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Isopycnicity of cratonic mantle restricted to kimberlite provinces

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ABSTRACT

The isopycnicity hypothesis states that the lithospheric mantle of ancient platforms has a unique composition such that high density due to low lithosphere temperature is nearly compensated by low-density composition of old cratonic mantle. This hypothesis is supported by petrological studies of mantle xenoliths hosted in kimberlite magmas. However, the representativeness of the kimberlite sampling may be questioned, given that any type of magmatism is atypical for stable regions. We use EGM2008 gravity data to examine the density structure of the Siberian lithospheric mantle, which we compare with independent constraints based on free-board analysis. We find that in the Siberian craton, geochemically studied kimberlite-hosted xenoliths sample exclusively those parts of the mantle where the isopycnic condition is satisfied, while the pristine lithospheric mantle, which has not been affected by magmatism, has a significantly lower density than required by isopycnicity. This discovery allows us to conclude that our knowledge on the composition of cratonic mantle is incomplete and that it is biased by kimberlite sampling which provides a deceptive basis for the isopycnicity hypothesis.

1. Introduction: isopycnic hypothesis – unresolved questions

According to the isopycnicity hypothesis (Jordan, 1978, 1981), there is a trade-off between temperature and compositional density in all tectonic settings which results in almost equal density profiles everywhere. It implies for old cratons that the low density at STP (Standard Temperature and Pressure) of the lithospheric mantle is compensated by increased density by low temperature which results in relatively low topography.

The evolution of the cratonic lithosphere remains enigmatic. It is formed by melting of the mantle, and the product of this melting forms the lithosphere, which is lighter than the residue. and due to its positive buoyancy forms the upper layer of the Earth. Due to secular cooling of the Earth, the melting conditions in the mantle change with time (Herzberg et al., 2010), resulting in different composition of the cratonic lithospheric mantle (Gaul et al., 2000) produced in the early Earth by high-degree melting and at higher pressures than during the later planetary evolution (Walter, 1998). The Archean (>2.5 Ga) lithospheric mantle is depleted in basaltic components, which makes it 2–3% lighter than younger lithospheric mantle (Carlson et al., 2005).

The Archean cratons have some of the coldest lithosphere (Artemieva, 2006), which should make them heavy and gravitationally unstable. However, no geoid anomalies are associated with the cratons, which led to the isopycnicity hypothesis, whereby excess density of thermal origin of the Archean lithospheric mantle is nearly ideally compensated by density deficit due to compositional depletion (Jordan, 1978). This hypothesis, based on the mismatch between global seismic observations (with fast arrivals for seismic waves which pass the continental lithosphere in contrast to slow arrivals of waves which travel through the oceanic lithosphere) and the absence of geoid anomalies over the stable continents, has received further support from petrological studies of mantle-derived xenoliths. Based on the mineral composition of xenolith peridotites from the Kaapvaal craton in South Africa, Jordan (1981) calculated seismic velocities and density typical of the cratonic lithospheric mantle and proposed a linear correlation between Mg# (which is a measure of mantle depletion) and mantle density. Note that this result is constrained by a geographically restricted dataset from Kaapvaal, which is further restricted to the regions of "Nature's sampling" (kimberlite provinces).

The validity of the isopycnic hypothesis has been questioned since it was proposed. Three main questions are discussed, regarding (i) lateral satisfaction of isopycnicity depending on geodynamic

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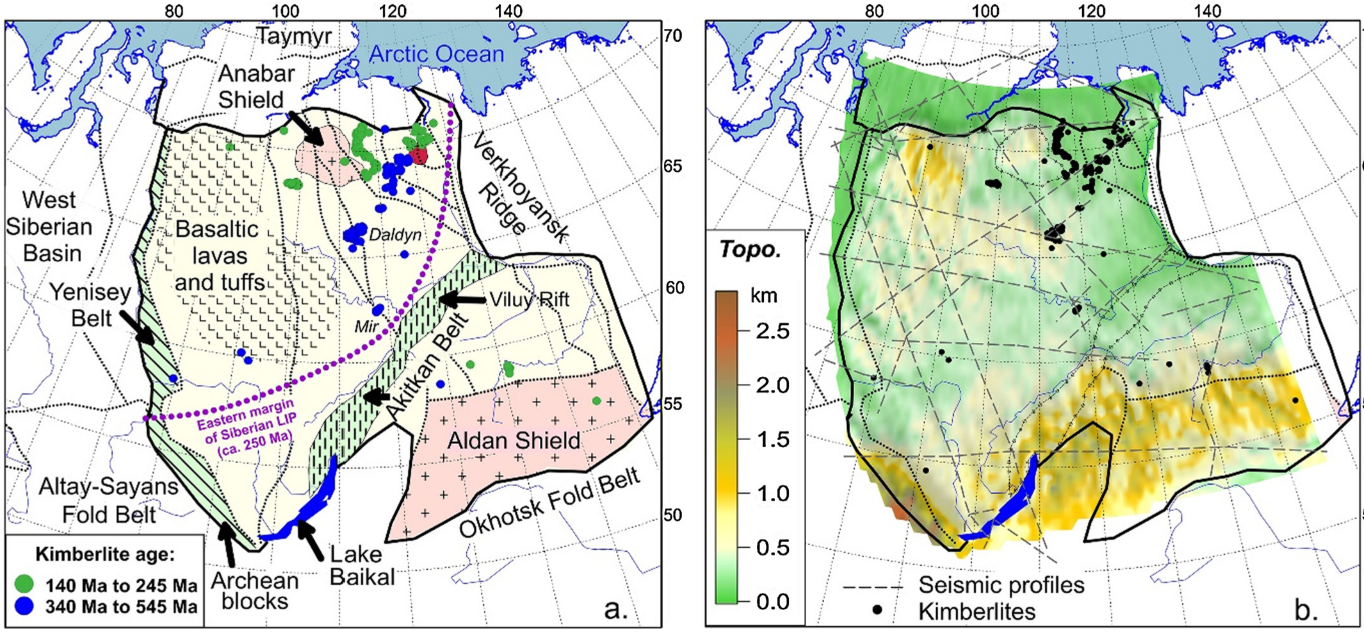

