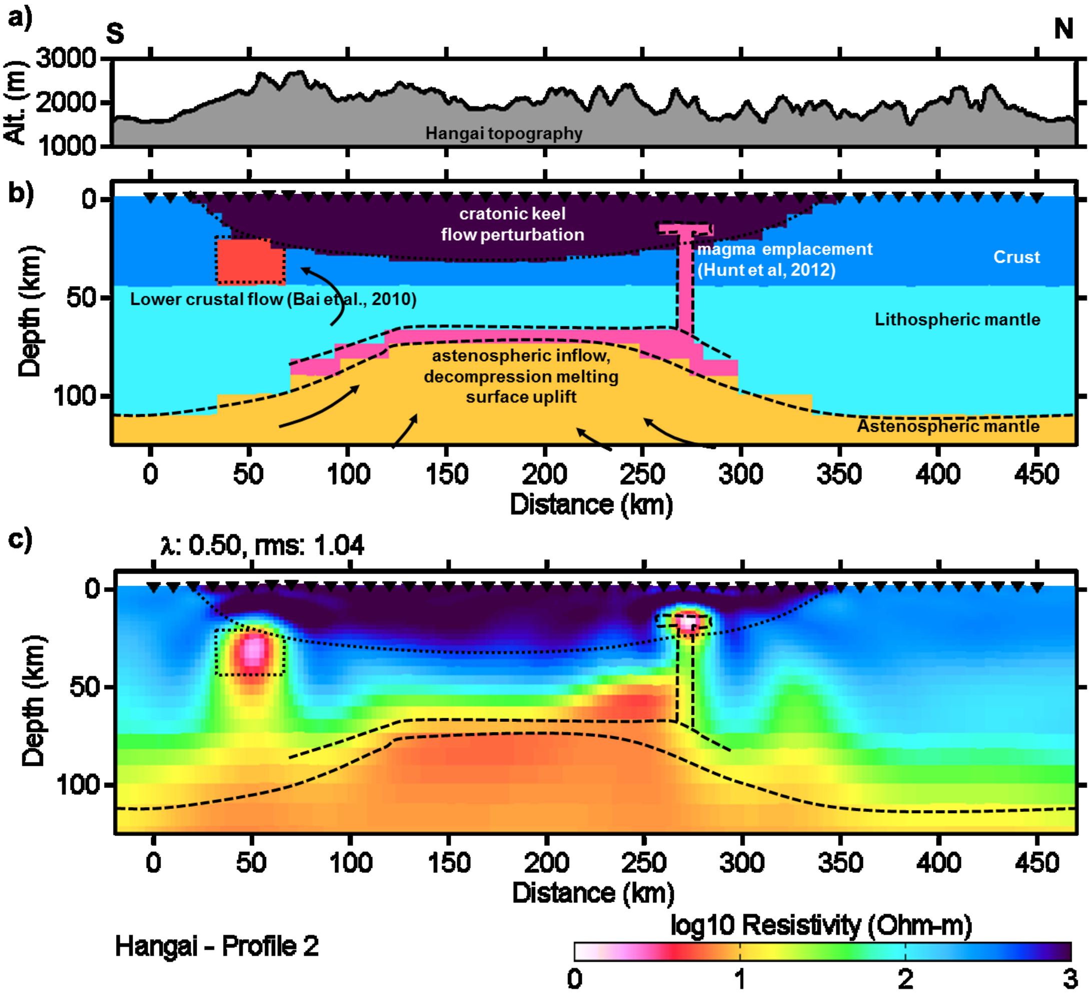


Figure 2. 2D MT model study along the NS-oriented (cf. Fig. 4) across the Hangai dome. The profile mimics the proposed profile 2 (cf. Fig. 4). **a)** Topography and **b)** hypothetical resistivity model, largely based on the lithospheric mantle flow model by Cunningham et al. (2001). The rigid crustal Hangai block is thought to deflect NE-directed mantle flow, resulting in upward flow along the cratonic edges and thinning of the mantle beneath the Hangai. Uprising asthenosphere partially melts and results in uplift and doming. Following Hunt et al. (2012), we introduced uprising magma, which is stalled at mid-crustal levels in the northern part. We also introduced a region of lower crustal flow at the southern edge of the craton (Bai et al., 2010). **c)** 2D Inversion result of noise-contaminated synthetic data generated with the model in panel b. The data are E- and H-polarization apparent resistivities and phases and the period range from 0.1-10000 s and with a site spacing of 10 km. 5 % and 2° Gaussian noise had been to the apparent resistivites and phases, respectively. We inverted for conductivity deviations (in logarithmic space) from a 1D layered model consisting of homogeneous 300 ohm-m lithosphere and a 10 ohm-m asthenosphere below 110 km depth. Topography was included in the modelling. The main features of the synthetic model can be recovered, including the upwelling conductive asthenosphere, and the zones of elevated conductivity within the lower and middle crust. An artefact occupies the deeper part of the model at the southern edge.

To test how MT imaging can contribute to improve the understanding of the geodynamic setting that has resulted in the Hangai uplift, we have performed a synthetic 2D model study. The model is inspired by the mantle flow model described in Cunningham et al. (2001). They suggested that the Hangai dome constitutes a rheologically rigid strong cratonic block that penetrates the mantle lithosphere and there deflects into a NE-directed mantle flow. The consequences include outward and upward flow diversion, upwelling mantle asthenosphere, decompression melting, and crustal uplift. We have translated these features into an electrical conductivity model, assuming that the Hangai is a resistive block (1000 Ohm-m) within an otherwise average resistive 50 km thick crust (300 ohm-m). The mantle lithosphere is set to 100 Ohm-m and the top of the asthenosphere is 10 ohm. Lithospheric thicknesses are set to 120 km at the model edges, rising to 70 km depth beneath the Hangai. Crustal and lithospheric thicknesses are

