GEOLOGICAL IMPLICATIONS FROM COMPLETE GONDWANA GOCE-PRODUCTS RECONSTRUCTIONS AND LINK TO LITHOSPHERIC ROOTS

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ABSTRACT

The GOCE gravity field is globally homogeneous at the resolution of about 80km or better allowing for the first time to analyze tectonic structures at continental scale. Geologic correlation studies propose to continue the tectonic lineaments across continents to the pre-breakup position. Tectonic events that induce density changes, as metamorphic events and magmatic events, should then show up in the gravity field. Applying geodynamic plate reconstructions to the GOCE gravity field places today's observed field at the pre-breakup position. The same reconstruction can be applied to the seismic velocity models, to allow a joint gravity-velocity analysis. The geophysical fields allow to control the likeliness of the hypothesized continuation of lineations based on sparse surface outcrops. Total absence of a signal, makes the cross-continental continuation of the lineament improbable, as continental-wide lineaments are controlled by rheologic and compositional differences of lithospheric mantle. It is found that the deep lithospheric roots as those found below cratons control the position of the positive gravity values. The explanation is that the deep lithospheric roots focus asthenospheric upwelling outboard of the root protecting the overlying craton from magmatic intrusions. The study is carried out over the African and South American continents.

1. INTRODUCTION

Mantle flow is the driving force of plate movement, leading to orogen buildup, rifting, and magmatism. The oldest lithospheric plates of Archean age focus deformation along plate borders, leading to repeated cycles of rifting, orogen buildup and metamorphism. Considering that several of the old lithospheric plates presently have or have had a deep lithospheric root of high viscosity, the repeated activity could be due to the interaction of deep lithospheric roots with mantle flow. Repeated deformation cycles alter crustal composition considerably due to geothermal processes that also affect rock density. Rock is densified through two principal processes, metamorphism and magmatic activation. The related density variations form the link between the geological processes and the GOCE observations. The GOCE products have proven to be extremely useful in the detection of the plate-wide geological focus-zones [1, 2, 3]. This is due to the global field recovery with improved precision and resolution which permits to identify these structures. The spatial resolution of 80 km at a precision of the field of 3mGal is sufficient to detect large scale features extending several hundreds of km in length as those that are correlated to the outlines of cratons. Investigations with pre-GOCE gravity fields were possible e.g. by GRACE products, but the spatial resolution was too small to detect any of the regional structures that are studied here. High resolution fields which combine satellite observations and terrestrial data could be used as well, however data distribution and precision of terrestrial coverage is inhomogeneous and locally has been shown to include spurious errors. The consequence is that there is no control on the correctness of an identified anomaly at global scales. Also altimeter derived global fields are of higher resolution than the GOCE field, but are not useful for continental investigations, as they retrieve only the field over present-day oceans and large inland waters.

Thus GOCE-fields bear an innovative tool to seek continuity of structures through their density variations, which can be combined with surface rock sampling, age dating and petrologic investigations. The investigation of continuity between the African and South American continent for instance, based on rock compositional and geomorphological evidence, has a long history due to the large content of mineral resources. GOCE fields allow an innovative aspect, because the fields sample the density variations of the entire crust, whereas the geologic investigations are limited to rock-outcrops. We show here some significant structures, which are important for mineral exploration due to the presence of known deposits correlating to these structures. The corresponding rock outcrops are too small to justify the observed gravity and gravity gradients. Therefore they can only be explained by an associated systematic crustal scale densification. This deep densification could be a key feature of the superficial products and linked to the genesis of the melting processes that enhance

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mineral accumulation to economic percentages. Here we present one example of a large scale feature in Brazil, which lines the border of the deep mantle lithospheric root of the Amazon craton. The deep roots are identified by an increase in seismic velocity Vp, recovered from a global tomographic model. This correlation cannot be purely by chance and is likely due to the interaction of the deep root with the upwelling asthenosphere.