Fig. 1. (a) Simplified geological map of the Siberian craton (after Rosen et al., 1994). Pink colors – Archean shields; dark red – the Olenek Uplift; solid black line – outline of the craton; dotted black lines – boundaries between major cratonic terranes; dotted purple line – margin of the Siberian LIP (after Howarth et al., 2014). Color dots – kimberlites (blue – erupted prior to the Siberian traps, green – post-trap). (b) Topographic map with the location of major crustal-scale seismic profiles superimposed by dashed lines used in the SibCrust regional crustal model (Cherepanova et al., 2013). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

setting, (ii) depth distribution of the density deficit in the lithospheric mantle to achieve isopycnicity, and (iii) the variation of isopycnicity with time:

(i) Global analysis of mantle gravity anomalies (Kaban et al., 2003) has demonstrated that the average density of stable continental lithospheric mantle may be close to the isopycnic condition, but with significant regional deviation (with density anomalies in the lithospheric mantle with respect to the asthenosphere of up to double amplitude compared to isopycnicity predictions).

(ii) Assuming isopycnicity is achieved, there may be many mechanisms of density layering to bring the bulk density of the entire vertical column of the lithospheric mantle to a near-isopycnic condition (Kelly et al., 2003), implying that at any particular depth interval isopycnicity may not be satisfied, while the entire lithospheric column may be close to isopycnic condition.

(iii) Given the ancient age of the cratonic lithosphere, one would expect that it may have been significantly affected by geotectonic and mantle processes. In fact, numerous petrological data from cratons worldwide provide evidence for significant metasomatic modification of the (at least, lower portions of) lithospheric mantle (Agashev et al., 2013; Howarth et al., 2014), leading to density increase in the lower portion of the lithosphere. Recent geodynamic study of isopycnic stability over time has demonstrated that it is unlikely that this condition is stable during cratonic evolution (Eaton and Perry, 2013).

We use gravity data to demonstrate that isopycnicity is only fulfilled locally in cratonic regions and that petrologically studied mantle-derived xenoliths all sample cratonic lithospheric mantle where isopycnicity is satisfied. It implies that pristine lithospheric mantle, which is unsampled by Nature through xenolith-bearing kimberlite magmatism may be significantly lighter than predicted from xenolith-data and isopycnic equilibrium. To bring this highly depleted mantle to the isopycnic state, cratonic lithospheric geotherms should be significantly colder than typical xenolith $P-T$ arrays suggest (Rudnick and Nyblade, 1999).

2. Tectonic evolution of the Siberian craton

We focus on the Siberian craton (Fig. 1), since this region is covered by a high-quality regional crustal model (Cherepanova et al., 2013) as required for the gravity analysis and by numerous kimberlite fields, many of which are presently studied petrologically, thus providing independent information on mantle composition (Thybo et al., 2013). Detailed data on the crustal structure is not available for other cratonic regions which host kimberlite provinces. This precludes similar studies for other cratons, given the importance of the crustal gravity correction for calculating mantle gravity anomalies (Herceg et al., 2016). Even for the Kaapvaal craton, which has some of the most abundant petrological data from mantle-derived xenoliths, the existing data on the crustal structure (Youssof et al., 2013; Nair et al., 2006; Kgaswane et al., 2009) is by far insufficient for this type of high-resolution gravity study, as it is restricted to Moho depth without reliable information on seismic velocity and density structure of the crust.

The Siberian craton is composed of two Archean terranes, that are exposed chiefly in the Anabar shield in the north-east and the Aldan shield in the south-east, and is otherwise buried under a thick layer of sedimentary rocks ranging in age from Precambrian to Cenozoic, which is interlayered with the Siberian trap basalts in the western half of the craton (Fig. 1a). Archean blocks also outcrop at the Yenisey Ridge which marks the western edge of the craton (Gladkochub et al., 2006). The Archean terranes are separated by the Proterozoic Akitkan mobile belt which extends roughly from the Paleozoic Viluy rifted basin in the east to the southern margin of the Baikal Rift zone in the south-west towards the outcrops of the oldest dated Archean rocks in Siberia at the south-western margin of the craton. The interior parts of the craton have experienced a series of Phanerozoic tectonic and magmatic events, including the emplacement of the Siberian traps (ca.