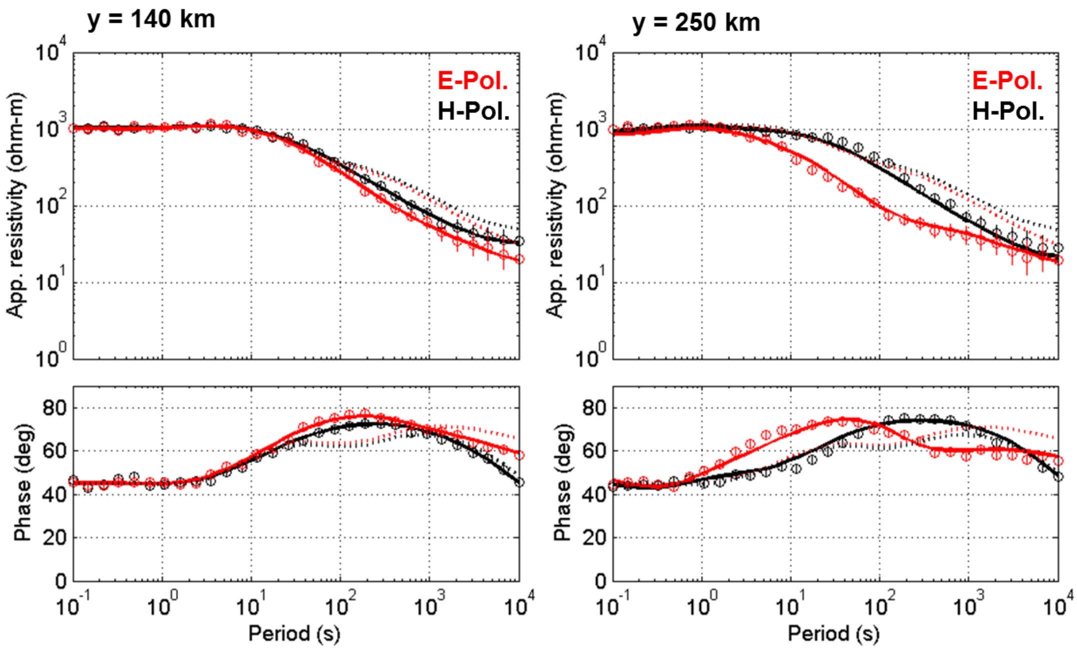


Figure 3. 2D MT responses at 140 and 250 km profile distance. Open symbols are the noise contaminated synthetic data, solid lines are the model responses of the inversion model, and dotted lines are the responses of a reference model with the conductive crustal anomalies and the asthenospheric upwelling removed.

based on seismological data (Priestley et al., 2006). Decompression melting is mimicked as a thin 3 Ohm-m layer on top of the upwelling lithosphere. We also added a conductive zone on the lower crust, corresponding to weak rheology supporting lower crustal flow as inferred from MT data in e.g. the northern Tibetan Plateau (Bai et al., 2010) as well as uprising magma that is stalled at mid-crustal levels (e.g. Hunt et al., 2012). In addition, we extracted gtopo30 topography data along a profile traversing the Hangai dome from south to north. The synthetic model is depicted in Fig. 2b. Note that no *a priori* information was available about lithospheric conductivities in this region. The objective here was to test, if the main features of the synthetic model can be recovered. The synthetic data are E- and H-polarization apparent resistivites and phases in the period range from 0.1-10000 s and recorded with a site spacing of 10 km. This setup corresponds to profile 2 of our proposed survey (see section 2.2).

Fig. 2c depicts the smoothing regularized inversion result that fits the data to within their synthetically generated random errors. Despite some artefact at the southern edge, the main features of the model are well recovered. This test shows that both crustal structures as well as shallow asthenosphere can be expected to be resolved.

The proposed MT survey is similar in extent and depth penetration to the ongoing seismological study by Lehigh University. Recognizing that MT and seismological observations complement each other, we envisage to combine our MT results with the seismological models from Lehigh (see section 2.1.3). We will use the MT results – and as far as available – seismological models to constrain thermo-mechanical modelling (see section X.x.x).

2.1.5 Geodynamic significance of previous MT studies

MT studies of continental high-plateaus such as Tibet (Unsworth et al., 2005; Bai et al., 2010), the Altiplano (Brasse et al., 2002) or Anatolia (Turkoglu et al., 2008) inferred low viscosity in the lower crust from broad high-conductivity zones reflecting the presence of rock-weakening partial melts and/or aqueous fluids. It was shown for northern Tibet that pronounced lower crustal high-conductivity channels extend laterally over more than 800 km, lending support to the hypothesis of large-scale crustal flow and/or relative lateral motion (shearing) of the lithospheric blocks in these regions (Bai et al., 2010). MT studies were also used to support "jelly-sandwich" type rheological models in extensional regimes such as the Basin and Range province, where observations of a weakened, electrically conductive lower crust argue for i) mechanical decoupling of upper crust and mantle, ii) a vertically heterogeneous deformation profile and, as a consequence thereof, iii) strain concentration in the lower crust (Wannamaker et al., 2007). These profiles could also image crustal fault-bounded connections between magma-sourced fluids and the upper crustal meteoric regime, some of them being related to modern geothermal systems.

The Anatolian and the Hangai blocks exhibit amazing similarity in their geometry and dimension as well as in the tectonic style of extrusion associated with block uplift: both plateaus are examples of block extrusion along strike slip faults in a V-shaped arrangement, which have the potential to generate major earthquakes. MT surveys in Anatolia found an anomalously conductive, partially molten upper mantle, and localized pockets of high-conductivity within the lower crust that are indicative of local melt accumulations (Turkoglu et al., 2008). These results would be conceptually in agreement with available non-MT observations of the Hangai, which suggest the existence of diversified, localized melt sources and distributed volcanism (Hunt et al., 2012, Tiberi et al., 2008).

