Lower crustal low-resistivity zones caused by compaction-induced fluid localization and stagnation – recent results from electromagnetic data in an intracontinental setting

Matthew Joseph Comeau (1), Michael Becken (1), James A. D. Connolly (2), Alexander Grayver (3), Alexey V. Kuvshinov (3), Johannes Käufl (3), Erdenechimeg Batmagnai (3), Shoovdor Tserendug (4), Sodnomsambuu Demberel (4)

(1) Institut für Geophysik, Universität Münster (WWU), Münster, Germany
(2) Institute für Geochemie und Petrologie, ETH, Zürich, Switzerland
(3) Institute of Geophysics, ETH, Zürich, Switzerland
(4) Institute of Astronomy and Geophysics, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.
Study area in central Mongolia. The Bulnay region is located at the northern margin of the Hangai Mountains and along the eastern segments of the Bulnay fault zone. Central Mongolia is composed of an intracontinental plateau dominated by the Hangai block, a Precambrian microcontinent. The region is embedded within the Central Asian Orogenic Belt (CAOB), between the rigid Siberian craton to the north and the North China and Tarim cratons to the south, which have a compressional regime. GPS measurements indicate northward directed motion in northern China and eastward motion throughout Mongolia.

Magnetotelluric (MT) data were collected as part of a large regional array (Käufl et al., 2020; Comeau et al., 2018, 2020a, 2020b, 2021a). Here we analyze three ~200 km long parallel profile segments, separated by ~50 km and ~150 km, with measurement sites having a spacing of <10 km.
Regional geophysical models. Other studies, including seismic studies and an MT transect across the Hangai Mountains, suggest that the lithosphere below central Mongolia is anomalously thin (70-80 km), compared to its surroundings (150-250 km). In combination with a thick crust (~50 km) this implies an unusually thin subcrustal lithosphere. Furthermore, the brittle-ductile transition zone (BDTZ) is expected to be located at a depth of ~25 km in this region. Bouguer gravity models revealed a localized low-density structure at a depth of 80-125 km below the Hangai Dome (Bouguer anomaly of < -250 mGal; Tiberi et al., 2008), coincident with the location of the shallow asthenosphere. An asthenospheric upwelling is expected to have caused decompression melting. This is in agreement with geochemical data that show melting at shallow mantle depths (>70 km) and high temperatures in the lower crust. In addition, such an upwelling is possibly related to intraplate volcanism and to intraplate surface uplift, supported by recent geodynamic modelling of lithospheric removal in this region (Becker et al., 2019; Comeau et al., 2021b). Note seismic measurement locations are from Meltzer et al., 2019. Near-surface features are related to faults, suture zones, terrane boundaries, and mineral zones (Comeau et al., 2020b, 2021a).
**Dimensionality analysis.** Phase tensor ellipses can help determine dimensionality of the MT data; high skew values can indicate 3-D effects. The average skew values were generally low, with the exception of locations near the Bulnay fault zone. Lower crustal anomalies are detected in the period range of 10-100 s, based on skin depth considerations. A rose diagram of the regional geo-electric strike direction shows a well-defined direction of N104°E, which is approximately aligned with the trend of the Bulnay fault and the Hangai mountains (cf. Line-2000 in Comeau et al., 2018). This analysis establishes that a two-dimensional model is largely valid.
Electrical resistivity models. We used the MARE2DEM algorithm (Key, 2016) for the inversion of magnetotelluric data. Near-surface features appear coincident with the diffuse Bulnay fault system and with surface expressions of hydrothermal activity. The upper crust (<25 km depth) appears, in general, highly resistive (∼10,000 Ωm), reflecting the cratonic setting of the Hangai microcontinent. In the lower crust (25-50 km depth), localized low-resistivity zones (3-30 Ωm) are imaged (depth of ∼30-40 km), embedded in a moderate resistivity background (200-300 Ωm). They have a distinct pattern of approximately equal width and separation (∼25 km). Their true vertical extent (thickness) is difficult to establish, but we estimate their thickness to be <10 km, because they are likely smeared downward by the inversion.
Comparison with 3-D modelling. The 3-D electrical resistivity model of Käufl et al. (2020) reveals connected conductive features that are linearly extended, in an east-west direction approximately parallel to the Bulnay fault segments (white lines). Magnetotelluric measurement site locations are marked with white cubes. Only model cells less than 70 Ωm are displayed.
**MT data and model fit.** The MT data are high quality and have a low noise level, due to the remote measurement location. Overall the model fit is good. There are no significant out-of-quadrant phases nor significant phase splits, which are often observed in anisotropic regions.
Electrical anisotropy. It has been determined that an alternating sequence of resistive and conductive dykes (macroanisotropy) in 2-D isotropic resistivity models may be an effect of unaccounted-for electrical anisotropy (e.g., Heise & Pous, 2001). Anisotropy may be modelled as: i) axis-aligned triaxial anisotropy, where anisotropy is aligned with the coordinate system, producing different resistivities in perpendicular directions: along and across geoelectric strike, as well as vertically; ii) arbitrary anisotropy, where rotations (about z) give an anisotropic strike ($\alpha_S$), (about x) an anisotropic dip ($\alpha_D$), and (about y) an anisotropic slant ($\alpha_L$) (e.g., Marti et al., 2014).

