The Oka Carbonatite Complex, Quebec: deep structure from joint 3D gravity and magnetic data inversion

Sander Geophysics

Abstract

The deep structure of the Oka Carbonatite Complex has been investigated by utilizing data from an airborne gravity survey and a radiometric and aeromagnetic survey both flown by Sander Geophysics. A prominent gravity high anomaly is attributed to the carbonatite and silicate rocks that make up the Complex which are denser than the host anorthosite and gneissic rocks. Strong magnetic anomalies define two intrusive centres of the Complex and also show internal compositional variations with magnetic annular rings around central, less magnetic cores for each intrusive centre. Forward modelling and 3D inversion of the gravity and magnetic data have been implemented to image the deep structure of the Oka Complex. The results support a cylindrical shape for the Complex with some minor near surface fanning out of the structure limited to its southeastern edge. While honouring known formation densities of the Oka Complex rocks, the model calls for high bulk magnetic susceptibilities with a mean of 0.3 SI to fit the observed magnetic anomalies.

Introduction

A chain of prominent hills cutting east-west from Montreal across the St Lawrence lowlands was identified by Adams (1903) as the Monteregian Hills Province. They represent erosional remnants of alkaline and granitoid plutons. The province was extended farther west and east by Gold (1967) to include Lower Cretaceous dykes, sills, plugs and pipes and fissures with alkalic and carbonatitic affinities. A deep seated fault uninfluenced by overlying crustal tectonic units is assumed to have controlled their emplacement (Gold, 1986). A progressive compositional change in the plutons occurs from silica-saturated rocks in the eastern part to highly undersaturated rocks and carbonatites in the west while iron content increases from west to east (Gold, 1986). The Oka Carbonatite Complex is one of the westernmost plutons.

The Oka Complex is a composite pluton emplaced into anorthosite and gneissic rocks. It consist of both carbonatite rocks and undersaturated silicate rocks whose relative emplacement history is uncertain (Chen and Simonette, 2014). Gold (1967) described it as two close intrusive centres with a distorted figure 8 shape in plan view (Figure 1). Each intrusive centre has an annulus of carbonatite and alkalic silicate rocks and a central plug of carbonatite. Gold (1967) also mapped dolomitic carbonatite dykes and alnöite breccia pipes which cut through the Complex. A zone of fenitization of the gneissic country rocks is mapped around the Complex (Figure 1).

A consensus in the emplacement of the Oka Complex is its protracted magmatic history spanning over 10 million years (Chen and Simonetti 2014). According to Chen and Simonetti (2014), the long history could either be a result of protracted magma differentiation in a closed system from a single melt generation or alternatively periodic small melt generation each undergoing independent differentiation paths. Chen and Simonetti (2014) present petrological and geochronological evidence in support of the latter. Chen and Simonetti (2014) also mention competing hypotheses for the formation of the Monteregian Hills Province, one related to intraplate melting in an extensional setting associated with the opening of the Atlantic ocean and the other, the result of the passage of the North American plate over the Great Meteor hotspot. They conclude that their results favour the former and that more studies are required to completely discount the hotspot hypothesis.

More attention has been focused on the Oka Complex than the other plutons in the Monteregian Hills Province, both because of its unusual rocks and ringlike structure, and for economic reasons. Niobium and rare earth mining operations have been carried out in the past, and there is economic potential for restarting operations in the present. Carbonatite and alkaline intrusive complexes as well as their weathering products are the primary sources of rare earth elements

The deep structure of the Oka Complex has been investigated by utilizing data from an airborne gravity survey and a radiometric and aeromagnetic survey both flown by Sander Geophysics spanning or targeting the Oka Complex. Forward modelling and joint 3D inversion of the gravity and magnetic data have been implemented to image the deep structure of the Oka Complex.

Geophysical data

In 1996 SGL conducted a radiometric and aeromagnetic survey for the Geological Survey of Canada over a 14 km by 10 km block which covered the Oka Complex. Data were acquired with a line spacing of 200 m at a bearing of N16°W and a mean clearance of 137 m. Final data were gridded with a 50 m grid cell size. In 2015 SGL conducted an AIRGrav survey (gravity and magnetic) over the Oka Complex with a flight line spacing of 500 m and control line spacing of 2000 m. A line direction of N45°E was used with a nominal survey altitude of 305 m and the data were gridded with a 100 m cell size. A rectangular crop of the data sets centred on the Oka Complex (Figure 2) was used in the modelling. The higher resolution magnetic data set was used with some padding in the southwestern corner using the lower resolution AIRGrav survey magnetic data.