2.2 Current state of PI and Co-PIs research

2.2.1 Current state of PI research (A. Kuvshinov, ETHZ)

PD Dr. Alexey Kuvshinov has a permanent position in ETH Zurich and leads EM induction sub-group which presently consists of two master students, one PhD student, two postdocs and a visiting scientist. Since 2010 he is the team leader from ETH in a large inter-institutional project aimed at developing and implementing scientific tools for processing and analysis of the data from the geomagnetic multi-satellite mission *Swarm*. Dr. Alexey Kuvshinov has worked extensively in the area of EM induction for more than 30 years. He has been developing mathematical approaches, algorithms and software to simulate EM fields in spherical and Cartesian Earth models with a 3-D conductivity distribution for a wide range of applications, including MT, induction logging, controlled-source electromagnetics and global induction (K13-K15, K17, K24, K61); references in this and next subsection are given in the form [Knn], [Bnn], [Gnn] and [Hnn], and refer to the attached lists of Kuvshinov's, Becken's, Gerya's and Khan's publications. He is perhaps best known for his work describing 3-D induction effects in the magnetic signals/responses from time varying sources of magnetospheric and ionospheric origin both in frequency and time domains (K27, K20, K23, K29, K41, K42, K44). Alexey Kuvshinov has also developed a 3-D EM integral equation frequency-domain numerical solver, which is used worldwide for various applications on global and regional scales. In recent years his research interests have diversified and now include the study of magnetic and electric signals from ocean tides, ocean circulation and tsunamis (K28, K31, K34, K37, K36, K45), space weather studies (K56), Schumann resonances studies (K32), as well as analysis and interpretation of satellite induction data (K33, K48, K58), and developing 3-D EM inversion schemes to interpret global satellite/ground-based induction data (K35, K48, K46, K49, K51, K52, K57, K59, K60, K63, K66). His most recent researches include MT field studies in geothermal zone of Ethiopian rift (K67), development of a new MT inverse code (K68), and elaboration of new non-conventional schemes in MT (K54, K65, K69).

2.2.2 Current state of Co-PI (M. Becken, UoM)

Prof. Michael Becken received a junior Professorship at the Institute of Geophysics at Münster University in 2010. He has been positively evaluated in 2013. He leads the applied Geophysics working group which currently consists of one permanent scientist, two postdoc and four doctoral students. The electronic and mechanic workshop of the institute has three staff. Becken's focus is on electromagnetic geophysics. He performed MT studies in various countries and in an interdisciplinary environment, ranging from small-scale investigations of a basin structure in Inner Mongolia, China, (B14, B15) to lithospheric-scale studies of the San Andreas fault in California (B13, B4, B3). Becken developed MT data analysis tools (B17), which are now used by many researchers, and he was concerned with fundamental properties of MT array responses (B12). He has an ongoing interest in MT but also broadened his perspective to airborne induction studies (B18), controlled source electromagnetics (B9) and to near-surface applications of EM induction systems (B1).

2.2.3 Current state of Co-PI (T. Gerya, ETHZ)

Prof. Dr. Taras Gerya is a titular professor at the Geophysical Fluid Dynamics group at the Institute of Geophysics, ETH Zurich. He has a profound expertise and long-term experience in geodynamics and numerical modeling of various geodynamic and planetary processes. He has developed the 2D and 3D visco-elasto-plastic finite-difference codes (I2ELVIS and I3ELVIS, G1, G44, G68) which appear to be extremely multidisciplinary tools and allow for studying various geodynamic and planetary problems and phenomena, such as, for example, dynamics of subduction and continental collision processes (e.g., G38, G43, G45, G59, G63, G65, G84, G87, G94, G97, G99, G107, G135, G153, B157, G159, G163, G172) slab detachment (G54, G111, G146, G149, G160), continental breakup (G158, G168, G170), oceanic spreading (G105, G133, G142, G152), crustal growth at active margins (G81, G122, G151), large-scale surface dynamics and feedback with deep lithosphere tectonics (G167, G173), plume-lithosphere interactions (G80, G161, G167) effects of fluids and melts on the lithosphere (G67, G77, G89, G97, G107, G117, G148, G155) etc. These efficient numerical codes will be used in the present project for testing of various geodynamic hypotheses proposed for the Hangai region evolution.

2.2.4 Current state of Co-I (A. Khan, ETHZ)

PD Dr. Amir Khan's past, in part, and particularly current research is centered on the study of inverse problems and their application using a broad range of geophysical data, including seismic, gravity and electromagnetic sounding data. However, rather than invert for the physical property to which a specific geophysical field gives rise to (e.g., inversion of seismic data for seismic wave speeds), Amir Khan jointly inverts different geophysical fields (seismic, gravity, electromagnetic) for composition and thermal state (e.g., H1-7). This is accomplished by combining thermodynamic modelling of mantle mineral phase equilibria with stochastic inversion of geophysical data. The methodology has been successfully applied to the Earth, the Moon, and Mars and is currently being used to explore the interiors of exoplanets (H8). The aim of his current research is to extend the joint inversion of geophysical data using thermodynamic methods to a more complex description of the Earth, including waveform tomography (H9).

2.3 Project objectives and detailed research plan

The aim of this proposal is to contribute to a better understanding of the mechanisms responsible for intra-plate deformation in space and time and ongoing uplift in the Hangai Mountains far away from active plate boundaries.

The key goals of the project are 1) to decipher the electrical conductivity structure of the crust and uppermost mantle beneath Hangai Dome and its adjacent areas from MT data; 2) to determine temperature, composition (including fluids and melts), and other physical properties that are consistent with the electrical conductivity and other available geophysical data; 3) to develop self-consistent high-resolution 4D numerical thermo-mechanical geodynamical models of the region capturing first-order complexities in its geological and geophysical structure.

The proposed project is a joint enterprise between ETH Zürich (ETHZ, Switzerland) and University of Münster (UoM; Germany) and will be carried out in cooperation with partners from RCAG in Mongolia). The funding is sought in the framework of the German-Austrian-Swiss (DACH) program where the Swiss NSF serves as lead agency.

Our efforts will be integrated with independent geophysical and geological studies currently being undertaken with US-NSF funding by Lehigh University and RCAG (see their letters of support).

2.3.1 MT Survey design, time schedule, and logistics

2.3.1.1 Overall survey design

Our overall experimental goal is to achieve a well-distributed MT station deployment over the entire Hangai area in order to derive 2-D and 3-D conductivity images of the deep crustal and upper mantle roots of the Hangai dome and adjacent areas. The experiment design (Fig. 2) combines two main profiles P1 (450 km) and P2 (350 km), traversing the Hangai dome in north-south direction, with a sparser but spatially extended array constituting of a number of auxiliary sites. The planned site spacing along the main profiles is 10 km; an average site spacing of 50 km is envisaged for the rest of the array (cf. filled red circles and black dots in Fig. 2).