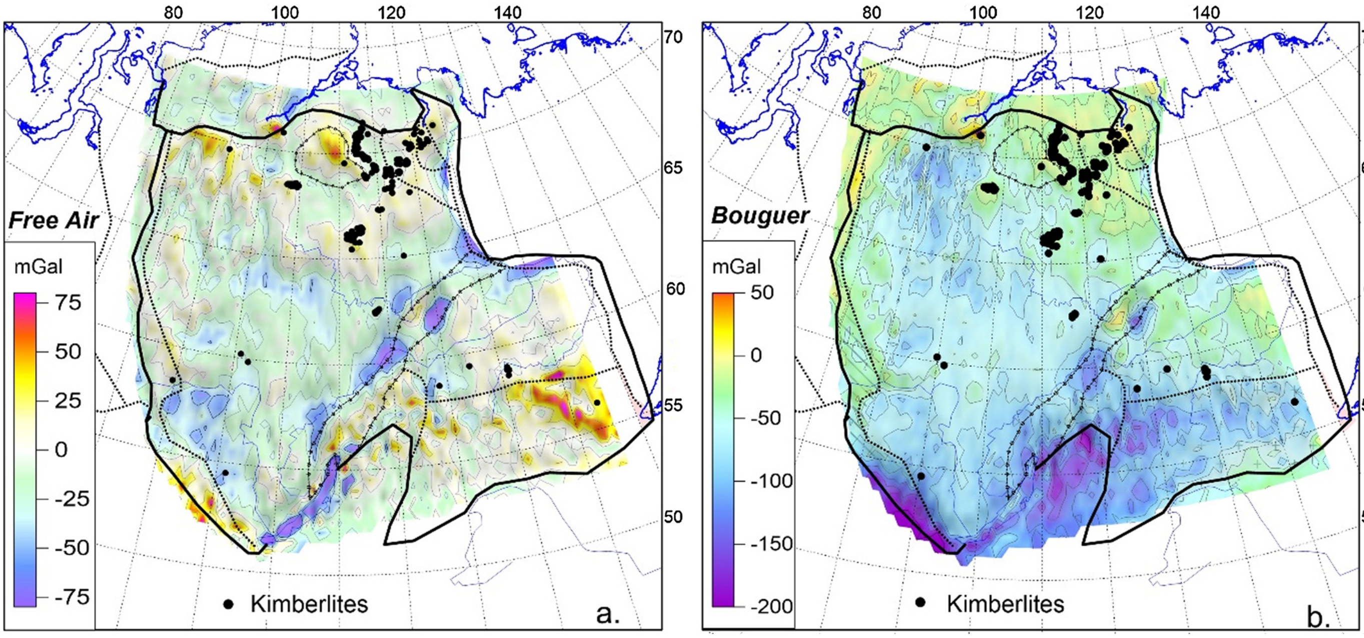

Fig. 2. Free air (a) and Bouguer (b) gravity anomalies based on EGM2008 gravity data (Pavlis et al., 2012). Dotted lines – major tectonic boundaries; symbols – kimberlites.

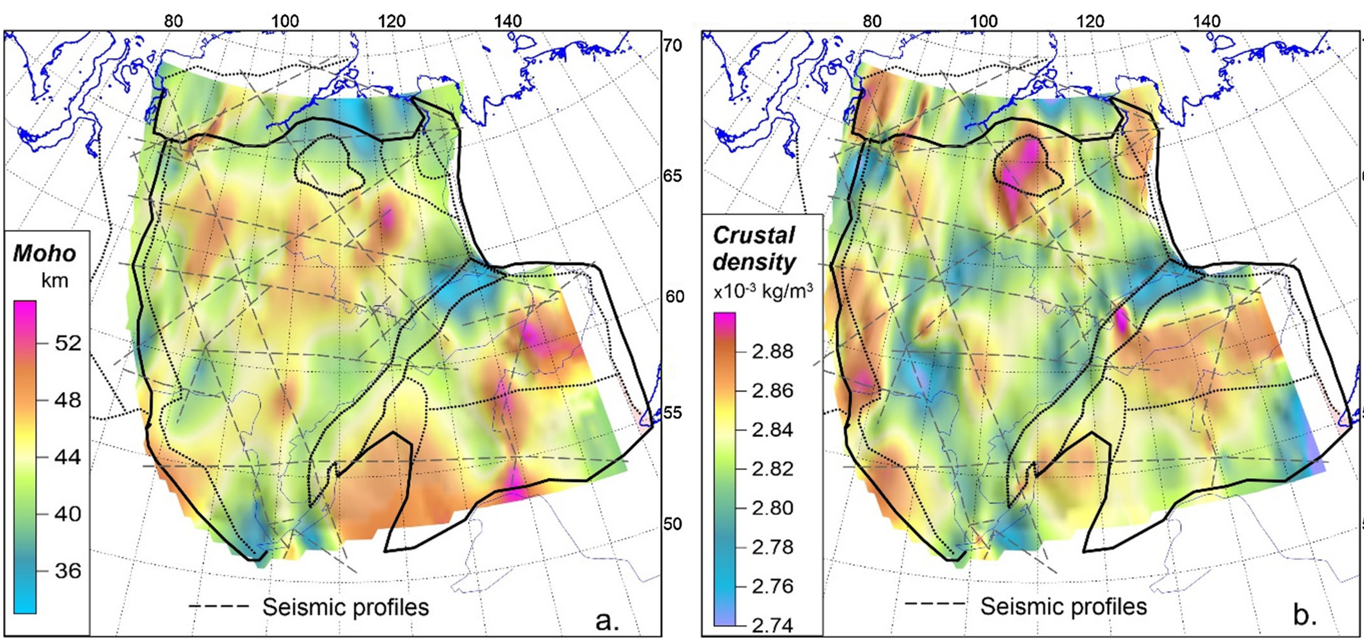

Fig. 3. Crustal structure of the Siberian craton (based on Cherepanova et al., 2013): (a) Moho depth, (b) average crustal density (including sediments). Dotted lines – major tectonic boundaries; dashed lines – crustal-scale seismic profiles.