Oka Complex rock densities from Gold et al. (1967) and presented by Thomas et al. (2015) were utilized (Table 1). The single value densities assigned to each of the country rocks (i.e. gneiss, anorthosite and fenite), were used in the models. Though densities for different Oka rocks were available (Table 1), no indication of percentage volume of the units is available to allow for combining them to get bulk densities of averaged units of the Complex needed in the modelling. Averaging the densities of rocks listed as alkaline rocks with equal weighting gives 2.93 g/cc and those listed as carbonatites gives 3.00 g/cc. These averages were taken to represent the density for the annular rings and the carbonatites cores respectively. An error of 0.05 g/cc was assumed for all densities assigned during the inversion process. It is apparent that the Oka rocks are almost all denser than the host anothosite and gneissic rocks and would therefore produce the observed positive gravity anomaly.

	Density - kg/m^3
various tills and clay	1900 - 2380
late lamprophyre dykes	2840
Alkaline Rocks	
alnoite	3090
alnoite breccia	2750
jacuparangite	3140
melanite urtite, melteigite, & wollastonite-melanite ijolite	2880
biotitized ijolite & biotite replacement rock	3060
microijolite and ijolite	2890
micourtite and juvite	2700
okaite group	2970
Carbonatites	
monticellite carbonatite	2950
dolomite carbonatite	2960
soda pyroxene carbonatite	3090
coarse-grained carbonatite	2880
very coarse-grained carbonatite	2840
melilite carbonatite	3020
niocalite carbonatite	2900
magnetite-apatite carbonatite	3410
Country Rocks	
anorthosite	2740
fenite	2700
gneiss	2750
Carbonatite Ore	
carbonatite ore mined (using 11.5 cu.ft/ton, volume mined, & continuous weighings from conveyor belt)	2790
carbonatite ore & waste from pit area	2800
After Gold et al. (1967)	

Table 1 Rock densities from Gold et al. (1967) in Thomas et al. (2015)

No magnetic susceptibility measurements were available for rocks from the Complex but Chen and Simonetti (2014) gave volume percentages of magnetite in the main rock types of the Complex. These vary from 5 to 10 % magnetite for carbonatite, Okaite, and alnöite and 2 to 10 % for jacupirangite and 0 to 5 % for ijolite.

Overview of geophysical anomalies

A simplification of the geology map of Gold et al. (1967) was made for incorporation into GeoModeller (Figure 1). The mapped outer edges of the Complex and the fenite zone are maintained. The internal parts are merged and simplified into two zones; a carbonatite core for each of the two intrusive centres of the Complex and the rest represent merged annular rings around the cores.

Figure 2 shows the cropped data sets over the Oka Complex used in the modelling. In the gravity data (Figure 2 (a) and (b)) a large gravity high anomaly, over 10 mGal in amplitude, coincides with the surface expression of the Complex, with the northern intrusive centre of the Oka Complex occurring within the extent of this gravity high. This suggests a source body extending roughly vertically from its mapped surface expression. There is no obvious internal structure in the observed gravity high, which is consistent with the small difference between the measured average densities of the carbonatite and silicate rocks. The southern intrusive centre is mapped extending farther to the southeast than indicated by the gravity high anomaly. The gravity data suggest a limited depth extent at the south-eastern extremity compared to the rest of the Complex. This calls for a modification from the simple vertical cylindrical deep structural for the Complex, suggesting an upwards fanning out of the overall structure to its present day surface.

A neighbouring smaller gravity high anomaly to the southwest of the mapped Complex poses the question of its relation to the main intrusive. It has no surface expression and is smaller in amplitude and has been interpreted to indicate a deeper level intrusion.

A high amplitude magnetic anomaly (over 6 000 nT amplitude, peak to peak) is associated with the Oka Complex (Figure 2 (c) and (d)). The anomaly correlates well with the surface expression of the Complex, with a clear indication of the two cores of the Complex and the annular rings. The two carbonatite cores are imaged as being less magnetic compared to the annular silicate rings.

There is no magnetic anomaly associated with the neighbouring smaller gravity anomaly noted above. This would suggest that it is not associated with the Oka Complex which generally is composed of predominantly magnetic rocks.

Radiometric data (Figure 2 (e) and (f)) supports the geological mapping. The annular rings stand out with anomalous high count rates predominantly due to high thorium concentrations. Uranium concentration has some spikes within the annular rings while potassium concentration correlates with topography and shows subtle lows associated with the annular rings of the Complex.

Initial GeoModeller 3D Model

GeoModeller allows for the creation of a geological model that incorporates all available geological information, prior to running an inversion. Allocation of time to create a realistic initial geological model and to test its appropriateness through forward modelling is essential. Monte Carlo techniques also require start models that honour the dominant features in the observed data. The anticipated overall structure of the Complex is pipe-like similar to the Sokli Carbonatite Complex (Figure 1 (d)) in Finland (Vartiainen and Paarma, 1976). A pipe model, extending to over 10 km below sea level was created (Figure 1 (c)). The cut-off depth was selected simply to represent a depth at which model changes would fall below system noise.