Other evidence, including seismic data, can be used to reliably determine if anisotropy is likely to exist. In the MT data presented here, no uniform split in the phases nor regions with significant out-of-quadrant phases are observed – which are both diagnostic of anisotropy in the data. Nevertheless, we investigated whether electrical anisotropy can explain the anomalous features recovered.
Anisotropic electrical resistivity model. We generated electrical resistivity models that allowed axis-aligned triaxial anisotropy (i.e., different resistivities aligned with the coordinate system: along and across geoelectric strike, as well as vertically). The figure shows models along the horizontal x-direction (a) and y-direction (b). The model shows a distinct pattern of localized low-resistivity zones, similar to the isotropic model. Comparable resistivities for both directions signify weak electrical anisotropy. This validates the hypothesis that the observed resistivity pattern is not merely an artifact, and indicates that axis-aligned triaxial electrical anisotropy is not a sufficient explanation for the pattern. Note that we do not consider arbitrary anisotropy (i.e., anisotropy oriented at an angle to the coordinate system).
**Anistropic electrical resistivity model.** Anistropic modelling for the the vertical z-direction (a), the ratio of horizontal x- and y-direction (b), and the ratio of the z- and y-direction (c). The anisotropic models show similar results to the isotropic models: an alternating pattern of conductive and resistive features. Note that $\rho_z$ is similar to $\rho_y$ and the horizontal ratio ($\rho_y/\rho_x$) is small, signifying only weak electrical anisotropy.
Estimate of porosity. The fluid-filled volume fraction (porosity) required to explain the bulk resistivity obtained can be estimated with the Hashin-Shtrikman bound, which considers the resistivity of the pore fluid and the rock matrix and represents normal interconnection for lithospheric fluids. We favour fluids as the simplest explanation for the origin of the low resistivity features. We propose that the thermally perturbed lower crust undergoes metamorphic dehydration and devolatization reactions, and thus produces fluids. In lower crustal settings, there exists evidence for fluids with conductivities on the order of 10 S/m (Manning, 2018). This is consistent with models that show that H2O-NaCl fluids in such settings have conductivities ranging from 1.4-24 S/m for plausible salinities of 0.10-3.3 wt% (weight percent NaCl; Sinmyo & Keppler, 2017).

If we assume a fluid conductivity of 10 S/m (salinity of ~1 wt%), then a bulk resistivity of 30 Ωm, representative of the low-resistivity zones imaged, requires a minimum fluid content of 0.45% to explain the electrical resistivity data. A bulk resistivity of 125 Ωm, the average over the entire lower crust from the electrical resistivity model, requires a minimum fluid content of 0.10%. If the fluids are less saline (less conductive) then a higher porosity is required.
Conductivity estimates of fluid compared to those of melt. The conductivities of saline fluids (H2O-NaCl fluids), over a range of salinities (measured as weight-percent NaCl), are estimated using the experimentally-derived model from Sinmyo and Keppler (2017). The conductivities (and resistivities) of silicate melts, over a range of water contents (measured as weight-percent H2O), are computed using the semi-empirical model of Pommier and LeTrong (2011). Note that, in some scenarios, values beyond the range given here may be plausible.
Constraining length scales with a conceptual model. The spatial distribution of the low-resistivity zones is remarkably consistent with the hypothesis that the brittle-ductile transition zone (BDTZ) acts as a barrier to compaction-driven expulsion of lower crustal fluids for both rheological and hydrodynamic reasons (Connolly & Podladchikov, 2004). Thermal activation of viscous mechanisms has the consequence that the lower crust strengthens upward on the length scale $\ell_\sigma$, which is a function of the activation energy for the effective viscous mechanism and the temperature at depth $z$. Regardless of any hydrodynamic effects, upward strengthening impedes viscous compaction and tend to cause transient accumulation of metamorphic fluids in the crust.