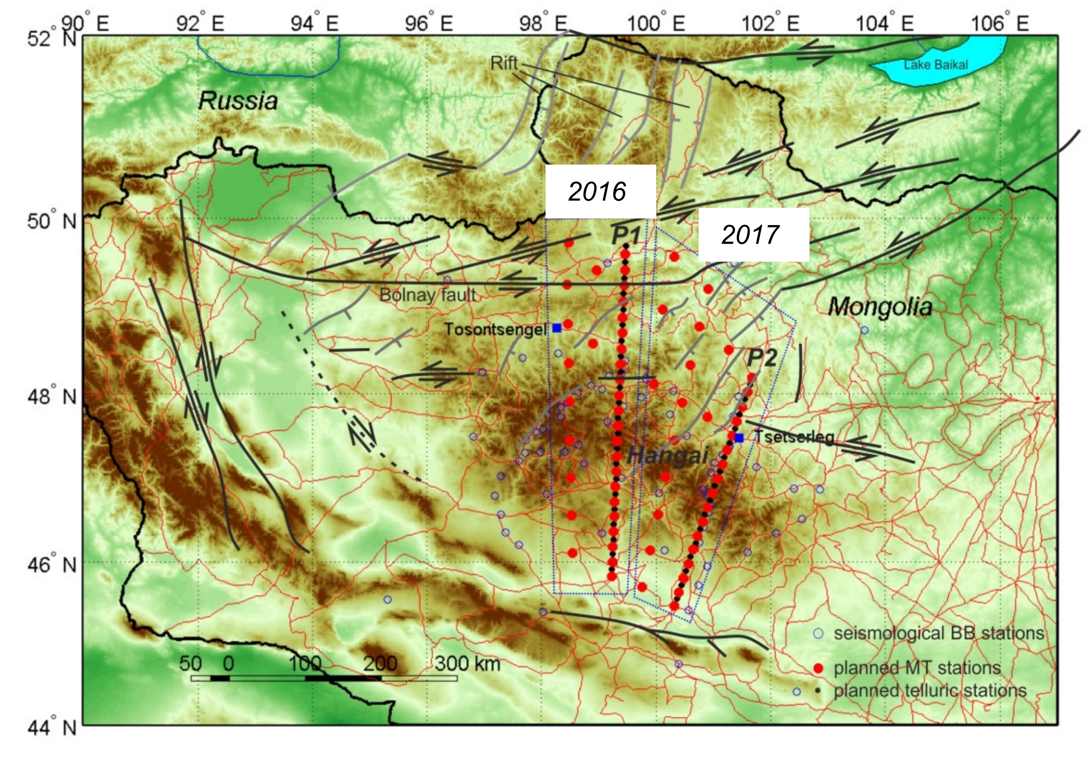


Figure 4. Sitemap: Planned MT (filled red circles) and telluric-only stations (black dots). Along the main profiles P1 and P2, we plan with a site-to-site spacing of 10 km, and alternating MT and telluric recordings. Auxiliary off-profile MT stations will be deployed to achieve a decent areal coverage with average site spacing in the order of 50 km within the array. Two field campaigns (Summers 2016 and 2017) are needed to acquire the data. Open blue circles show locations of seismological stations. Fault and rift zones are indicated and taken from Windley and Allen (1993) and Walker et al. (2008).

The proposed site spacing represents a compromise between site density, areal coverage and spatial extent of the array. A 10 km site spacing has proven useful in numerous regional-scale MT profile surveys (e.g. Brasse et al., 2002; Unsworth et al., 2005; Turkoglu et al., 2008), and modern large-scale MT array measurements utilize an even larger site-to-site distance in comparison to our planned array. The US array (e.g. Schultz et al., 2010), for instance, consists of MT stations placed 70 km apart. 3-D inversion results from the US array demonstrate that unbiased conductivity images may be obtained from arrays with such large site spacing (e.g. Patro and Egbert, 2008). We note here that we will carry out the measurements in remote areas with a very low population density, suggesting that we will experience excellent data quality and little problems with man-made noise sources. In summary, we expect that we will be able to resolve the most important features of the regional-scale conductivity structure beneath Hangai with the proposed survey design.

We also note that our planned regional scale array constitutes a framework for future, higher-resolution MT studies (e.g. across the Bolnay fault), or for studies extending into adjacent regions (e.g. the rifting zones - lake Hovsogol in northern Mongolia), all of which representing possible study areas for MT.

2.3.1.2 Time schedule of the planned survey

Because of the continental climate in Mongolia, measurements must be carried out in summer. We have divided data acquisition into two phases lasting from June to July in 2016 and 2017. In a first phase (Phase I, summer 2016), we will operate from a base camp at Tosontsengel to complete Profile P1 and the western part of the array. The second phase (Phase II, summer 2017) will utilize a base camp at Tsetserleg to complete profile P2 and the eastern array sites. The towns of Tosontsengel and Tsetserleg have been utilized as base camps in previous campaigns from our cooperation partners at RCAG.

2.3.1.3 MT instruments

Overall, we plan to deploy ~ 100 stations. We will combine five-component long-period (L-MT, period range 20 s – 20000 s) with broad-band (B-MT, 0.01 s – 4000 s) MT recordings (red circles in Figure 2) and two-component broad-band telluric-only (B-T) measurements (black dots). UoM owns two B-MT, three L-MT and 20 B-T systems; additional ten B-MT and ten L-MT instruments will be requested from the geophysical instrument pool Potsdam (GIPP, http://www.gfz-potsdam.de/portal/gfz/Struktur/Departments/Department+2/sec22/gipp). For a previous version of this proposal, our request for instruments from the GIPP had already been positively evaluated on scientific grounds. What is important to stress is that this pool is cost-free for German universities, and thus for the partner from UoM**.**

Since more than 20 MT and up to 20 telluric stations will be deployed simultaneously in the field, we will have a multitude of options to local transfer functions as well as inter-station station transfer functions between local telluric and remote magnetic or telluric recordings. With these data, we will have the opportunity to implement the recently introduced interstation phase tensor concept (Bakker et al., 2015); see details in section 2.3.3.2.