The model was created by assuming the same structure of the Complex as mapped at the surface at number of progressively deeper horizontal sections and then interpolation of the geology in between. A number of preliminary alternative models with shallower depths to bottom of the Complex were also created for the purpose of assessing their feasibility through forward modelling.

Forward modelling

A GeoModeller model is defined by a set of equations from which a voxel model is created for use in the forward modelling and inversion. For the final models presented, a 100 x 100 x 85 voxet, with 85 voxels in depth, was created. This gave voxels with horizontal dimensions of 85 m x 85 m but with varying (vertical) thickness. Thirty two voxels with a thickness of 20 m cover the model from the surface to a depth of 140 m below sea level and then the thickness increases with each voxel step from 30 m by a factor of 1.05 to a depth of 10 km.

The final results of forward modelling are presented in Figures 3. Measured densities reported above were assigned to the formations. There are no magnetic susceptibility values available except for the up to 10 % magnetite in the Oka rocks (Chen and Simonetti, 2014). A value of 0.3 ± 0.05 SI, after a number of forward modelling iterations, was assigned to the annular ring as the only magnetic unit with all other formations assumed to be non-magnetic.

In map form the calculated fields for all models fit the shape of both the measured gravity and the magnetic data and supports the surface mapping. The discrepancies are primarily in anomaly amplitudes. Barring the smaller neighbouring gravity anomaly to the southwest, which has not been incorporated into the initial model, the calculated gravity anomaly for the pipe model comes very close to the observed field. However a slightly higher density contrast would improve the fit if the shape is not modified, or the volume of the Complex could be slightly increased. Thus the pipe model sets a lower limit to the volume of Oka rocks required to fit the observed data.

Similar results are obtained with the calculated magnetic anomalies. The pipe model generates magnetic anomaly amplitudes comparable with the observed data keeping in mind that the model utilizes a rather high bulk susceptibility of 0.3 SI for the annular ring rocks of the Oka Complex.

The results from the forward modelling indicate a structure of the Complex that predominantly maintains the same size as its surface expression with depth.

Inversion

Inversion allows for additional modification of the 3D geological model which has been tested and modified using forward modelling to fit the dominant features in the observed data. Model improvements are then possible through exploration of plausible shapes and physical properties of the different model formations. This allows for an assessment of a degree of confidence in the final model and a sensitivity estimation to its different components. An unconstrained inversion is likely to produce a good fit to the observed data using geologically unrealistic models thus some degree of constraining is always essential. Constraining an inversion has to be supported by justifiable a priori geological information and formation physical properties. Constraining without justification earns the common label of inversion “giving you what you want".

Monte Carlo techniques require starting models that honour the dominant features in the observed data. After ensuring that the model honours the main structures, GeoModeller has a multitude of initial settings that control the inversion process to allow available geological information and rock geophysical properties and their associated data errors to be incorporated into the inversion process. These implement geology tests which limit variations to the initial mode and are then followed by geophysical misfit tests. A commonality factor is used to limit the geological changes by maintaining a percentage overlap with the starting model. A shape ratio is used to limit the degree of roughness and variation in formation shape. A volume ratio limits formation volume changes. The process of setting and tuning the multitude of options available can be a daunting task for an inexperienced user relying on evaluating the inversion results to assess the appropriateness of initial settings.

With the fairly high degree of confidence in the pipe like model for the Oka Complex and the decent agreement with the observed gravity and magnetic data from forward modelling, a commonality factor of 80% overlap with the initial model, a shape ratio centred on 30% rougher for the predicted geology and a volume factor centred on 30% increase in volume were employed. The shapes of the carbonatite cores of the Complex were fixed though their density and magnetic susceptibilitywere allowed to change. Gravity only inversion is considered better suited for inverting for volume and mass while magnetic only inversion is better suited for depth to top and body orientation.

Figures 4 (a) and (b) present the observed gravity and magnetic anomaly data while Figures 4 (c) and (d) present gravity only and magnetic only inversions grids respectively. Gravity and magnetic anomaly grids from joint inversion of the data sets are present in Figure 4 (e) and (f) respectively. In order to highlight the anomaly amplitude differences, data along a profile are presented in Figure 5 (a) and (b). Associated 3D models are presented in Figure 5 (c) and (d).

It is apparent that the gravity only or magnetic only inversions produced better fits to their associated observed data. The joint inversion produced a smoother model with a poorer fit particularly in the higher frequency signal in the data. All the models generally support the pipe model. The mapped southeast limit of the Complex with no associated gravity high is modelled with a shallow depth to bottom. The isolated smaller gravity high in the south western corner of the area is modelled as a separate body with a depth to top of about 1 km.