2. GEOPHYSICAL DATA

The gravity potential field is calculated from the spherical harmonic expansion model GO_CONS_GCF_2_TIM_R5, produced by the Graz University of Technology, Institute for Theoretical and Satellite Geodesy, University of Bonn, Institute of Geodesy and Geoinformation and TU München, Institute of Astronomical and Physical Geodesy [4]. The data are available through ESA (http://www.esa.int) and at the International Centre for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de/ICGEM/). The height of calculation is 4000 m guaranteeing to be above topography and be able to make the topographic reduction with the data points above the topographic masses. Grid resolution is 0.25°. The gravity anomaly values have been decorrelated with a digital terrain model with a regression analysis [2, 5]. The digital terrain model refers to ETOPO1 [6]. The regression analysis is tightly connected to the isostatic compensation theory, and is fulfilled considering the equivalent topography instead of the topography, so calculations are transparent to oceanic and continental areas [2, 5]. The decorrelation of Bouguer values with equivalent topography nearly eliminates the signal of the isostatic crustal root. In case of isostatic compensation, the topographic gravity signal is slightly greater than that of the isostatic root. Therefore the gravity anomaly correlates slightly to topography, also in the case of full isostatic compensation. The decorrelation of free air anomaly with topography reduces this signal. The residual is very similar to that of the decorrelated Bouguer field. We use the seismic Vp velocity to identify the presence of a deep lithospheric root. The global tomographic model LLNL-G3Dv3 [7] gives Vp velocities at a 1° grid resolution for upper mantle, and at 2° grid resolution for the lower mantle. We consider the slices of upper mantle up to a depth of 355km.

3. BIUNIVOCAL RELATION BETWEEN GRAVITY AND CRUSTAL DENSIFICATION

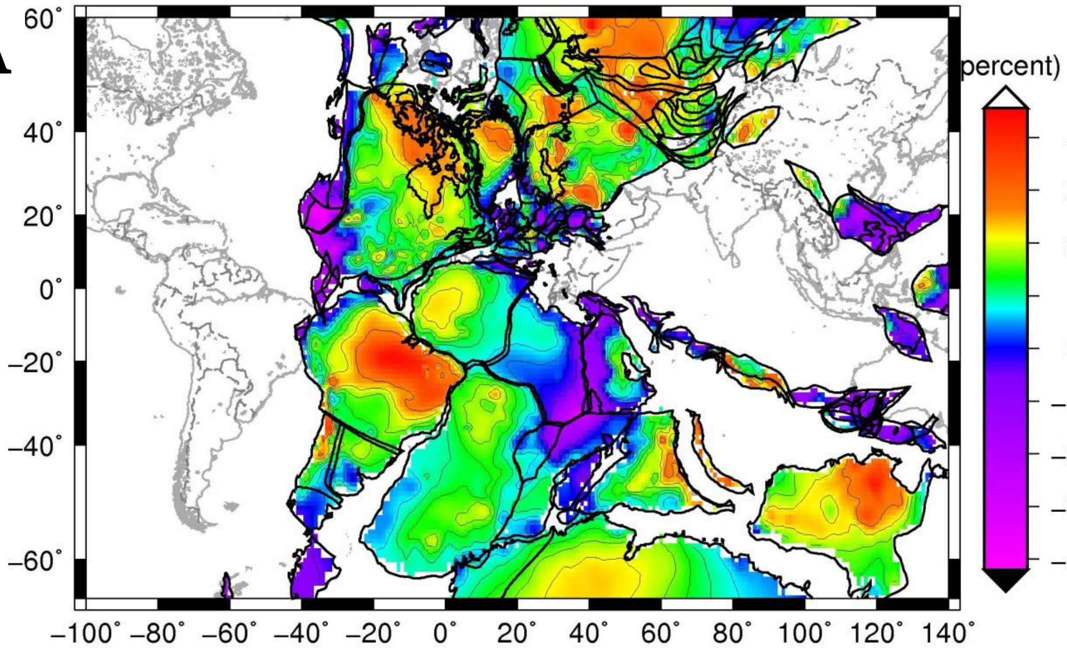
The GOCE fields have been shown to have sufficient resolution to detect crustal scale geologic features. Geologic events induce rock densification when they involve metamorphic rock transformation or magmatism. Examples are orogens, subduction metamorphism, Large Igneous Provinces (LIP), magmatic arcs, uplifted lower crust, aborted rifts affected by rift magmatism. These processes can have occurred any time in Earth history and are an integrated constituent of today’s continental crust. They affect the entire crust on the order of 100km across and several 100km along the feature, typically. The size is therefore compatible to features detectable with the GOCE fields, be it gravity field or gradient tensor fields. These features can be inferred on the Earth surface only partially, either because the lead metamorphic or magmatic rocks outcrop only in limited places or because they have been covered by later sedimentation. The topography may have been eroded, so that topographic evidence is limited. Continuity along the entire feature is seldom available, so that distant isolated rock samples of similar age and petrology, are used as evidence for continuity of a crustal scale geodynamic event. An example is the hypothesized 2500km long Ediacaran orogen which has been perceived from interpolation of isolated rock samples in Brazil and West Africa [8]. The analysis of the rock samples demonstrate Ultra High Pressure Metamorphism (UHP), which produces rocks of high density. It is impossible that such an extended feature, comparable in size to the Himalayan orogen arc, would only locally alter the temperature and pressure conditions of the crust to produce locally the UHP rocks. Rather the UHP metamorphism must affect a portion of the crust that extends along the entire orogen. Since UHP rocks have a positive density with respect to average crust, this feature must generate a gravity high, extended over the entire length of the hypothesized orogen. Since GOCE has been demonstrated to be able to catch such signals, the GOCE products are a new tool to verify the validity of the hypothesized interpolation of isolated UHP rock sample as supporting evidence of a unique orogen. If the hypothesized feature lacks the continuous gravity signal, the presence of its continuity must be questioned. The lack of continuity of the gravity signal could only be explained with complete erosion and transportation of the UHP rocks. But then also geologically the continuity cannot be proved, due to lack of evidence. If presence of continuity is claimed, then the gravity signal must be present and must be continuous. For the case of the Ediacaran orogen the continuity is not obviously seen. The gravity signal confirms the UHP rocks where they have been found, as a positive gravity or gradient signal is found. The continuity of the signal must be investigated in greater depth.