2.3.1.4 Details of survey and logistics

MT and telluric stations will be deployed in an alternating arrangement along the two main profiles. All (auxiliary) off-profile stations utilize five-component MT stations. With this setup, 64 MT stations will be combined with 38 telluric stations. At all stations, broad-band recordings with recording times of 5 days on average will be carried out. This will allow us to estimate transfer functions for periods up to 4000 s at all sites. Additional long-period recordings will be carried out at ~36 locations to yield transfer functions for periods up to 20000 s. We will move long-period systems during half-time of the survey, resulting in run-times of ~ 20 days at each of the long-period stations. The broad-band measurements can be completed before moving the long-period systems. Calculating 20 days recording at maximum for each long period station and including 10 days for logistics, packing and shipping of instruments before and after field work, we estimate the total survey time to be 50 days.

Our colleagues from Lehigh University have already demonstrated that the installation of a regional scale geophysical array in these remote and sparsely populated areas is feasible. However, enough man-power is required to handle field logistics, site-access and instrument deployment and re-deployment. For the initial deployment phase, we plan with four teams/cars for instrument installation and two teams/cars to manage field logistics, site access, communicate with local families, hire site guards for the long-period systems, and guard broad-band systems where necessary. After the re-deployment phase of long-period stations, the survey can be completed by two deployment teams. In summary, six teams will complete the initial long-period and the entire broad-band survey, including field logistics, within four weeks, and two teams will complete the long-period measurements after their re-deployment within another two weeks. Shipment of the instruments to Ulan Bator and return must be via air cargo and will take one week in each direction. Heavy loads (batteries, expedition equipment, etc.) will be transported via container cargo to reduce shipping costs.

2.3.1.6 Important remarks

PD Dr. Alexey Kuvshinov (PI, ETHZ,), has collaborated in the past with Prof. Usnikh Sukhbaatar who is now director of Research Center of Astronomy and Geophysics (RCAG) of Mongolian Academy of Sciences. As a result we will have support from the Mongolian side during the field campaigns through the collaboration with Dr. Usnikh Sukhbaatar and his colleagues (see also Letter of Support from RCAG). Dr. Michael Becken (Co-PI, UoM), was formerly a member of the Geo-Electromagnetics working group at the GFZ Potsdam. He is familiar with the MT instruments from the GIPP. During his time at GFZ, he has gained experience in carrying out large-scale MT campaigns (e.g. Becken et al. 2011). We also state that ETHZ, UoM, and RCAG have enough man-power within Master and PhD personnel to be able to successfully perform two field campaigns.

2.3.2 MT time series processing, data analysis, and inversion

2.3.2.1 Time series processing

As already outlined, we expect high-quality data because the measurements will be carried out in remote areas where no noise is expected. For the estimation of MT and magnetic transfer functions, we will make use of MT processing techniques elaborated by Egbert and Booker (1986). Recently, Dr. Michael Becken also implemented time series processing in MATLAB, following the lines of Egbert and Booker (1986). The MATLAB code has implemented robust single-site and remote reference processing; implementation of robust multi-remote reference is on the way. A great advantage of the MATLAB code is that all time series data are incorporated into a common database which facilitates quick access to and graphical display of synchronous time series readings, spectra, and transfer functions between arbitrary channel combinations for in-field data quality control. Different data formats can be read, including the format produced by the instruments from the GIPP. In addition, since a remote reference site will be occupied with magnetic and electric sensors throughout the entire campaigns, we will have a multitude of choices to estimate inter-station transfer functions between simultaneously operating systems, which will be of particularly importance to process data from the telluric-only stations.

2.3.2.2 Dimensionality and directionality analysis

MT data contain inherent measures on dimensionality and directionality of the geoelectrical structure. Regional-scale structural information contained in the impedance estimates can, however, be shadowed by the galvanic distortion effect of charges accumulating at small-scale near-surface heterogeneities (e.g. Groom and Bailey, 1989). It is important to identify distortion and to extract and analyze the regional scale characteristics of the data before subjecting the data to any inverse model calculation. Using tensor decomposition techniques (e.g. Groom and Bailey, 1992; Becken and Burkhardt, 2004), undistorted impedances (except for some scaling factors) can be determined in case of a 2-D regional-scale structure with local 3-D distortion. MT data can also provide undistorted quantities, even in the case of a regional 3-D structure. These include all types of magnetic transfer functions and the MT phase tensor (Caldwell et al., 2004). In addition to the data characteristics to be inferred from individual soundings, a spatially extended array as proposed for this study facilitates testing for spatial consistency of the data and to identify zones of current concentrations or structural heterogeneities from maps of magnetic transfer functions (e.g. Schmucker, 1970) and phase tensors. All of these aspects will be included in the data analysis to obtain a comprehensive understanding of the data.

2.3.2.3 2D inversion

The proposed survey design includes two main profiles in the north-south direction, which permit 2D interpretation provided that the data are not too strongly affected by 3D effects. 2D approaches have the advantage that thorough model validation and resolution analysis can be accomplished within reasonable computational time (Becken et al., 2008), even if a large number of data is combined with a finely discretized model. Some deviation from strict 2D conditions can be accounted for with appropriate downweighting of the 3D data (e.g. Booker et al., 2004, Becken et al., 2008). 2D inversion will be accomplished with widely used non-commercial programs such as Occam (de Groot-Hedlin and Constable, 1990) and Rebocc (Siripunvaraporn and Egbert, 2000). UoM will also make use of their own 2D inversion code, which combines the finite element forward scheme from Lee et al. (2009) with different inversion algorithms. This program can also handle topography (see the modelling stidy in Figure 2, that has been undertaken with this program). UoM has also implemented a sparse inversion concept employing L1-norm regularization of a wavelet parameterized model domain during 2D inversion (Becken, 2013). Ultimately, the recovered 2D cross-sections will be compared with the results of full 3D inversion.

2.3.2.4 3D inversion

In this project, we will make use of publicly available the modular 3D code ModEM3D (Egbert and Kelbert, 2012) to invert our data. ETHZ and UoM have used this code intensively for 3D inversion of data recently acquired in Scandinavia (Nittinger et al., 2013) and in Ethiopia (Samrock et al., 2015). Both UoM and ETHZ have a close relationship to the working group at GFZ Potsdam, which is involved in developing this code further (e.g. Megbel, 2011, Tietze, 2013; Chen, 2013). Furthermore, Dr. Cherevatova, who has implemented a multi-grid approach into ModEM3D, will become member of the working group at UoM and add further expertise in 3D inversion to the team.