Conclusions

A gravity high anomaly associated with carbonatites and silicate rocks of the Oka Carbonatite Complex defines the gravity signature of the Complex. With almost no difference in densities between averaged carbonatites and silicate rocks within the Complex the gravity data only maps the overall structure of the Complex.

A high magnetic anomaly associated with the annular rings of the two intrusive centres of the Complex dominate the magnetic signature. Though reported magnetic susceptibility measurements suggests both carbonatites and silicate rocks are magnetic, the observed data suggest the cores of the two intrusive centres which are predominantly carbonatite are less magnetic. It is possible that the carbonatite in the annular ring are more magnetic than those in the core, or that the silicate rocks which are predominantly in the annular rings dominate the magnetic signature. Higher bulk magnetic susceptibilities than currently reported are required to produce a fit to the observed magnetic anomalies.

Forward modelling and 3D inversion of the gravity and magnetic data support a cylindrical shape for the Complex with some minor near surface fanning out of the structure limited to its south-eastern edge.

A neighbouring gravity high to the southwest of the mapped Complex has been modelled as a separate intrusive with a 1 km depth to top extending to depth and maybe even merging with the Complex at depth.

References

Adams, F. D. 1903. The Moteregian Hills – A Canadian Petrographic Province. Journal of Geology, 11, pp. 239-282.

Chen, W. and Simonetti, A. 2014. Evidence for the Multi-Stage Petrogenetic History of the Oka Carbonatite Complex (Québec, Canada) as Recorded by Perovskite and Apatite. Minerals 2014, 4, 437-476; doi:10.3390/min4020437.

Gold, D.P. 1967. Alkaline ultrabasic rocks in the Montreal area, Quebec. In, P. J. Wyllie, Ed,., Ultrama:fic and Related Rocks. John Wiley and Sons, Inc., New York, pp. 288-302.

Gold, D.P., Eby, G.N., Bell, K., & Vallee, M. 1986. Carbonatites, diatremes, and ultra-alkaline rocks in the Oka area, Quebec. Geological Association of Canada, Mineralogical Association of Canada, Canadian Geophysical Union, Joint Annual Meeting, Ottawa '86, Field Trip 21 Guidebook, 51 p.

Thomas, M. D., Ford, K. L., and Keating, P. 2015, Exploration Geophysics for Intrusion-related rare metals. KEGS PDAC Symposium 2015, Exploration for Strategic Minerals.

Vartiainen, H. and Paarma, H. 1979. Geological Characteristics of the Sokli Carbonatite Complex, Finland. Economic Geology. Vol. 74, pp 1296-1306.

