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An Asthenospheric Upwelling Beneath Central Mongolia — Implications for Intraplate Surface Uplift and Volcanism

Matthew J. COMEAU[1, *], Michael BECKEN[1], Alexey V. KUVSHINOV[2], Alexander GRAYVER[2], Johannes KÄUFL[2], Erdenechimeg BATMAGNAI[2, 3], Shoovdor TSERENDUG[3] and Sodnomsambuu DEMBEREL[3]

[1] *Institut für Geophysik, Universität Münster, Germany*
[2] *Institute of Geophysics, ETH, Zürich, Switzerland*
[3] *Institute of Astronomy and Geophysics, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia*

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Intraplate processes, such as continental surface uplift and intraplate volcanism, are enigmatic and the underlying mechanisms responsible are not fully understood. Central Mongolia is an ideal natural laboratory for studying such processes because of its location in the continental interior far from tectonic plate boundaries, its high-elevation plateau, and its widespread, low-volume, basaltic volcanism. The processes responsible for developing this region remain largely unexplained — due in part to a lack of high-resolution geophysical studies — and thus are open questions.

A recent project undertaken to map the crust and upper mantle structure of central Mongolia has collected a large magnetotelluric array (~700 km × ~450 km) (Käufl et al., 2020; see also Comeau et al., 2018a) (data described in Becken et al., 2021a, b). In addition, other groups have deployed networks of seismic recorders across the region (e.g., Zhang et al., 2017; Meltzer et al., 2019), creating a valuable opportunity for joint interpretation and analysis. These new datasets add to a rich collection of geological and geochemical information across Mongolia (e.g., Barry et al., 2003, and references therein), including recent thermobarometry, geochronology, and petrological analysis of surface lavas and xenoliths (e.g., Ancuta et al., 2018; Sheldrick et al., 2020).

For its part, modern thermo-mechanical numerical modeling can provide insights by simulating the temporal evolution of dynamic tectonic processes, offering an opportunity to test various explanations. To better understand the evolution of the lithosphere, multi-disciplinary results can be integrated into the geodynamic modeling. The simulation model can be evaluated against the available observational evidence and physically plausible mechanisms can be explored as potential explanations for intraplate surface uplift.

Results: Multi-scale magnetotelluric modeling

The magnetotelluric method is a geophysical exploration technique that uses natural electromagnetic signals (generated in the atmosphere and ionosphere) to image the subsurface electrical resistivity structure. Electromagnetic fields measured at the Earth's surface over a broad range of frequencies allows the exploration of multiple spatial scales: short-period data are sensitive to shallow structures and long-period data are sensitive to deep structures (e.g., Unsworth and Rondenay, 2012).

Multi-scale magnetotelluric modeling generated electrical resistivity models that show features of interest at all scales (Käufl et al., 2020), and provides insights on continental uplift and intraplate volcanism (Comeau et al., 2018a, b), as well as the deep controls on mineral emplacement (Comeau et al., 2021a), and the tectonic history and lithospheric evolution of Mongolia (Comeau et al., 2020a).

The results show that a large low-resistivity feature is located in the upper mantle directly below the high plateau and congruent with a low Bouger anomaly determined from gravity data (Tiberi et al., 2008). This feature is interpreted to be an asthenospheric upwelling and a location of melt generation, likely from decompression melting. The depths of the inferred melting are consistent with constraints derived from petrological data. This feature is consistent with a locally thinned lithosphere and a doming lithosphere-asthenosphere boundary, as determined by seismic data.

Furthermore, the models reveal pervasive lower-crustal low-resistivity features. These can be explained by fluid localization and stagnation (i.e., fluid-rich domains trapped below the brittle-ductile transition zone) in a thermally perturbed lower crust that underwent metamorphic dehydration and devolatilization reactions. Comeau et al. (2020b) determined that this is consistent with a conceptual hydrodynamic model from Connolly and Podladchikov (2004), as well as numerical models that show compaction - induced fluid localization operates on local length scales. Moreover, from the governing equations the depth, vertical extent, and horizontal extent of the oblate fluid domains were predicted, based on estimated crustal properties, and were entirely consistent

* Corresponding author. E-mail: matthew.comeau@uni-muenster.de

with the geophysical images.

Localized, fluid-rich domains in the lower crust are significant because the presence of fluids — even in small amounts — is known to affect the crustal rheology and to significantly reduce the viscosity, and thus reduce the mechanical strength (e.g., Rosenberg and Handy, 2005). This is consistent with post-seismic slip analysis along major faults in central Mongolia that determined that a low viscosity was necessary in the lower crust (several orders of magnitude lower than the surroundings) (Vergnolle et al., 2003). Furthermore, it is compatible with the elevated temperatures inferred from petrology.

Results: Geodynamic investigations

In light of these results, a geodynamic investigation using self-consistent thermo-mechanical numerical modeling is used to explore whether potential explanations for the underlying mechanisms causing intraplate surface uplift are physically plausible (Comeau et al., 2021b; see also Stein et al., 2021). To keep the modeling realistic, constraints on input parameters are based on the geophysical results (magnetotellurics and seismics) as well as on the geological and geochemical data — a step towards integrating multi-disciplinary studies.

By systematically varying physical parameters, their influence and control on the style and timing of lithospheric removal and asthenospheric upwelling, as well as surface deformation, is tested (Comeau et al., 2021b; Stein et al., 2021). Lithospheric removal is allowed to develop dynamically by applying a phase transition and density jump — hypothesized to be a consequence of metamorphic eclogitization in a thickened crust — rather than simply imposing an initial dense block to initiate instability. The critical conditions for lithospheric thinning and mantle upwelling are determined to be satisfied beneath central Mongolia. Critically, this includes a weak and high-temperature lower crust, in a convergent regime.

The output and temporal evolution of the simulations are evaluated against the observational evidence and show that removal of the lithosphere due to small-scale convective instabilities leads to an asthenospheric upwelling similar to the structure observed beneath central Mongolia and generates the dome-shaped topographic pattern and elevated surface observed. Additionally, it causes elevated temperature at the crust-mantle boundary, compatible with the available petrological evidence, and likely mantle decompression melting. A sudden lithospheric removal event is supported by geochemical evidence in Mongolia (e.g., Sheldrick et al., 2020). In fact, lithospheric removal has been used to explain Mesozoic magmatism across central and eastern Asia (e.g., Sheldrick et al., 2020). Additionally, mantle upwellings may have influenced later Cenozoic intraplate volcanism in Mongolia (Papadopoulou et al., 2020; see Comeau et al., 2021). Therefore lithospheric removal and asthenospheric upwelling is determined to be a physically plausible mechanism, consistent with the available evidence, and a potential explanation for the intraplate surface uplift, and the intraplate volcanism.

Key words: magnetotellurics, electrical resistivity, lithosphere structure, intraplate volcanism, surface uplift, mantle upwelling, lithosphere removal, thermo-mechanical modeling

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About the first and corresponding author

Matthew J. COMEAU, Ph.D., currently Research Associate at the Institut für Geophysik, Universität Münster, Germany. Primarily engaged in applying (electromagnetic) geophysics to answer scientific questions related to broad-scale tectonics, mineral exploration, and volcanic and hydrothermal regions; recent interests include thermo-mechanical modeling to investigate lithospheric dynamics. E-mail: matthew.comeau@uni-muenster.de.