It has been shown numerically (Connolly & Podladchikov, 1998) that in thermal regimes where $\ell_\sigma$ is greater than the viscous compaction length $\delta$ (Scott & Stevenson, 1984), compaction processes localize fluid on the local compaction length scale. In contrast, if $\delta$ is greater than $\ell_\sigma$, the local compaction length dictates the horizontal length scale for compaction processes, and $\ell_\sigma$ controls the vertical length scale. On the basis of these considerations, we interpret the oblate geometry of the low-resistivity zones imaged in the electrical resistivity models to indicate the latter regime, with a viscous compaction length of $\delta = 25$ km – i.e., the (imaged) width of the electrical resistivity anomalies, or the distance between the centre of the inter-domain regions and the centre of the domains.
Constraining length scales with a conceptual model. Given that the vertical extent of the low-resistivity zones is a somewhat uncertain aspect of the electrical resistivity model, the aforementioned simple rheological argument does not constrain $\ell_\sigma$ precisely. A more precise constraint on the vertical length scale $\ell_\sigma$ follows from the hydrodynamic mechanism posited by Connolly and Podladchikov (2004), which explains the accumulation of fluids beneath the brittle-ductile transition zone (BDTZ) as a (quasi-steady state) phenomenon in compressive tectonic settings related to the viscous relaxation of upper crustal stress in the lower crust. Note that the inversion model provides no temporal resolution, the existence of the quasi-steady state hypothesized in the stagnation mechanism is speculative, but the somewhat uniform depth of the low-resistivity zones supports the hypothesis.

A simple model of this mechanism shows that the depth from the BDTZ to the centre of the fluid zones is a function of the vertical length scale $\ell_\sigma$ and the depth of the BDTZ (zbd). This model predicts that fluids released by lower crustal metamorphism will collect in zones $\leq 9.2$ km below the BDTZ – for $zbd \leq 25$ km. This is in agreement with the electrical resistivity models of the Bulnay region; the centre of the fluid zones is imaged at a depth of $\sim 35$ km. In this case, the vertical length scale $\ell_\sigma$ is less than 9.2 km. This is consistent with the vertical extent of the low-resistivity zones imaged with the electrical resistivity models. The corresponding activation energy, estimated from the conceptual model, is 270-360 kJ/mol. These are plausible values, and suggest the viscous mechanism is dislocation creep, helping to demonstrate the consistency of the compaction model.
**Consistency with crustal hydromechanical properties.** The relation of the viscous compaction length to experimentally measured rock properties provides an additional test for the hypothesis that lower crustal low-resistivity zones are consistent with compaction-induced localization of metamorphic fluids. From the governing compaction equations (Scott & Stevenson, 1984), the viscous compaction length is a function of the viscosity, the pore-fluid viscosity, the porosity, and the grain size. Models of postseismic deformation determined that the viscosity of the lower crust in central Mongolia must be $<10^{18}$ Pa·s (Vergnolle et al., 2003), which is low compared to other crustal settings. However, it is compatible with elevated temperatures, as inferred from petrological analysis (e.g., Ionov et al., 1998), and consistent with a weak, fluid-rich lower crust. The pore fluid viscosity can be estimated from experimental measurements and the average grain size in the lower crust can be estimated based on the crustal properties and setting. The characteristic porosity is 0.10%, based on the spatially average resistivity of the present-day lower crust. A higher porosity necessitates a lower effective viscosity to explain the same viscous compaction length (for example if fluids are less saline).
Consistency with crustal hydromechanical properties. Using the estimated parameters gives a viscous compaction length of $\delta = 25$ km. This is consistent with the geophysically imaged low-resistivity zones. This analysis suggests that the independent estimates for the specific hydraulic and rheological properties of this region are not unreasonable and that the length scales are consistent with basic assumptions and with independent geodynamic inferences. In fact, this can be used to independently constrain acceptable ranges for parameters, such as the lower crustal effective viscosity, which is found to be low.

The figure shows the viscous compaction length ($\delta$; lines) for varying grain size and viscosity. Different porosities ($\phi$), computed for a spatially average resistivity of 125 $\Omega$m, correspond to different conductivities ($\sigma$), which are controlled by the fluid salinity (S, wt% NaCl). Considering partial melt may have a conductivity $<0.3$ S/m, low-salinity fluids ($<1$ wt%) are most plausible in the lower crust (with corresponding porosities of $>0.1\%$), within the conceptual model. See Comeau et al., 2020a for details.
**Consistency with crustal properties.** A higher porosity – for example, if fluids are less saline – implies a lower effective viscosity is required to explain the same viscous compaction length ($\delta$). The average grain size ($d_g$) in the lower crust can be estimated based on the crustal properties and setting; it is expected to range from $0.1 \times 10^{-3}$ m to $1 \times 10^{-3}$ m.

A combination of parameters gives a viscous compaction length ($\delta$) of 25 km. This is consistent with the geophysically imaged zones in the Bulnay region, Mongolia; other regions will have distinct properties and therefore may have a different compaction length. If the compaction length is small (for example, $<1$ km), then the zones may be below the resolution of the electromagnetic data and inversion process – that is, they may not be discernable in the geophysical model.
Images of the electrical resistivity structure below the intracontinental Bulnay region (Mongolia), reveal discrete low-resistivity zones in the lower crust.