FIGURES

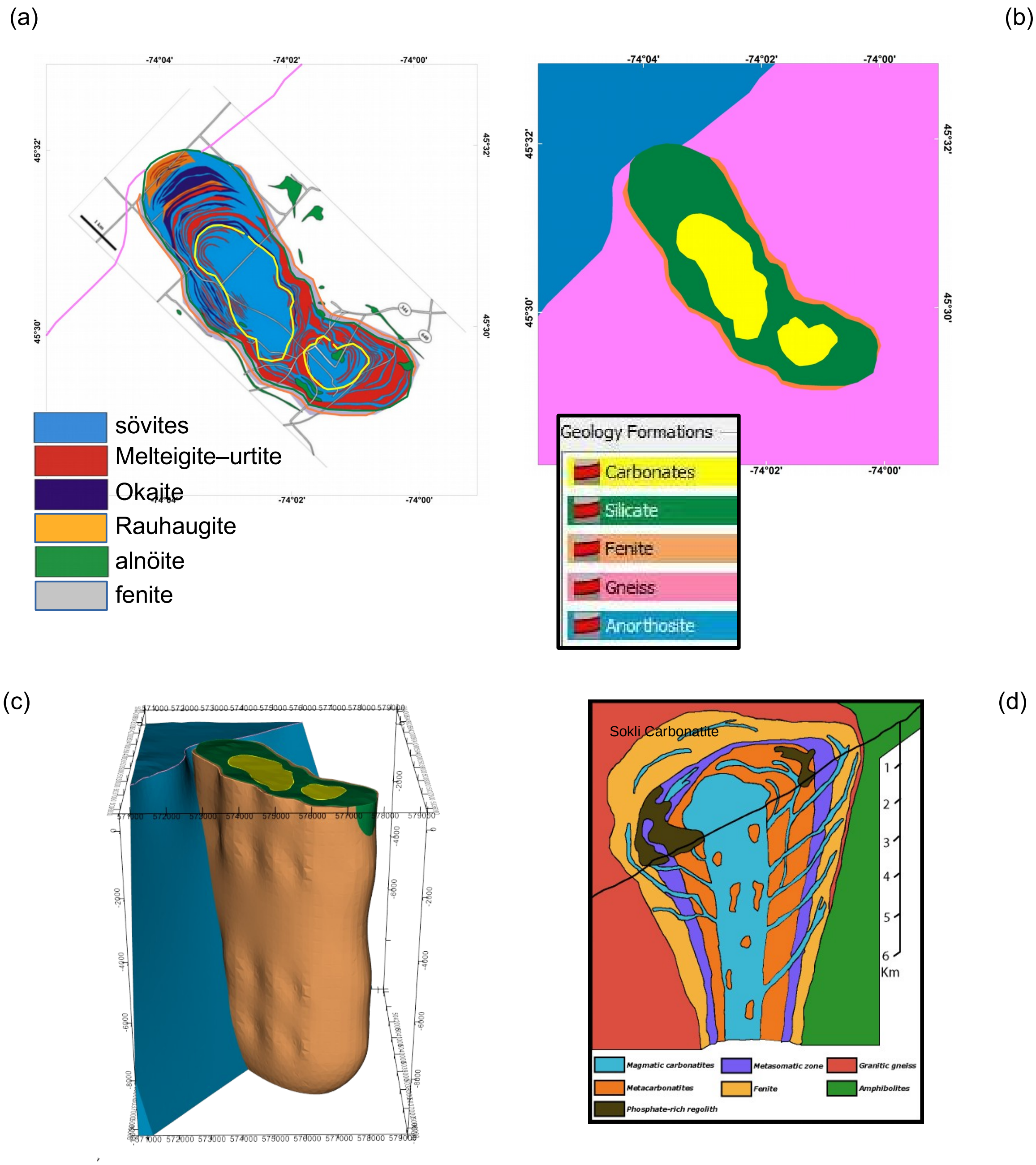

Figure 1 (a) Oka complex surface geology (Gold, 1986) (b) simplified surface geology (c) 3D model (GeoModeller) (d) Sketch of Sokli complex (Vartiainen and Paarma, 1976)

