Towards integrating results from electrical resistivity models into geodynamic modeling to better understand the evolution of the lithosphere

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1 Introduction

Thermo-mechanical numerical modeling can provide valuable insights by simulating the temporal evolution of dynamic processes. The simulation model can be evaluated against the available observational evidence and physically plausible mechanisms can be further explored. To better understand the evolution of the lithosphere, multi-disciplinary results can be integrated into the geodynamic modeling, creating more realistic and reliable models. What's more, such modeling offers an excellent opportunity to test various hypotheses and to constrain the possible ranges of parameters. By systematically varying physical parameters, their influence and control on dynamic tectonic processes can be tested.

Here we present work that uses Central Mongolia as a case study (Comeau et al., 2021a). This location is an ideal natural laboratory for studying surface deformation and intraplate uplift because of its high-elevation plateau in a location in the continental interior — far from tectonic plate boundaries. Intracontinental surface deformation is enigmatic, and the underlying mechanisms responsible are not fully understood. However, because deformation solely by means of tectonic plate motion is not possible in an intraplate setting, crust-mantle interactions (e.g., driven by mantle convection) are likely required to explain the origin and evolution of intracontinental deformation.

Explanations for surface uplift in the continental interior include: 1. hot, buoyant, deep-rooted mantle plumes; 2. crustal thickening from mafic magmatic underplating; 3. broad-scale mantle-flow and thermal convection processes that produce dynamic topography; and 4. small-scale asthenospheric upwelling prompted by isolated lithospheric removal. We use self-consistent thermo-mechanical numerical modeling to investigate a subset of the latter explanation: lithospheric removal by delamination or a Rayleigh-Taylor instability (e.g., Bird, 1979; Kay & Kay, 1993). We explore the conditions under which delamination can occur and investigate the timing and amplitude of the consequent surface deformation.

2 Geophysical, geochemical, and geological data

A recent project collected a large magnetotelluric array (~700 × ~450 km) across central Mongolia (data described in Becken et al., 2021a, and Becken et al., 2021b) and produced models of the crust and upper mantle electrical resistivity structure (Käufl et al., 2020; Comeau et al., 2018a). Meltzer et al. (2019) deployed networks of modern seismic recorders across the exact same region, improving on older data (e.g., Mordvinova et al., 2007) and regional datasets (e.g., Priestley et al., 2006) — and creating a valuable opportunity for joint interpretation and analysis. Additional gravity data and models cover the region (see Tiberi et al., 2008, and references therein). These geophysical datasets add to a rich collection of geological (e.g., Cunningham, 2001, and references therein; Badarch et al., 2002) and geochemical information across Mongolia (e.g., Barry et al., 2003, and references therein), including recent thermobarometry, geochronology, and petrological analysis of (Mesozoic and Cenozoic) lavas and xenoliths (e.g., Ancuta et al., 2018; Sheldrick et al., 2020a, 2020b).

3 Electrical resistivity models

The electrical resistivity models show features of interest at all scales, including: 1. signatures of intraplate volcanism throughout the lithospheric column (Comeau et al., 2018b; Comeau et al., 2022); 2. fluid localization and stagnation in the lower crust (Comeau et al., 2020a); 3. deep controls on mineral emplacement (Comeau et al., 2021b, 2021c); 4. faults and sutures related to the tectonic history and evolution by terrane accretion (Comeau et al., 2020b); and 5. evidence for a mantle upwelling (Comeau et al., 2018). Of particular interest here is the latter result that shows a large low-resistivity feature in the upper mantle directly below the region of high elevation. Furthermore, this feature is congruent with a low Bouger anomaly determined from gravity data (Tiberi et al., 2008). This feature is interpreted to be an asthenospheric upwelling. What's more, it is inferred to be a location of melt generation and the source region for intraplate volcanism (Comeau et al., 2022), with the depths consistent with constraints from petrological data. This feature is consistent with a locally thinned lithosphere and a doming lithosphere-asthenosphere boundary. A thin lithosphere and thick crust, implying a very thin mantle lithosphere, has been detected with seismic studies (e.g., Mordvinova et al., 2007).