2.3.3 Utilizing recent methodological developments for MT inversion

2.3.3.1 Using a new 3-D MT inverse code

It is well-known that the inversion of real data is not straightforward, owing to the non-uniqueness of the inverse problem and the variety of parameter settings that can influence the inversion results. Recently Miensopust et al. (2012) presented results from a benchmarking study in which synthetically generated data were inverted with the use of different 3D inverse codes, and by different users. The authors demonstrated that substantially different 3D models can be obtained from the same data set. Therefore, it is important to use different inversion approaches in order to mutually test for consistency and robustness of the inversion models.

In addition to ModEM3D, ETHZ will use for inversion an alternative 3-D inverse code recently developed by Bakker (2015). As ModEM3D, it is built in a modular way and allows for an easy exchange of 1) inverted responses, 2) implementation of different optimization and 3) regularization schemes. Furthermore – as ModEM3D - it is parallelized with respect to frequencies and polarization, and invokes the adjoint source approach (e.g. Pankratov and Kuvshinov, 2010) to calculate efficiently the gradient of the misfit. This makes both codes suitable to invert large data sets as planned here.

Note that ETHZ code differs from ModEM3D in several aspects: 1) as a forward engine, the code exploits a contracting integral equation (CIE) approach (e.g. Pankratov et al, 1995), in contrast to ModEM3D which uses finite differences (FD). Whereas in FD formulation one solves sparse matrix systems, in CIE one works with dense matrices, but these matrices are much more compact than FD matrices. Also note that the CIE matrices are well-conditioned irrespective of discretization, frequency and contrasts of conductivity. Because of this, the CIE is less computationally demanding than the FD. In addition, in ETHZ inverse code the CIE approach is exploited by isolating the calculation of the Green's tensors and this trick substantially accelerates the inversion; 2) an optimization in ETHZ code is based on a quasi-Newton optimization method, whereas ModEM3D exploits nonlinear conjugate gradients; 3) in contrast to publicly available ModEM3D in which forward and inverse parameterizations coincide (at least in lateral direction), in our code the forward and inverse parameterizations are independent. Moreover ETHZ code admits flexible parameterization of the inverse domain, in a sense that one can merge any subset of cells in order to account for potentially irregular distribution of observation sites.

2.3.3.2 New transfer functions

Bakker et al. (2015) proposed to revive the telluric method, which was widely used in the mid-20th century. The method is based solely on electric field measurements, and operates with the electric tensor (ET) which relates the horizontal electric fields at survey and base sites. At that time the method was favored for its simplicity and low computational cost. However, the ET provides only qualitative information about subsurface structures because of the presence of galvanic effects which locally distort the electric field. These galvanic effects could neither be taken into account in the ET nor corrected for, resulting in less use of the telluric method. Bakker et al. (2015) introduced two new transfer functions which are also based solely on electric field measurements at the survey sites but which are almost and entirely free from distortion effects. The first transfer function is the electric phase tensor which is only distorted by galvanic effects (if they exist) at the base site. The second tensor, the quasi-electric phase tensor is entirely free from galvanic effects. Our model studies demonstrate that the sensitivity of the new phase tensors is comparable with the sensitivity of the standard magnetotelluric (MT) phase tensor. Bearing this in mind, we plan to estimate newly introduced tensors from Hangai MT data and use them during 3-D inversion.

2.3.4 Converting geophysical observables into thermo-mechanical parameters

In a series of studies Dr. Amir Khan (e.g., Khan et al., 2008; Khan and Shankland, 2012, Khan et al., 2013; among others) has been developing a quantitative approach that combines results from mineral physics, petrological analyses of Earth's minerals, and geophysical inverse calculations, in order to map geophysical data directly for Earth's composition (major element chemistry and water content) and thermal state. In particular, this approach provides a natural way of integrating widely different data sets, e.g. density, seismic velocities and electrical conductivity (see Table 1). The recovered thermo-chemical parameters are envisaged to be used for guiding 4D thermo-mechanical modelling, discussed in section 2.3.5.

data		parameters		parameters		parameters		data
		$\boxed{\text{c}}$				ρ	$\longrightarrow$	$\mathbf{d}_{\text{gravity}}$
$\mathbf{d}_{\text{chemistry}}$	$\swarrow$ $\nwarrow$		$\searrow$ $\nearrow$	M	$\searrow$ $\longrightarrow$ $\nearrow$	V_p, V_s	$\searrow$ $\longrightarrow$	$\mathbf{d}_{\text{seismic}}$
$\mathbf{d}_{\text{heat flow}}$	$\longleftarrow$	$\boxed{\text{T}}$				σ	$\longrightarrow$	$\mathbf{d}_{\text{electromagnetic}}$
geochemical, geothermal		composition, temperature		mineralogy		physical properties		geophysical, geodynamical

Table 1. Boldface letters designate data, framed letters the fundamental parameters of interest, physical properties are density (ρ), isotropic P and S wave speed (Vp, Vs), and electrical conductivity (σ). Arrows signify theoretical relationships. The scheme shown is exemplary and by no means exhaustive. The generality of the formulation allows us to augment the scheme by including additional data, prior information, parameters, physical theories, and chemical components.

2.3.5 4D Thermo-mechanical modelling

The availability of Hangai geophysical, geological, and geomorphological database, combined with newly obtained MT data and an approach for converting geophysical observables into thermo-mechanical parameters provides a unique opportunity to develop self-consistent high-resolution 4D numerical thermo-mechanical geodynamical models of the region capturing first order complexities in its geological and geophysical structure and the processes that produced that structure. Various feedbacks between crustal and mantle deformation and geomorphic processes will be addressed by performing realistic high-resolution 4D geomorphological-thermo-mechanical modelings (Fig. 5 illustrates the functionality of the code), which will be used for testing three geodynamic hypotheses proposed for the Hangai dome origin (e.g., Hunt et al., 2012; Petit et al., 2002). In particular, the thermo-mechanical modelling algorithm allows for simulation of crustal and mantle partial melting processes as well as of volcanic and plutonic crustal growth (Zhu et al., 2013; Vogt et al., 2012), which can be compared with generated MT models (this project) and documented magmatic rock record (e.g., Hunt et al., 2012). We aim to concentrate at the two inter-linked key questions:

(A) Can lithospheric delamination, mantle plume, lithospheric erosion and magmatic underplating scenarios be discriminated by combining numerical modelling predictions with natural data?
(B) How did an ongoing lithospheric deformation modify lithospheric-asthenospheric interactions, magmatism and topography of the Hangai dome region?