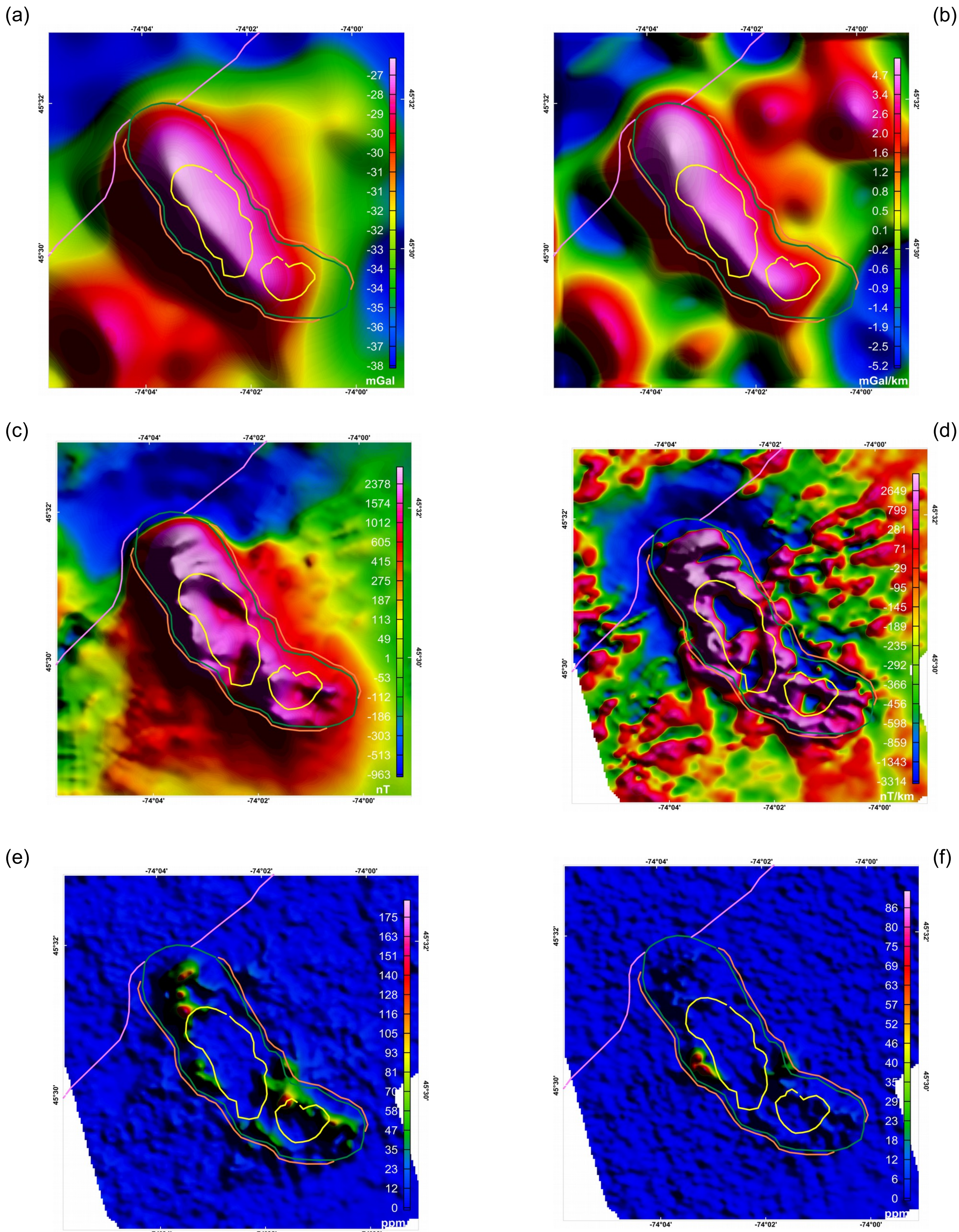

Figure 2 (a) Measured Bouguer gravity (b) first vertical derivative of Bouger gravity (c) magnetic anomaly (d) first vertical derivative of the magnetic anomaly (e) Thorium equivalent concentration (f) Uranium equivalent concentration