3.1. Gondwana reconstructions

The reconstruction of the gravity and gradient fields to the position they had before continental breakup allows following the structures across continents. We consider the reconstruction of Gondwana, the most recent plate

Vp 30 to 150km at 255Ma

A



Vp 150 to 355km at 255Ma

B

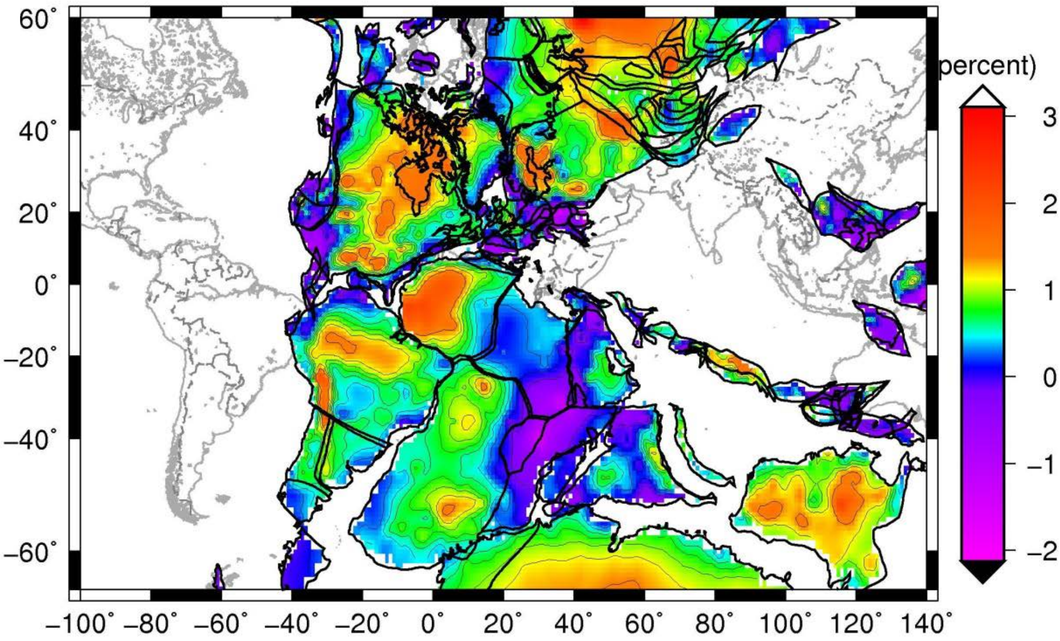


Figure 1. Averaged body wave velocity Vp rotated to Gondwana. Vp velocity modelLLNL-G3Dv3 [7]. *A) Shallow upper mantle layers between Moho and 150km depth. B) Deep upper mantle layers between 150km and 355km depth.*