Numerical modelling will be performed with the original geomorphological-thermo-mechanical code I3ELVIS-DAC (Ueda et al., in preparation) available at ETH-Zurich. This numerical modelings activity requires funding of one PhD student for 3 years.

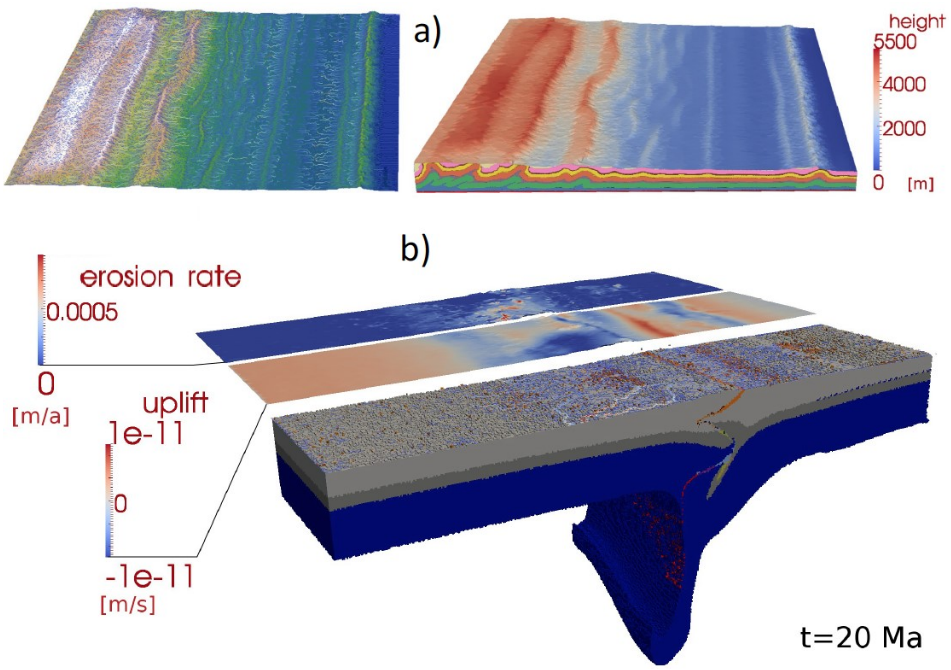


Figure 5. Preliminary results from geomorphological-thermo-mechanical code I3ELVIS-DAC (Ueda et al., in preparation), which will be used in this project. a) River pattern (left panel) and topography (right panel) above a fold-and-thrust belt. B) Model of slow

convergence and slab drip-off showing erosion rate (top panel), uplift (middle panel, blue colors) and preferential river network development (bottom panel, surface lines).

2.3.6 Synergy of ETHZ and UoM expertise

On a practical level, there is much to be gained by combining the efforts of ETHZ and UoM in this proposal: UoM is supplying instruments, while scientific contacts in Mongolia and knowledge of local logistics are supplied by ETHZ. On a more profound level, we expect a lot of synergy through the mutual and complementing competences of ETHZ and UoM. For example, ETHZ will benefit from the competence of UoM in: 1) MT data acquisition; 2) data processing and dimensionality analysis; 3) 2D data inversion. Likewise, UoM will benefit from ETHZ proficiency in: 1) 3D forward modelling and inversion of EM data; 2) application of adjoint source approach to calculate gradients for any type of MT response, and for arbitrary parameterization of the model space; 3) converting electrical conductivity into thermos-chemical parameters; and 4) 4D thermo-mechanical modelling.

2.7 Schedule and milestones

The project is self-contained and it is designed to be suitable for a 3-year study. A timeline and a list of milestones of the project are given in Table 1 and explained below. However, the planning will be adjusted from time to time, following the progress of tasks and research outcomes. The planned starting date of the project is April 1, 2016. This date is closely correlated with the summer field campaign of 2016.

2.7.1 Field work:

F1: Instruments' preparation (ETHZ and UoM) and cargo;

F2: Reconnaissance trip (ETHZ and UoM);

F3: Field campaign (ETHZ, UoM and RCAG) in 2016 (50 days);

F4: Field campaign (ETHZ, UoM and RCAG) in 2017 (50 days);

2.7.2 Tasks of PhD student in MT (UoM):

M1: Participation in field work, data quality control, in-field processing, post-processing of time series data (data cleaning, single-site, remote reference and multi-remote reference magnetotelluric transfer functions); data processing codes and results will be shared with and mirrored at ETHZ;

M2: Data analysis: tensor decomposition, strike and dimensionality of the data;

M3: 2D inversion along profiles with existing software, but with appropriate modifications to account for interstation magnetotelluric and telluric transfer functions. The 2-D inversion models will be used as input for first interpretations and for subsequent 3D modeling;

M4: 3D inversion of the data using ModEM3D. Comparison with the results obtained with the ETHZ 3D inverse code (cf. Task Y4, ETHZ);