250 Ma), several pulses of kimberlite magmatism (ca. 420–380 Ma, 380–340 Ma, 245–240 Ma, and 170–140 Ma), mostly in the northern and eastern parts of the craton, and the Paleozoic large-scale Viluy rifting at the eastern terminus of the Akitkan mobile belt (Rosen et al., 1994).

3. Gravity analysis

Most of the Siberian craton is in regional isostatic equilibrium as demonstrated by near-zero (+10 to −20 mGal) free air gravity anomalies (Fig. 2a), except for isolated positive (+40 +50 mGal) anomalies in the Archean shields and negative (−70–80 mGal) anomalies along the Akitkan mobile belt and the Baikal Rift zone. Bouguer gravity anomalies (Fig. 2b) are between −50–150 mGal in most of the craton due to the combination of gravity effects of a relatively thick crust (Fig. 3a) and low-density upper mantle.

Our approach is to calculate mantle gravity anomalies as the difference between free air gravity anomalies and the gravitational effect of the crust with respect to the gravitational effect of a reference model. The reference model includes a 45 km thick crust with a density of 2.82×10^{-3} kg/m^3 and a 25 km thick mantle layer with density of 3.35×10^{-3} kg/m^3. In this study, free air anomalies are based on EGM2008 gravity data (Pavlis et al., 2012). However, we also performed a similar analysis (Herceg et al., 2016) using satellite gravity data from the GOCE mission (Pail et al., 2011), and the results based on the two different gravity models are consistent. The gravitational effect of the crust is computed based on the regional crustal model SibCrust (Cherepanova et al., 2013) (Fig. 3),

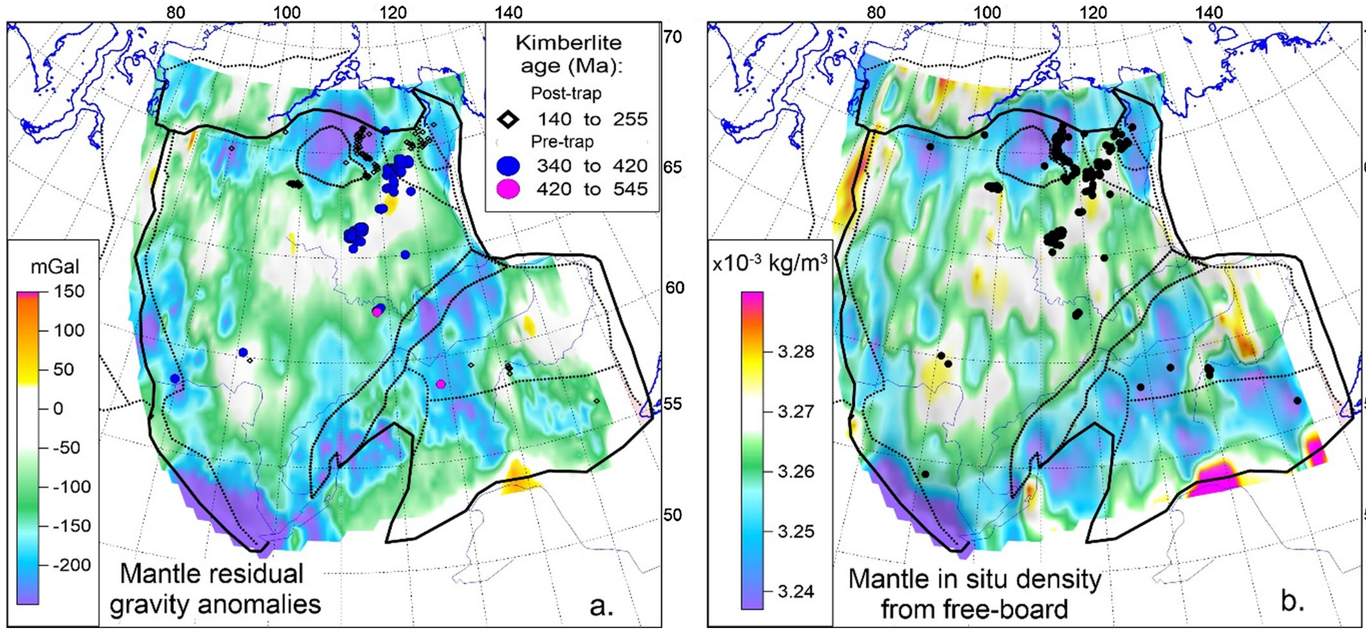

Fig. 4. (a) Mantle residual gravity anomalies calculated from EGM2008 gravity data. The anomalies reflect density heterogeneity of lithospheric mantle beneath the Siberian craton. In case the isopycnic condition is satisfied, thermally-induced density excess is balanced by compositionally-induced density deficit, and residual mantle gravity anomalies are near-zero. Isopycnicity is satisfied in white areas; the uncertainty of gravity anomalies is not larger than ±50 mGal (Herceg et al., 2016). (b) In situ mantle density anomalies based on free-board modeling (after Cherepanova and Artemieva, 2015). The anomalies are assumed to be restricted to the layer between the Moho and 180 km depth. The lithospheric mantle below 180 km and down to the lithosphere base is assumed to have constant density of 3.38 g/cm^3 (at room $P-T$ conditions). Density of sublithospheric mantle at room $P-T$ conditions is assumed to be 3.39 g/cm^3. The strong agreement between the gravity (a) and density (b) models of lithospheric mantle suggests that layered structure of cratonic lithosphere may be a common phenomenon. Dotted lines – major tectonic boundaries; symbols – kimberlites (color-coded by eruption age in (a)).

which is constrained solely by seismic data and thus is suitable for gravity analysis. The SibCrust model contains information on Vp-seismic velocity and thickness of 5 crustal layers (sediments, upper, middle and lower crust, and a high velocity lower crustal layer which probably represents underplated material above Moho, where present) as well as the Pn velocity in the sub-Moho uppermost mantle (Fig. 3).