The spatial distribution of the zones is remarkably consistent with a conceptual model that hypothesizes that, in compressive tectonic settings, metamorphic fluids released in the lower crust will collect in oblate zones and stagnate just below the BDTZ (Connolly & Podladchikov, 2004). It is also consistent with numerical models that show compaction-induced fluid localization operates on local length scales (Connolly & Podladchikov, 1998).

From the governing equations, we can compute the thickness $\ell_\sigma$, depth $\Delta z$, and compaction length $\delta$ of the localized fluid zones, as well as the activation energy $Q$. These are dependent on properties that can be estimated or derived from measurements (e.g., porosity, material viscosity, pore-fluid viscosity, grain size, temperature).

The resistivity models constrain the lower crustal viscous compaction length to be $\sim 25$ km, in the Bulnay region, which is entirely consistent with predictions from the relevant hydraulic and rheological properties. In turn, we can independently constrain crustal properties (e.g., fluid salinity, lower crustal viscosity).

Patterns of compaction-induced localization are imposed on tectonic deformation and lithological structure (Connolly & Podladchikov, 2013). Therefore, these effects may explain the elongation of the low-resistivity zones, and their orientation approximately parallel to the adjacent Bulnay fault zone segments and perpendicular to the far-field compressive tectonic stress (i.e., northward motion from China and Tibet).

The results imply that it is tectonic and compaction processes that control lower crustal fluid flow, rather than lithological or structural heterogeneity.
REFERENCES


APPENDIX

SOME MATERIAL ORIGINALLY DISCUSSED IN:


Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL088455

Key Points:

- Electrical resistivity models across a compressive intracontinental region image a pattern of low-resistivity zones in the lower crust.
- The pattern is consistent with hydrodynamic stagnation of crustal fluids due to thermally activated compaction.
- The results demonstrate that compaction processes, rather than lithological structure, control the regional lower crustal fluid flow.

Compaction-Driven Fluid Localization as an Explanation for Lower Crustal Electrical Conductors in an Intracontinental Setting

Matthew J. Comeau¹, Michael Becken¹, James A. D. Connolly², Alexander V. Grayver³, and Alexey V. Kuvshinov³

¹Institut für Geophysik, Universität Münster, Münster, Germany, ²Institute für Geochemie und Petrologie, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, ³Institute of Geophysics, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
Lower crustal low-resistivity zones caused by compaction-induced fluid localization and stagnation – recent results from electromagnetic data in an intracontinental setting

We investigate how a conceptual hydrodynamic model consisting of fluid localization and stagnation by thermally activated compaction can explain low-resistivity anomalies observed in the lower crust (>20 km depth). Electrical resistivity models, derived from magnetotelluric data collected across the intracontinental Bulnay region, a subset of a larger regional array across central Mongolia, are generated. They reveal low-resistivity (3-30 Ωm) domains with a width of ~25 km and a vertical extent of <10 km in the lower crust, with their tops ~5 km below the brittle-ductile transition zone. In 3-D these features appear as laterally extended (tube-like) structures, 300 km long, rather than disconnected ellipsoids. The features are oriented parallel to the adjacent Bulnay fault zone segments and perpendicular to the far-field compressive tectonic stress (i.e., northward motion from China and Tibet). These low-resistivity domains are consistent with the presence of saline metamorphic fluids. Deeper features imaged with the data include a large upper mantle conductor that we attribute to an asthenospheric upwelling, and thin lithosphere, related to intraplate surface uplift and volcanism, in agreement with recent geodynamic modelling of lithospheric removal in this region.

Based on the observed thermal structure of the crust, and assuming the mean stress at the brittle-ductile transition is twice the vertical load, the hydrodynamic model predicts that fluids would collect in zones <9 km below the brittle-ductile transition zone, and the zones would have a vertical extent of ~9 km, both in agreement with the resistivity models across the Bulnay region. The hydrodynamic model also gives plausible values for the activation energy for viscous creep (270-360 kJ/mol), suggesting that the mechanism is dislocation creep.

From the electrical resistivity models, the lower crustal viscous compaction-length is constrained to be ~25 km - in this region. Within the conceptual model, this length-scale is entirely consistent with independent estimates for the specific hydraulic and rheological properties of this region. In fact, this can be used to independently constrain acceptable ranges for the lower crustal effective viscosity, which is found to be low (on the order of 10^{18} Pas). Accordingly, the results indicate that low-salinity fluids (likely 1-0.01 wt% NaCl), and correspondingly low porosities (likely 5-0.1 vol%), are the most plausible. These key findings suggest partial melts are not favoured to explain the anomalies. Overall, the results of this contribution imply that it is tectonic and compaction processes that control lower crustal fluid flow, rather than lithological or structural heterogeneity.

APPENDIX
CONFERENCE ABSTRACT:

Comeau et al., EGU 2021