2.7.3 Tasks of PhD student in MT (ETHZ):

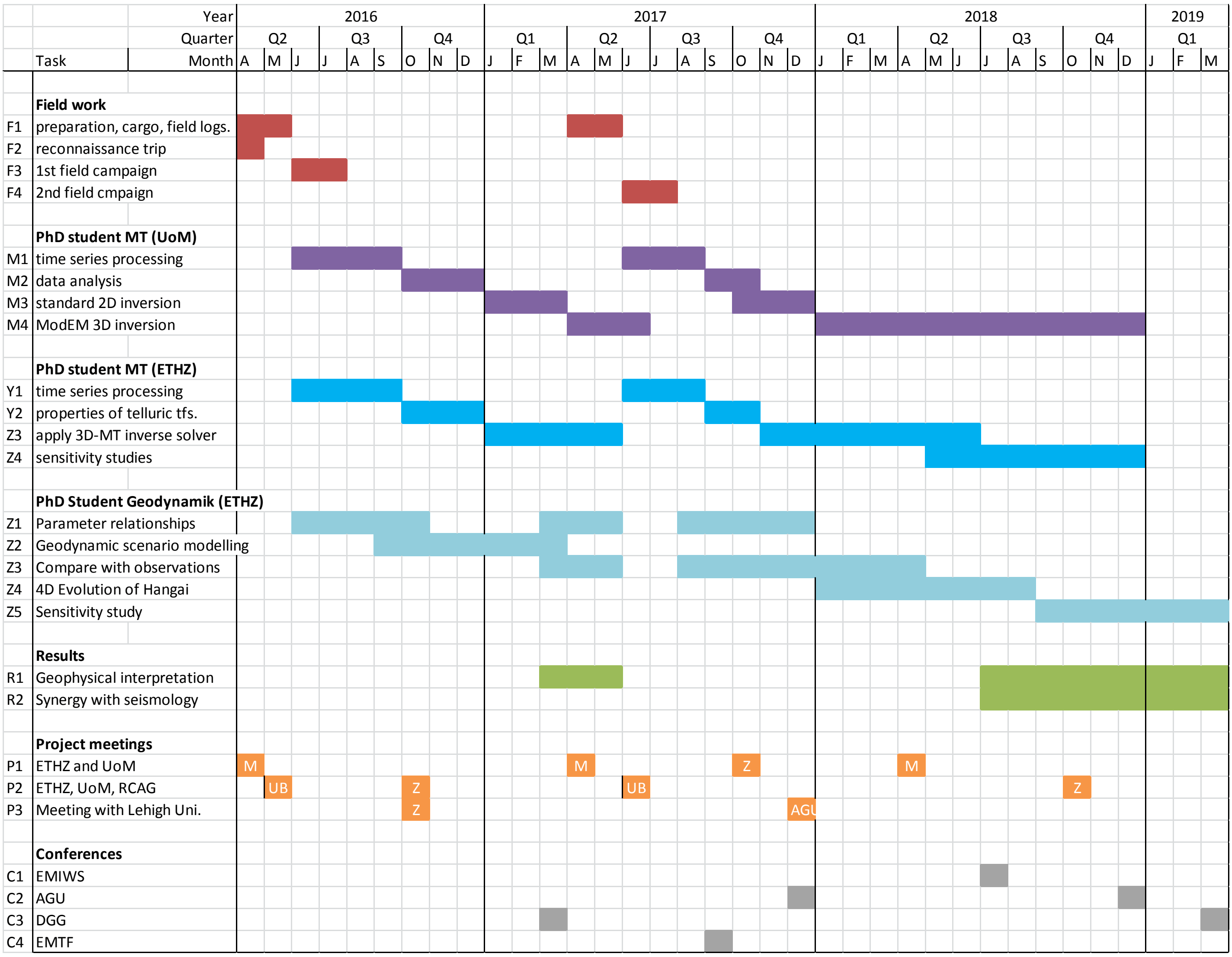
Y1: Participation in field work, data quality control, in-field processing, post-processing of the time series data with a focus on interstation magnetic and telluric transfer functions

Y2: Investigating properties of telluric transfer functions, and of electric and quasi-electric phase tensors

Y3: 3D inversion of the data using ETHZ 3D inverse code. Comparison with the results obtained with the ModEM3D code (cf. Task M4, UoM);

Y4: Sensitivity studies using various combinations of transfer functions, and model resolution studies. Estimation of fluid/melt distributions, comparison with other geophysical data, and qualitative integration.

Table 2. Time schedule. Individual entries are briefly detailed in the text.



2.7.4 Tasks of PhD student in geodynamics (ETHZ):

Z1: Converting geophysical observables into thermo-mechanical parameters;

Z2: Developing preliminary geomorphological-thermo-mechanical numerical models for lithospheric delamination, mantle plume, lithospheric erosion and magmatic underplating scenarios for the Hangai region.

Z3: Investigating topographic, crustal and mantle evolution for these scenarios and comparing them to geophysical-geological-geomorphological observables for the Hangai region.

Z4: Developing detailed geomorphological-thermo-mechanical 4D model for the evolution of the Hangai region based on preliminary numerical models and geophysical-geological-geomorphological observables.

Z5: Investigating sensitivity of the detailed 4D model to various rheological, geomorphological and geophysical parameters.

Note that various work packages are linked to each other. However, we make sure that each of the PhD projects are self-contained.

2.7.5 Results

R1-2: Geophysical interpretation of the results. Final interpretation will rely on full 3D inversion models, results from 4D geomorphological-thermo-mechanical modelling, and will include results from other geophysical disciplines and from geological observations. Quantitative combination (i.e. joint inversion of MT and seismic data) is not planned within this project given the stringent timeline.

2.7.6 Project meetings

Project meetings between PIs, Co-I, and PhD students are planned at all stages of the project. This includes organizing field work, data handling, discussion of modelling results, and general project review. Meetings are expected to be held bi-annually in Zurich and in Münster. Our partners from RCAG will also be involved at all project stages. We plan to invite them for project meetings to Zurich. Additional project meetings will be held in Ulan Bator during a reconnaissance trip. If this project is funded, we will request funding for a Mongolian PhD student from the German academic exchange program (DAAD sandwich program).

2.7.7 Conferences

We plan to present the results of our studies at AGU, EGU, EM induction workshop, and Schmucker-Weidelt colloquium.

2.8 Importance and impact

The project described is in the area of “blue skies” curiosity-driven science. As such it is difficult to envisage potential “end-users” of the results, other than the scientific community. During field campaigns and exchange visits we will train Mongolian students and personnel from RCAG to work with modern MT instruments and introduce them to advanced approaches to processing, analyzing, modelling and inverting MT data. This allows for promoting EM studies in Mongolia. As part of this project we plan to make 3D MT inverse code at ETHZ publicly available for academia.

2.9 Justification of resources

The largest budget item is salary for three PhD students. The second major budget item is organizing and performing two field campaigns. The expenses will be shared with the Co-PI from University of Münster who requests a budget equivalent to support one PhD student from DFG, and for half of the expenses for the two field campaigns. Justification of the budget for two field campaigns, along with other minor expenses (publication fee, conference attendance etc.) is attached.

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