Gravity calculations require knowledge of the crustal density (Fig. 3b) and for each crustal layer we use a mid-curve for velocity-density conversion as reported in different laboratory studies (Christensen and Mooney, 1995). For the sedimentary cover we use densities on the upper end of the corresponding Vp velocities, due to the fact that deep sedimentary basins within the Siberian craton host voluminous magmatic intrusions associated with the Siberian trap event and intracratonic rifting of the Viluy basin (Fig. 1a). The largest uncertainties in the calculation of residual mantle gravity (Herceg et al., 2016) arise from the choice of velocity-density conversion curve (up-to 0.7–1.0% for density) and the uncertainty of the thicknesses and densities of sedimentary strata (up to 0.3% for density). However, in regions with a dense network of geophysical and geological observations, the real uncertainties are significantly smaller than in synthetic tests, because both the structure and composition of the sediments are constrained by observations, and physical properties of rocks are known from regional laboratory studies. Our SibCrust model is based on the wealth of data for Siberia and has high resolution of the whole crust. A dedicated analysis indicates that for the Siberian craton the uncertainty of the mantle residual anomalies may be up to ca. ±50 mGal, as caused by uncertainty in the seismic model of the crust (thickness of crustal layers and Vp velocity in them) and uncertainty in the Vp-density conversion (Herceg et al., 2016). The observed mantle gravity anomalies are, however, significantly larger (with a range of ca. 400 mGal) than the maximum possible uncertainty of the gravity calculation (Fig. 4a).

4. Mantle gravity anomalies

We assume that the mantle residual gravity anomalies (Fig. 4a) primarily reflect density anomalies distributed within the lithospheric mantle and integrated over the entire thickness of the chemical boundary layer above a less heterogeneous mantle below. The depth distribution of density anomalies is unknown due to inherent properties of potential fields. Gravity inversion provides information on density anomalies at in situ conditions with contributions from both compositional and thermal anomalies, which cannot be separated without additional information (Kaban et al., 2003). In case the isopycnic condition is satisfied, mantle gravity anomalies should be near-zero, with thermally-induced density excess being balanced by compositionally-induced density deficit.

The results show that, within the Siberian craton, mantle gravity anomalies range between ca. −300 mGal and ca. +50 mGal with generally negative values over the entire craton (Fig. 4a). The strongest negative residual gravity anomalies are associated with the Archean blocks which include the Anabar craton (ca. −300–250 mGal), the Yenisey Ridge (ca. −200 mGal), and the western part of the Aldan Shield (ca. −200–150 mGal) with the strongest anomaly (ca. −350 mGal) in the oldest Archean block at the SW edge of the craton near the Baikal Lake. Thus the craton as a whole is not obeying isopycnicity. Negative residual mantle anomalies indicate the presence of a significant in situ density deficit within the chemical boundary layer, which is not compensated by low cratonic lithospheric temperatures. Earlier low-resolution gravity modeling (Kaban et al., 2003) constrained by GRACE satellite data and the coarsely constrained CRUST5.0 model has indicated that the craton-average of mantle residual gravity in different Precambrian cratons may vary between ca. −90 mGal (South Africa) and ca. +70 mGal (Siberia), and we attribute the difference between the two studies for Siberia to low resolution of the crustal structure in the earlier model (Cherepanova et al., 2013).

Near-zero mantle gravity anomalies attest to the isopycnic condition. Kimberlite magmatism, predating the Siberian traps, is only known in areas with near-zero mantle gravity, and these kimberlites are the only parts of the Siberian craton for which abundant petrological data based on mantle xenoliths exist (Fig. 4a). These kimberlites include the diamondiferous kimberlite fields of Malo-Botuoba (pipe Mir) and Daldyn-Alakit, and the kimberlite fields of the Olenek province (Fig. 1a). Near-isopycnic condition is also observed in the western part of the craton which is covered by the Siberian traps. Within kimberlite provinces, notable deviations from isopycnicity are only in regions with young (mostly 140–170 Ma) kimberlites, such as along the eastern slope of the Anabar Shield, where mantle gravity anomalies are negative. However, for the kimberlites around the Anabar Shield (except for the Kharamai field) (Griffin et al., 2005), geochemical studies are limited to the emplacement age and do not provide information on the composition and thereby on density of the lithospheric mantle.

We conclude that all petrologically studied kimberlite-hosted xenoliths sample anomalous mantle of the Siberian Craton that exhibits isopycnic behavior. On the whole, only much less than half of the Siberian Craton shows mantle gravity anomalies around zero, corresponding to isopycnicity equilibrium, whereas the major part of the craton (where geochemical data on mantle composition is absent) shows large deviations from zero mantle gravity anomaly. In particular, the pristine Archean mantle in the Aldan and Anabar shields and in the Archean blocks along the western margin of the Siberian craton has a significantly smaller mantle density than isopycnicity predicts. Similarly, major parts of the central and western Siberian Craton show low mantle gravity anomalies of ca. −100 mGal or lower.

Our results for the Siberian craton are similar to recent results for the cratons of southern Africa (Artemieva and Vinnik, 2016a, 2016b), where the isopycnicity condition is also satisfied only locally and mostly in the kimberlite provinces of the northwestern Kaapvaal craton, with the largest deviations in the Limpopo belt where the density of the lithospheric mantle is higher than in the Kaapvaal. Similar to the Siberian craton, the lithospheric mantle with the lowest density lies outside of the south African kimberlite clusters.