amalgamation that united today's five continents (Africa, Americas, Eurasia, Australia, Antarctica). The reconstruction requires the knowledge of rotation poles through time of the continental fragments, about which exhaustive models exist that are based on palaeomagnetic records of plate rotation. In this study the definition of the outlines of the continental fragments as well as the rotation poles are based on the work of [9] and their successive updates. The reconstruction assigns homogeneous rotation to continental fragments. The fragments are defined on the basis of geological assumptions, observation of faults, sutures, lineaments demonstrating relative plate movement. Some fragments are not univocally defined and include subjective reasoning by the authors of the plate reconstruction. The reconstruction bases therefore on two equally important components, the outlines of the continental fragments and the rotation poles in time. To rotate the gravity, gradient and velocity we select the data values covering the continental fragment, and rotate each grid point. The ensemble of rotated data points is then interpolated on a new seamless grid.

3.2. Mantle Vp velocity layers

In order to define the craton root for further comparison with the gravity field we consider stacking and averaging of the depth levels of velocity. The aim is to create a map that distinguishes a cratonic root from the remainder mantle. The layers just below the Moho reflect temperature a lot and have a close correlation to the location of oceanic spreading centers and rifts. In order to identify the deep cratonic roots the lower layers of the upper mantle must be considered to distinguish them better from more superficial velocity variations. In order to enhance the signal we stack the layers and sum them up. Thickness of layers varies, so for each layer the velocity anomaly is multiplied by the thickness of the layer and then summed over the stack of layers and divided by the total thickness of the stacked layers. The resulting map gives the averaged velocity variations over the layers. In Fig. 1 the average velocity rotated to Gondwana for the superficial stack from the Moho to 150km and for the deeper stack from 150km to 355km is shown. It can be verified in the original publication [7] that the shallower layers strongly reflect the oceanic and continental crust and the mid ocean spreading centers.

In the Gondwana reconstruction we see that the positive velocity variation over continental areas is widespread. Comparing to the stacked velocity anomalies for the deeper layers, we find that they are hardly affected by the mid oceanic spreading centers (see on original publication), and show more focussed positive velocity anomalies in the continental areas. These correspond to the cratonic lithosphere roots, which we manage therefore to discriminate more clearly. The subducted lithospheric plates are seen as well, with linear increased velocity features (e.g. Andes subduction, Indonesia, Western Pacific Ocean subduction ring.

3.3. Positive Free Air Gravity anomaly residual field correlation to deep Vp outlines

Comparison of the free air gravity residuals to the deep cratonic roots identified by the increased Vp velocity reveals that the two quantities are anti-correlated in some cases. The correlation is subtle and it is not straightforward to demonstrate, but some patterns are recognizable in the two maps. We illustrate it here by zooming into North America and into the Africa-South American margin. Fig. 2 shows the residual free air gravity anomaly for North and South-Western Gondwana. North-Western Gondwana is occupied mostly by North America. Superposed are selected Vp isolines that define the direction outboard of the cratonic root. The color coding for the Vp percentage increase for North-Western Gondwana (grey: 1.6%, white: 1.3%, yellow: 1.2%, red: 1.0%, purple: 0.9%) has slightly lower values compared to South-Western Gondwana (grey: 2.0%, white: 1.2%, yellow: 1.0%, red: 0.6%, purple: 0.5%). The different color coding is due to the different levels of velocity perturbations for the two areas. The outer limits of the deep cratonic root is found by moving from the red isoline towards the purple isoline. The arrows give the direction that points outboard of the cratonic root.

The deep reaching lithospheric root in North America corresponds to a broad area of negative gravity values, that follow closely the pattern of the increased velocity, with its two arms pointing towards South-West and South-East. The increased gravity values fall outboard of the red and purple Vp isolines of near to 1% velocity increase. There are some exceptions to this rule, as in Longitude -20°, Latitude 5°. Another area that seems to fit the observation is in Scandinavia, where the more positive gravity values along Western Norway fall outboard of the deep lithospheric root.

For South-Western Gondwana the observations made in North-Western Gondwana apply partially as shown in Fig. 2b. The two conjugate margins of South America and Africa are lined with a positive gravity field which follows the outboard limit of the deep lithosphere roots identified by the red (0.6%) and purple (0.5%) isolines. Another area is the Arabian plate, with positive gravity and absence of increased Vp velocity along the western part of the plate, and high velocity and low gravity on the eastern side of the plate.