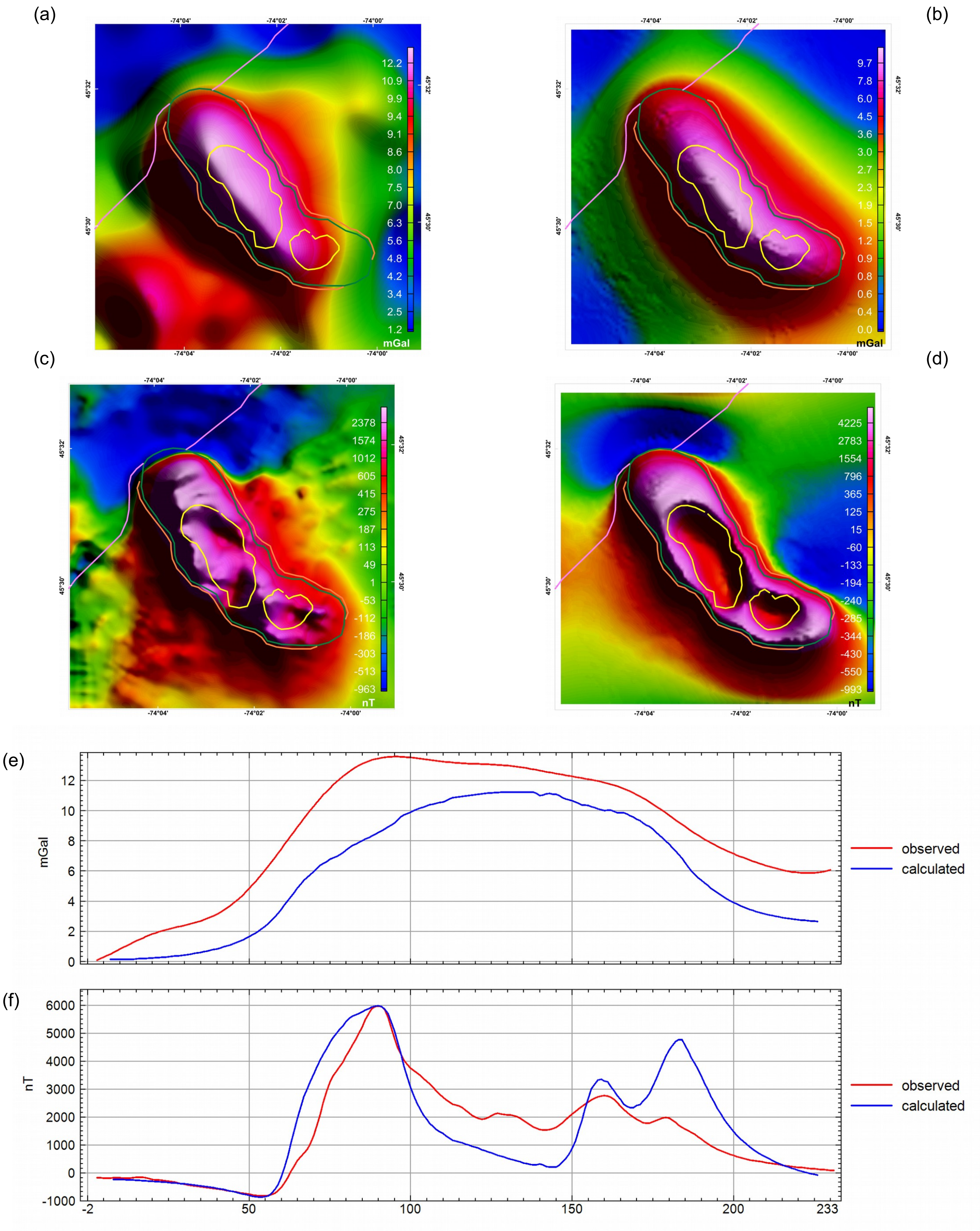

Figure 3 Pipe model: (a) measured Bouguer gravity (b) calculated Bouguer gravity (c) measured magnetic anomaly (d) calculated magnetic anomaly (e) gravity profile (f) magnetic profile

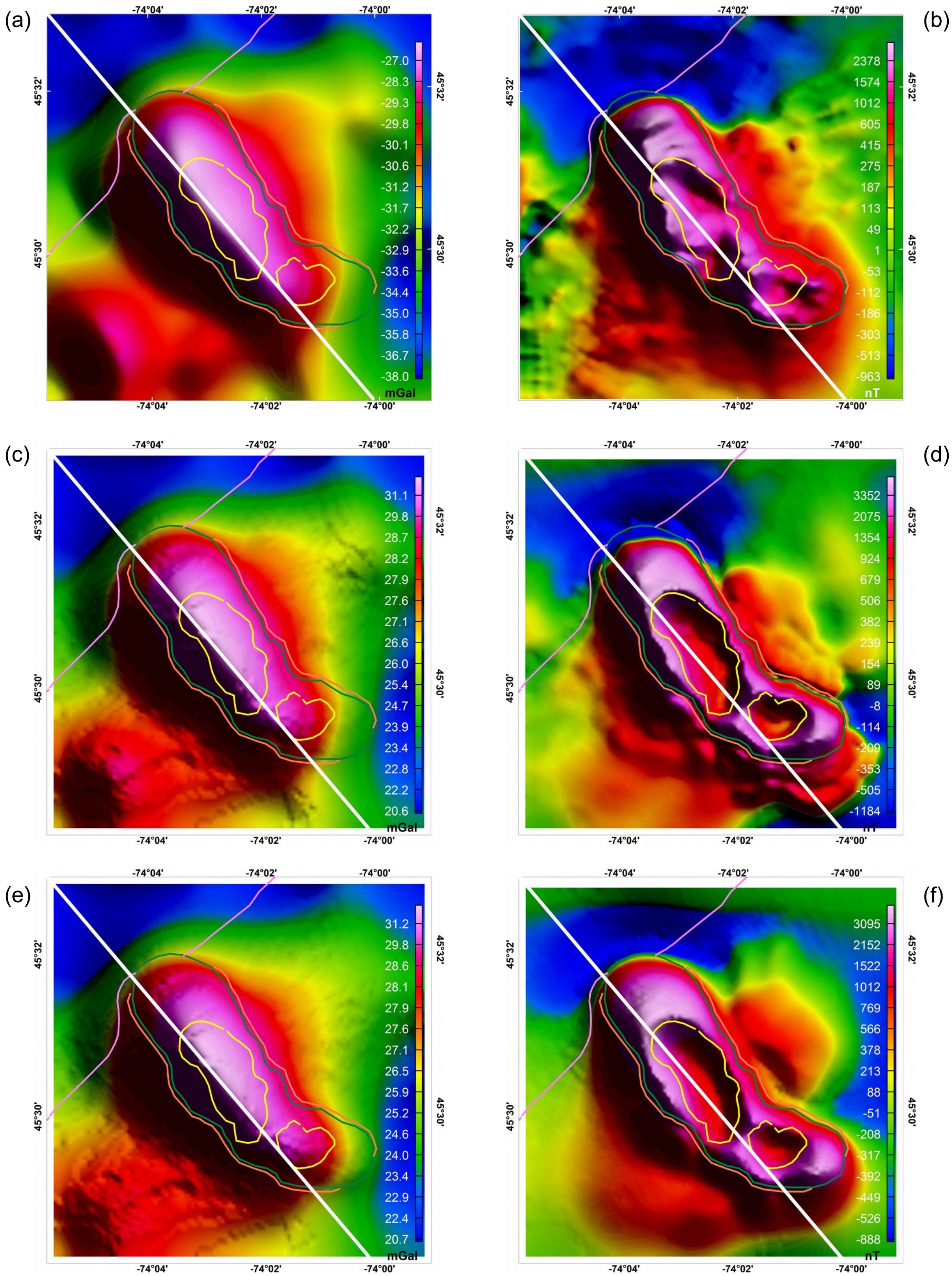

Figure 4 Inversion results grids. (a) Measured Bouguer gravity (b) measured magnetic anomaly (c) calculated Bouguer gravity from gravity only inversion (d) calculated magnetic anomaly from magnetic only inversion (e) joint inversion calculated gravity (f) joint inversion calculated magnetic anomaly. Location profile in Figure 5 marked.