Our results support early observations of uncharacteristic sampling of the cratonic lithosphere mantle by mantle-derived xenoliths based on the spatial correlations between xenolith locations and in situ anomalies in upper mantle seismic velocities (Griffin et al., 2009). Furthermore, seismic velocity anomalies corrected for lateral temperature variations also have reduced amplitude in cratonic regions affected by kimberlite magmatism as compared to strong positive Vs velocity anomalies of non-thermal origin typical of the “intact” cratonic mantle (Artemieva, 2009), which have been interpreted as the evidence that kimberlite-hosted xenoliths provide biased sampling of cratonic mantle.

5. Discussion

We test our results by an independent approach which is based on free-board constraints (Cherepanova and Artemieva, 2015) and overlaps with our gravity calculations only in the use of the same crustal density model. Free-board calculations are based on the assumption of regional isostatic equilibrium, which is justified by near-zero free air gravity anomalies (Fig. 2a). The approach is based on Archimedes' principle and assumes that surface topography originates from buoyancy of the crust and the lithospheric mantle which depend on thickness and average density of the corresponding layers. As crustal thickness and density, as well as lithosphere thickness and temperature are constrained, one can calculate regional variations in density of the lithospheric mantle at in situ and room $P-T$ conditions from the topography. We limit the comparison of gravity and free-board calculations to in situ conditions, given that mantle gravity anomalies (Fig. 4a) and the isopycnicity condition both refer to in situ pressures and temperatures.

The results show geographical correlation between mantle gravity anomalies and mantle density anomalies when density anomalies are assumed to be distributed within the layer from the Moho down to the lithosphere base (Aulbach et al., 2013) (the latter is constrained by heat flow and xenolith geotherms (Artemieva, 2006)). However, the results of the gravity and free-board analysis are in a striking agreement (Fig. 4a, b) when assuming a layered structure of the lithospheric mantle, where the density anomalies reside mainly in an upper depleted layer between the Moho and a depth of 180 km above a fertile lower layer extending from 180 km depth down to the lithosphere base. This assumption of a layered compositional structure of the lithospheric mantle is supported by xenolith data from the Slave and the Karelian cratons (Aulbach et al., 2013; Lehtonen et al., 2004), and may be a common feature of cratonic lithosphere as demonstrated by some geophysical studies (Artemieva, 2009). Regional xenolith studies from the Siberian craton also indicate a strong metasomatic signature in the lower part of the Siberian lithospheric mantle (Agashev et al., 2013), with a sharp increase of the portion of melt-metasomatized peridotites in the Archean Siberian mantle below a depth of ca. 150–180 km (Griffin et al., 2003).

In accord with petrological studies, we interpret the increased density of the lithospheric mantle in kimberlite provinces of the Siberian craton (as compared to regions unaffected by the Devonian kimberlite magmatic event) by regional-scale melt-metasomatism associated with voluminous intrusions of basaltic magmas into depleted cratonic lithosphere (Howarth et al., 2014; Griffin et al., 2009; Aulbach et al., 2013; Nielson and Wilshire, 1993) (Fig. 5). Such magmatism is associated with introduction of iron-rich melts which have high density (thus positive residual gravity anomalies) and low seismic (in particular, Vs) velocity (Carlson et al., 2005; Lee, 2003). The role of other mineral phases (such as a decrease in orthopyroxene content during metasomatism and changes in the content of garnet and clinopyroxene) on bulk physical properties of lithospheric mantle may also be important; but there is insufficient laboratory data on bulk density of peridotite mantle as a function of orthopyroxene content (Kopylova et al., 2004) to assess their roles.

We observe negative mantle gravity anomalies in the northwestern part of the Siberian craton, which is covered by the Siberian traps and presumably was affected by the Siberian LIP (Howarth et al., 2014). Such anomalies are typical of most of the Siberian craton north of the Akitkan belt, where geochemical data from abundant kimberlite-hosted xenoliths indicate the presence of depleted and moderately metasomatised cratonic mantle (Agashev et al., 2013). We speculate that large-scale magmatism associated with the Siberian LIP would have produced a significant metasomatic reworking of the cratonic mantle, which we do not observe in mantle gravity anomalies. Our results provide support for a thermomechanical model (Sobolev et al., 2011) of the Siberian LIP province, where the impact of a mantle hotspot was assumed to be along the north-western margin of the craton. Our observation therefore indicates that the source of the Siberian LIP is likely to lie outside the craton.

6. Conclusion

Our results show that:

(i) the Siberian lithospheric mantle is highly heterogeneous as evidenced by large regional variations in in situ density,