The Amazon is another nice example, where the borders of the deep cratonic root are lined with sharp linear gravity features.

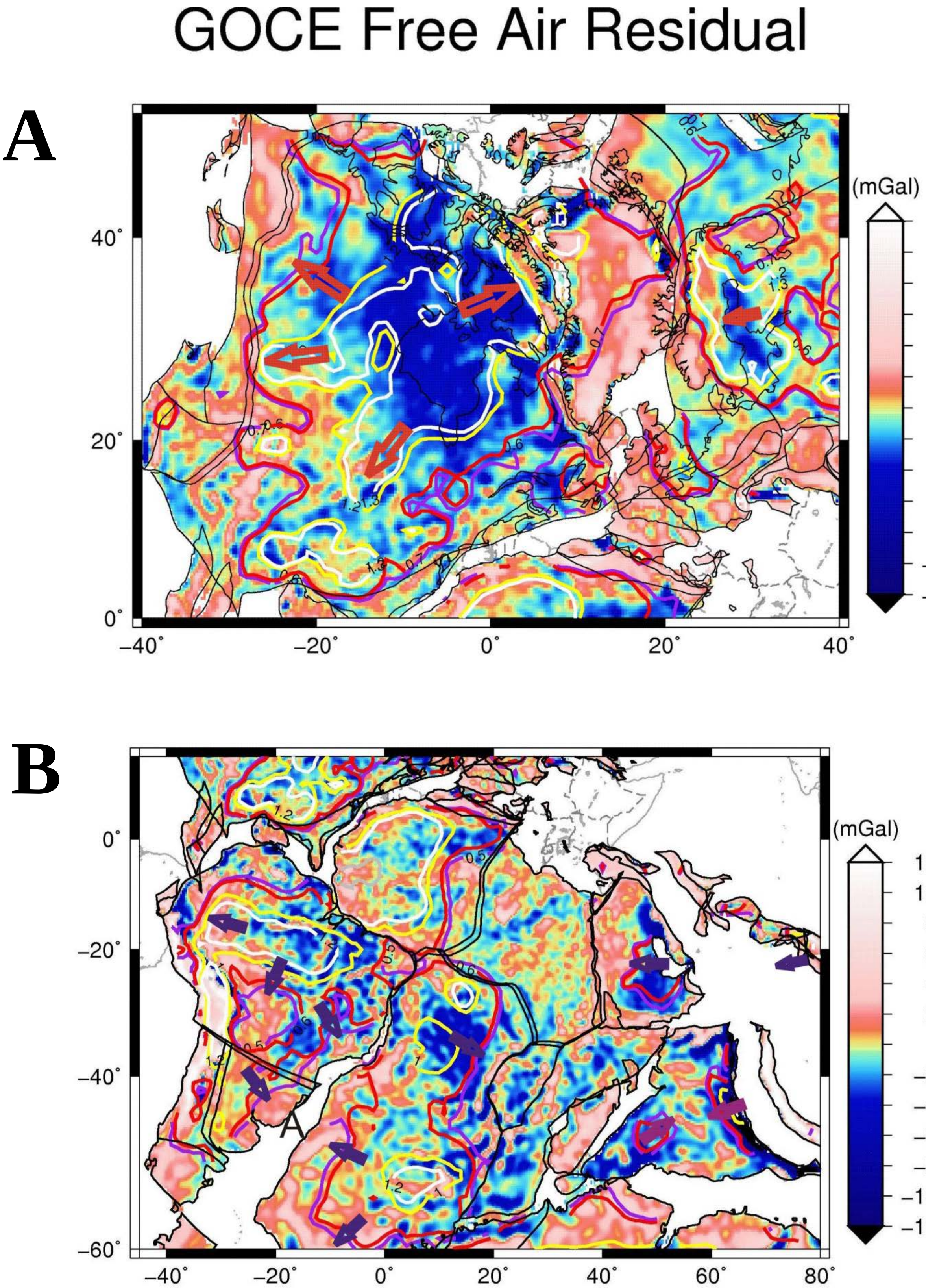


Figure 2 Residual Free Air Gravity Anomaly A) North-Western Gondwana (color map) with isolines of stacked deep upper mantle Vp velocities. Color coding for positive velocity anomaly: grey: 1.6%, white: 1.3%, yellow: 1.2%, red: 1.0%, purple: 0.9%. B) South-Western Gondwana (color map) with isolines of stacked deep upper mantle Vp velocities. Color coding for positive velocity anomaly: grey: 2.0%, white: 1.2%, yellow: 1.0%, red: 0.6%, purple: 0.5%. The arrows give the direction outboard of the deep lithosphere root.