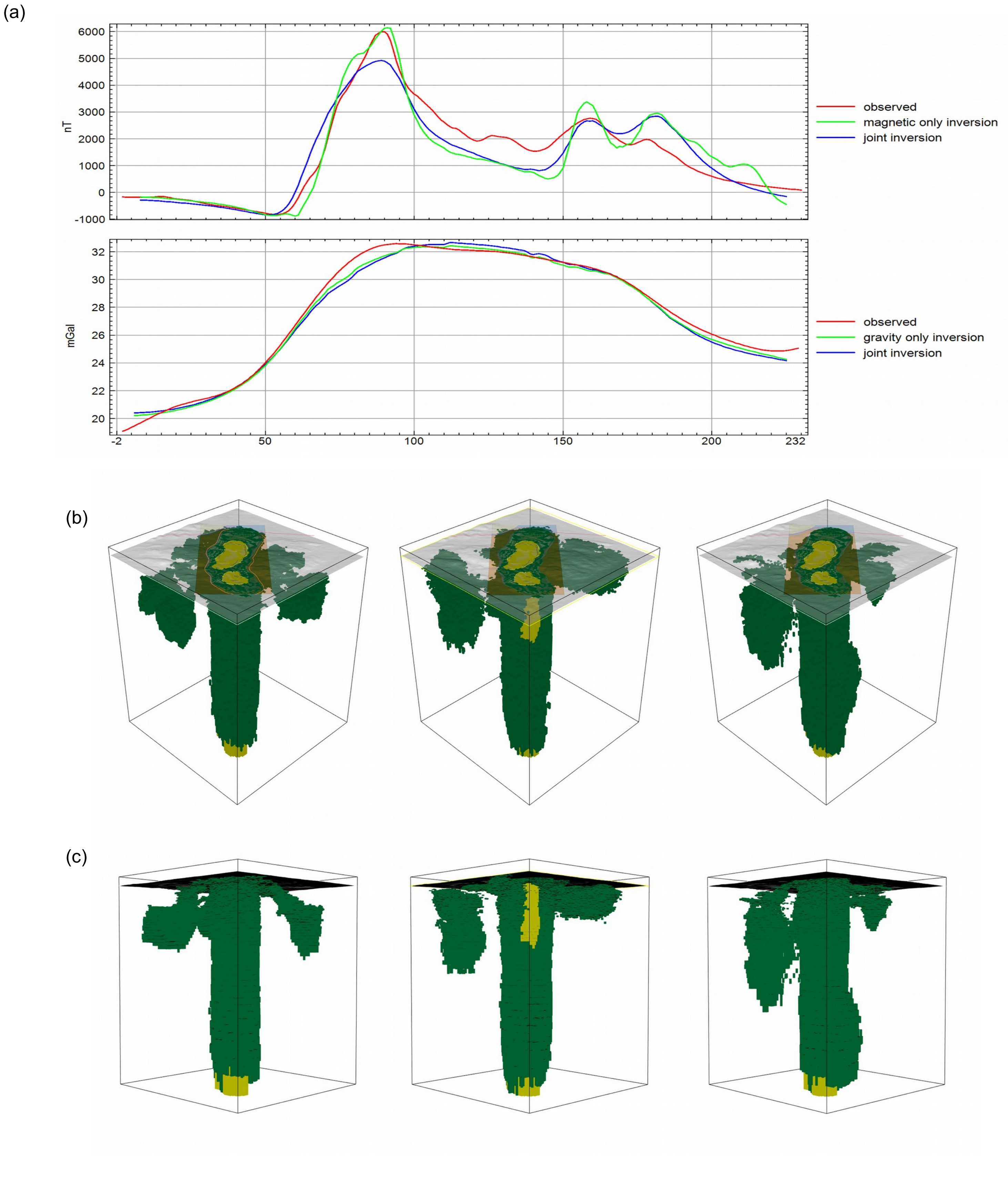

Figure 5 (a) Profile with observed data in red, gravity or magnetic only inversion in green and joint inversion in blue. (b) and (c) 3D views of inversion results showing silicate rocks in green and carbonates in yellow. Images on the left are from magnetic data only inversion, in the middle images from gravity data only inversion and images on the right are from joint gravity and magnetic data inversion. All figures have no vertical exaggeration.