The electrical resistivity models reveal widespread, heterogeneous, low-resistivity features in the lower crust. These have been explained as fluid-rich domains trapped below the brittle-ductile transition zone in a thermally perturbed lower crust (Comeau et al., 2020a), which was found to be consistent with a conceptual hydrodynamic model from Connolly and Podladchikov (2004). The presence of fluid-rich domains in the lower crust is important because they can significantly reduce the viscosity. This is consistent with post-seismic slip analysis along major faults in central Mongolia that found a very low viscosity was necessary in the lower crust (Vergnolle et al., 2003), possibly several orders of magnitude lower than the surroundings.

3 Geodynamic modeling

A geodynamic investigation using self-consistent thermo-mechanical numerical modeling was carried out to better understand the evolution of the lithosphere. The aim was to explore whether potential explanations for the mechanisms causing intraplate surface uplift are physically plausible and if the required parameter ranges are consistent with what is inferred in central Mongolia (Comeau et al., 2021a; see also Stein et al., 2022). To keep the modeling as realistic as possible, the input parameters were based on geophysical, geochemical, and geological data — a step towards integrating multi-disciplinary studies.

Computations were done using ASPECT version 2.1.0 (Kronbichler et al., 2012; Bangerth et al., 2019). For simplicity, two-dimensional models were generated; future work is required to investigate the complexities of three-dimensional models. Rather than imposing an initial dense block in the simulations (to initiate instability), we allow lithospheric removal to develop dynamically and self-consistently by applying a phase transition to simulate metamorphic eclogitization. The lower part of a thick continental crust can undergo prograde metamorphism and form eclogite, which is denser than the original material — i.e., a density jump. Eclogitization is promoted by the presence of fluid, even in small amounts, and thus the hydration state of the lower crust may control eclogitization (see Krystopowicz & Currie, 2013). By systematically varying physical parameters — including: density contrast, lower crustal viscosity, temperature profile, convergence rate — we explore controls on the style of lithospheric removal and asthenospheric upwelling, the timing of the processes, and the type and amplitude of surface deformation and uplift (Comeau et al., 2021a; see also Stein et al., 2022).

4 Results

By testing various parameters, it is determined that the critical requirements for generating delamination-style lithospheric removal and dome-shaped uplift are: 1. a low-viscosity and dense lower crust; 2. a warm crust-mantle boundary; 3. and a moderate convergent rate. These critical conditions are determined to be satisfied in central Mongolia. Critically, this includes a low-viscosity lower crust.

The temporal evolution of the simulations is evaluated and shows that removal of the lithosphere due to small-scale convective instabilities (e.g., delamination) leads to an asthenospheric upwelling consistent with the structure inferred and observed beneath central Mongolia, and can generate an elevated surface and dome-shaped topography similar to the present-day pattern. Additionally, it causes elevated temperatures at the crust-mantle boundary, compatible with the available petrological evidence.

The numerical models show that lithospheric removal and surface uplift can occur within a short period of time (~5 Myr). This is consistent with both geochemical evidence that points to a sudden lithospheric removal event (e.g., Sheldrick et al., 2020) and thermochronology data that indicates uplift and exhumation that created topography (McDannell et al., 2018) over timescales of less than 20 Myr. These events occurred in the Cretaceous; thus, the lithospheric removal may have pre-conditioned the region for later events, including other mantle upwellings that may have influenced Cenozoic intraplate volcanism in Mongolia (see Papadopoulou et al., 2020).

In summary, the results suggest that lithospheric removal by delamination, and the consequent asthenospheric upwelling, is a potential explanation — and a physically plausible mechanism — for the observed enigmatic intracontinental surface uplift in the case study region of central Mongolia.

5 Conclusions

Employing thermo-mechanical numerical modeling can provide valuable insights and help to better understand the evolution of the lithosphere. Multi-disciplinary information can be integrated into the geodynamic modeling to ensure realistic and reliable models. In this work we 1. simulated the temporal evolution of dynamic processes, 2. evaluated the simulation models against the available observational evidence, and 3. systematically varied the physical parameters to test their influence and to constrain their possible ranges.

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