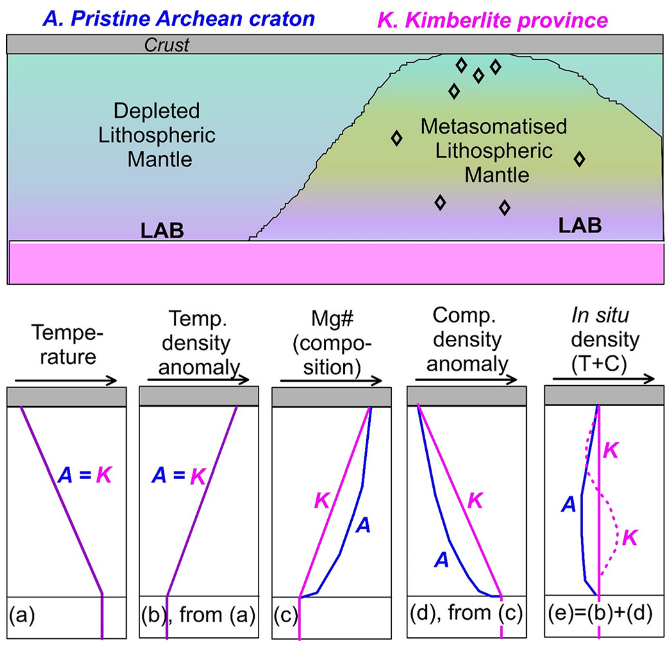

Fig. 5. Sketch of the principle of isopycnicity (Jordan, 1978, 1981). Upper panel: schematic model of a pristine Archaean mantle lithosphere (A) and a metasomatised mantle lithosphere typical of kimberlite provinces (K). Both regions have the same thickness of the thermal boundary layer, i.e. the same depth to the Lithosphere–Asthenosphere Boundary (LAB). Lower panel: The five diagrams show schematic depth profiles for the following parameters: (a) temperature and (b) density anomaly caused by temperature (these lines overlap for profiles A and K because they have the same LAB depth); (c) Mg# where the pristine Archaean lithosphere is highly depleted in basaltic components and has higher Mg# values than the metasomatised lithosphere; (d) compositional density anomaly caused by variation in Mg#; and (e) in situ density from combining (b) and (d). The constant in situ density depth profile in the metasomatised mantle shows perfect isopycnicity (isopycnicity in its strong form, solid line). Alternatively (and probably more likely), isopycnicity may be satisfied not at every depth but when averaged over the entire vertical column of the lithospheric mantle (isopycnicity in its weak form, dashed line). Due to high depletion, high Mg#, and low compositional density, the undisturbed Archaean lithospheric mantle has lower in situ density such that isopycnicity is not satisfied.

(ii) xenolith evidence on isopycnicity is restricted to cratonic mantle which may have been reworked by voluminous magmatism and where gravity calculations also indicate isopycnicity;
(iii) the Siberian lithospheric mantle is likely to have compositional (density) layering with a marked transition at a depth of 160–180 km;
(iv) the source of the Siberian LIP is likely to lie outside the craton.

The fact that xenolith-analyzed magmatism is only observed in regions that are in isopycnicity equilibrium, indicates that this is a transient condition which is not inherent to the pristine Archean mantle. A direct consequence of this conclusion is that our knowledge on the composition of the cratonic mantle is biased by Nature's sampling. As a result, the composition of the pristine cratonic mantle remains unknown and laboratory studies of densities and seismic velocities of mantle-derived peridotites from kimberlite provinces cannot be used for meaningful interpretation of the general composition of the pristine mantle from seismic and gravity data. Furthermore, lack of information on the composition of the most pristine parts of the Archean lithospheric mantle hampers our understanding on the mechanisms of lithosphere formation in the Archean (Lee, 2006) and the mechanisms of long-term preservation of cratonic lithospheric keels (Lenardic et al., 2003).

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References

Agashev, A.M., Ionov, D.A., Pokhilenko, N.P., et al., 2013. Metasomatism in lithospheric mantle roots: constraints from whole-rock and mineral chemical composition of deformed peridotite xenoliths from kimberlite pipe Udachnaya. Lithos 160, 201–215.

Artemieva, I.M., 2006. Global 1° × 1° thermal model TC1 for the continental lithosphere: implications for lithosphere secular evolution. Tectonophysics 416, 245–277.

Artemieva, I.M., 2009. The continental lithosphere: reconciling thermal, seismic, and petrologic data. Lithos 109, 23–46.

Artemieva, I.M., Vinnik, L.P., 2016a. Density structure of the cratonic mantle in Southern Africa, 1: implications for dynamic topography. Gondwana Res. 39, 204–216.

Artemieva, I.M., Vinnik, L.P., 2016b. Density structure of the cratonic mantle in Southern Africa, 2: correlations with kimberlite distribution, seismic velocities, and Moho sharpness. Gondwana Res. 36, 14–27.

Aulbach, S., Griffin, W., Pearson, N., et al., 2013. Nature and timing of metasomatism in the stratified mantle lithosphere beneath the central Slave craton (Canada). Chem. Geol. 352, 153–169.

Carlson, R.W., Pearson, G., James, D.E., 2005. Physical, chemical, and chronological characteristics of continental mantle. Rev. Geophys. 43, RG1001.

Cherepanova, Y., Artemieva, I.M., 2015. Density heterogeneity of the cratonic lithosphere: a case study of the Siberian craton. Gondwana Res. 28, 1344–1360.

Cherepanova, Y., Artemieva, I.M., Thybo, H., Chemia, Z., 2013. Crustal structure of the Siberian craton and the West Siberian basin: an appraisal of existing seismic data. Tectonophysics 609, 154–183.

Christensen, N.I., Mooney, W.D., 1995. Seismic velocity structure and composition of the continental crust: a global view. J. Geophys. Res., Solid Earth 100, 9761–9788.

Eaton, D.W., Perry, H.K.C., 2013. Ephemeral isopycnicity of cratonic mantle keels. Nat. Geosci. 6, 967–970.

Gaul, O.F., Griffin, W.L., O'Reilly, S.Y., Pearson, N.J., 2000. Mapping olivine composition in the lithospheric mantle. Earth Planet. Sci. Lett. 182, 223–235.

Gladkochub, D., Pisarevsky, S.A., Donskaya, T., et al., 2006. Siberian Craton and its evolution in terms of Rodinia hypothesis. Episodes 29, 169–174.