4. DISCUSSION

The link between the crustal magmatic intrusions and deep lithospheric roots resides in the melting process that accompanies upwelling asthenosphere. Reference [10] combine a chemical thermodynamic model with a multiphase geodynamic model to describe early melting during opening and spreading of the lithosphere. Assuming a cold lithospheric root (1100°C) and a hotter underlying asthenosphere (1470°C) the stretching of lithospheric mantle induces upwelling of the asthenosphere. Melt continuously accumulates at the upper portion of the upwelling mantle, until the area occupied initially by lithospheric mantle is replaced by asthenospheric mantle.

At this stage melt is extracted to the surface. It can be extrapolated that the dissociation of two cratonic lithosphere roots cause an analogous upwelling with melt creation, which does not affect the lithospheric roots, but focuses the melt at the border of the cratons. This scenario would be repeated during successive cycles of plate amalgamation and disruption, leading to a succession of rifting and magmatic processes at the borders of the lithosphere that has a deep root. The inside of the craton would be much less affected by the intrusions, because the melting asthenosphere would not penetrate the thick root. The magmatic intrusions into the crust generate a positive density anomaly due to the higher density of the intrusion respect to the average crustal density. Consequently a positive gravity anomaly is observed. This type of scenario could be invoked to explain the observation that there is an increased amount of positive gravity anomalies outboard of the deep lithosphere roots, and a preferentially lower level of gravity anomaly above the deep lithosphere root. The thick lithosphere root could induce a negative gravity signal due to density lower than the asthenospheric mantle. This would indicate an anomaly in the relation between velocity and density for Archean lithosphere, in that increased Vp velocity would correlate with reduction in density. Or else the reduction in density is to be searched in the thick cratonic crust or in the sublithospheric mantle.

5. CONCLUSIONS

The gravity anomaly variations (or free air gravity values) are due to density variations throughout the entire Earth section, from the core-mantle boundary, through the mantle, across the crust-mantle or Moho boundary, up to crustal density variations. We analyze the global scale properties of the gravity anomaly residual. Here the observations have been reduced by the linear regression factor with equivalent topography to reduce the correlation with topography. The gravity field is compared to the tomographic model of mantle seismic Vp velocities up to the depth of 355km. The tomography model identifies localized deep lithospheric roots which are attached to the oldest fragments of crust, almost as old as Earth history, between 2000 and 4000 Ma. These oldest areas, termed cratons or platforms are considered to be stable, in the sense that they have not been affected in their interior by tectonic events younger than about 2000Ma. The tectonic activity is confined to the border of the platforms. The comparison of the gravity field and the seismic velocity at depth shows that the two quantities are anti-correlated in some areas. This observation is accentuated when reconstructing the tectonic plates to the position they had in Gondwana. We find that outboard of the deep lithospheric roots defined from seismic tomography positive gravity anomalies are found. The positive anomalies are due to an increased density, which is either due to metamorphism or magmatism, both processes generating rocks with high density. We interpret this finding with the fact that the deep cratonic roots prevent magmatic upwelling into the crust above the root, focussing the magmatism at the cratonic border. The lithospheric root protects the overlying crust from tectonic events that lead to crustal densification. In some cases as the Amazonas, where the velocity mantle perturbation is relatively large, the border of the lithospheric root is lined by a well defined linear gravity lineation on three sides of the root. We conclude that the tectonic processes are controlled by the lithospheric roots which focus the asthenospheric flow along the border of the root, due to their increased viscosity. One scenario could be the upwelling asthenosphere driven by thermal buoyancy induced by a stretching lithosphere, or by the separation of close lithospheric fragments. The large scale gravity lineaments seen with the resolution of GOCE could reside in the crust in the form of intrusions and underplating, without the need to have reached the surface to produce extrusive magmatism.

6. ACKNOWLEDGEMENTS

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