Griffin, W.L., O'Reilly, S.Y., Abe, N., et al., 2003. The origin and evolution of Archean lithospheric mantle. Precambrian Res. 127, 19–41.

Griffin, W.L., Natapov, L.M., O'Reilly, S.Y., et al., 2005. The Kharamai kimberlite field, Siberia: modification of the lithospheric mantle by the Siberian Trap event. Lithos 81, 167–187.

Griffin, W.L., O'Reilly, S.Y., Afonso, J.C., Begg, G.C., 2009. The composition and evolution of lithospheric mantle: a re-evaluation and its tectonic implications. J. Petrol. 50, 1185–1204.

Herceg, M., Artemieva, I.M., Thybo, H., 2016. Sensitivity analysis of crustal correction for calculation of lithospheric mantle density from gravity data. Geophys. J. Int. 6. https://doi.org/10.1093/gji/ggv431.

Herzberg, C., Condie, K., Korenaga, J., 2010. Formation of cratonic lithosphere: an integrated thermal and petrological model. Earth Planet. Sci. Lett. 292, 79–88.

Howarth, G.H., Barry, P.H., Pernet-Fisher, J.F., et al., 2014. Superplume metasomatism: evidence from Siberian mantle xenoliths. Lithos 184, 209–224.

Jordan, T.H., 1978. Composition and development of the continental tectosphere. Nature 274, 544–548.

Jordan, T.H., 1981. Continents as a chemical boundary layer. Philos. Trans. R. Soc. Lond. A 301, 359–373.

Kaban, M.K., Schwintzer, P., Artemieva, I.M., Mooney, W.D., 2003. Density of the continental roots: compositional and thermal effects. Earth Planet. Sci. Lett. 209, 53–69.

Kelly, R.K., Kelemen, P.B., Jull, M., 2003. Buoyancy of the continental upper mantle. Geochem. Geophys. Geosyst. 4 (2), 1017.

Kgaswane, E.M., Nyblade, A.A., Julia, J., et al., 2009. Shear wave velocity structure of the lower crust in southern Africa: evidence for compositional heterogeneity within Archaean and Proterozoic terrains. J. Geophys. Res. 114, B12304.

Kopylova, M.G., Lo, J., Christensen, N.I., 2004. Petrological constraints on seismic properties of the Slave upper mantle (Northern Canada). Lithos 77, 493–510.

Lee, C.-T.A., 2003. Compositional variation of density and seismic velocities in natural peridotites at STP conditions: implications for seismic imaging of compositional heterogeneities in the upper mantle. J. Geophys. Res., Solid Earth 108, 2441.

Lee, C.-T.A., 2006. Geochemical/petrologic constraints on the origin of cratonic mantle. In: Benn, K., Mareschal, J.-C., Condie, K.C. (Eds.), Archean Geodynamics and Environments. In: AGU Geophys. Monogr., vol. 164.

Lehtonen, M., O'Brien, H.E., Peltonen, P., Johanson, B.S., Pakkanen, L., 2004. Layered mantle at the Karelian Craton margin: $P-T$ of mantle xenocrysts and xenoliths from the Kaavi–Kuopio kimberlites, Finland. Lithos 77, 593–608.

Lenardic, A., Moresi, L.N., Muhlhaus, H., 2003. Longevity and stability of cratonic lithosphere: insights from numerical simulations of coupled mantle convection and continental tectonics. J. Geophys. Res., Solid Earth 108 (B6), 2303.

Nair, S.K., Gao, S.S., Liu, K.H., Silver, P.G., 2006. Southern African crustal evolution and composition: constraints from receiver function studies. J. Geophys. Res. 111, B02304.

Nielson, J.E., Wilshire, H.G., 1993. Magma transport and metasomatism in the mantle: a critical review of current geochemical models. Am. Mineral. 78, 1117–1134.

Pail, R., Bruinsma, S., Migliaccio, F., et al., 2011. First GOCE gravity field models derived by three different approaches. J. Geod. 85, 819–843.

Pavlis, N.K., Holmes, S.A., Kenyon, S.C., Factor, J.K., 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). J. Geophys. Res. 117, B04406.

Rosen, O.M., Condie, K., Natapov, L.M., Nozhkin, A.D., 1994. Archean and early Proterozoic evolution of the Siberian Craton: a preliminary assessment. In: Condie, K. (Ed.), Archean Crustal Evolution. Elsevier, pp. 411–459.

Rudnick, L.R., Nyblade, A.A., 1999. The thickness and heat production of Archean lithosphere: constraints from xenolith thermobarometry and surface heat flow. In: Fei, Y., Bertka, C.M., Mysen, B.O. (Eds.), Mantle Petrology: Field Observations and High Pressure Experimentation: A Tribute to Francis R. (Joe) Boyd. In: Spec. Publ. – Geochem. Soc., vol. 6, pp. 3–12.

Sobolev, S.V., Sobolev, A.V., Kuzmin, D.V., et al., 2011. Linking mantle plumes, large igneous provinces and environmental catastrophes. Nature 477, 312–316.

Thybo, H., Artemieva, I., Kennett, B. (Eds.), 2013. Moho: 100 years after Andrija Mohorovičić. Tectonophysics, vol. 609. 734 pp.

Walter, M.J., 1998. Melting of garnet peridotite and the origin of komatiite and depleted lithosphere. J. Petrol. 39, 29–60.

Youssof, M., Thybo, H., Artemieva, I.M., 2013. Moho depth and crustal composition in southern Africa. Tectonophysics 609, 267–287.