Environ Geol (2005) 47: 889–897
DOI 10.1007/s00254-004-1198-6

ORIGINAL ARTICLE

C. Prezzi
M. J. Orgeira
H. Ostera
C. A. Vásquez

Ground magnetic survey of a municipal solid waste landfill: pilot study in Argentina

Received: 18 July 2004
Accepted: 23 October 2004
Published online: 26 January 2005

C. Prezzi · M. J. Orgeira
C. A. Vásquez
CONICET, Instituto de Geofísica Daniel Valencio, Dpto. de Cs. Geológicas, FCEyN, Ciudad Universitaria, Pabellón 2, 1428 Buenos Aires, Argentina

C. Prezzi · M. J. Orgeira · H. Ostera
FCEyN, Depto. de Cs. Geológicas, Universidad de Buenos Aires, Pabellón 2, 1428 Buenos Aires, Argentina

C. Prezzi (✉)
Alexander von Humboldt Fellow, Institut für Geowissenschaften, Abteilung Geophysik, Christian Albrechts Universität, Otto Hahn Platz 1, 24118 Kiel, Germany
E-mail: prezzi@gl.fcen.uba.ar
Tel.: +54-11-45763329
Fax: +54-11-47883439

H. Ostera
CONICET, INGEIS, Ciudad Universitaria, 1428 Buenos Aires, Argentina

C. A. Vásquez
CBC, Universidad de Buenos Aires, Argentina

Abstract This paper shows the results of a ground magnetic survey carried out to study solid waste landfills. The area located southward of Gualeguaychú town was chosen as a pilot case. This zone was selected considering the available knowledge about the cessation of operations, and the interest of the local authorities in verifying the existence of anomalies indicative of possible dangerous pollutants. The total magnetic field was measured along six profiles, and the corresponding anomalies were calculated. The profiles were modelled in 2.5 D, and along them Euler's deconvolution was used to estimate the depth to the sources. The first and the second derivatives of the residual magnetic field were calculated, in order to sharpen the anomalies. Our interpretation suggests that the characteristics of the modelled bodies and the magnitudes of the detected anomalies do not indicate the presence of drums in the sanitary infill.

Keywords Ground magnetic survey · Solid waste landfills · Pollution · Gualeguaychú · Argentina

Introduction

To achieve an appropriate management of solid waste, plans and projects at different scales should be created. The trend in most developed countries shows a decrease in the quantity of waste produced, and an important increase in the amount of recycling programs. The major part of the waste in new sanitary landfills comes from sources like homes, offices and small shops, which do not use and discard dangerous materials. However, such apparently inoffensive waste contains frequently toxic substances. As the discarded objects are decomposed or biodegradated, they release their pollutant constituents. These toxic chemicals mix with water and moisture forming the leachate. If such leachate is uncontrolled, it can migrate and contaminate groundwater and/or aquifers (US EPA 1988; Robinson and Gronow 1995; Statom et al. 2004). In some cases, solid waste is disposed in unsuitable and/or clandestine places, producing important environmental damage. In other cases, the regulations established in order to protect the environment in authorized waste landfills are not observed (Piratoba Morales and Fenzi 2000). Therefore, it is convenient to maintain an efficient and multidisciplinary monitoring system.

Geophysics has already been successfully applied to many waste landfills investigations (Benson et al. 1984). It has been used to define plumes, locate buried drums, detect boundaries of burial trenches and determine geological settings (Carpenter et al. 1990; Aristodemu et al. 2000; Meju 2000a, b). Some geophysical methods offer a direct means of detecting contaminant plumes and flow directions in both the saturated and unsaturated zones. Others offer a way to obtain detailed information about subsurface soil and rock conditions and buried objects. For example, metal detectors and magnetometers are useful in locating buried wastes. Ground penetrating radar can define the boundaries of buried trenches and other subsurface disturbances. Electromagnetic and resistivity methods can help to detect plumes of contaminants in groundwater (Pellerin 2002). Resistivity and seismic techniques are useful in determining geological stratigraphy and landfill structure (Carpenter et al. 1991).

Magnetic surveys detect characteristic magnetic signatures associated with different geologic settings, structures, buried objects, etc. Such anomalies arise from both an induced magnetization component, due to the earth's magnetic field interacting with the magnetic susceptibility of the object, and a permanent magnetization which depends on the metallurgical properties, and the thermal, mechanical and magnetic history of the specimen, and is independent of the field in which it is measured (Breiner 1973). In general, iron objects exhibit permanent and induced magnetizations. The harder the steel, the more permanent magnetization it possesses, which can be ten times or more than the induced magnetization (Breiner 1973). Usually, one cannot predict the orientation of the permanent moment of a buried object. A single large object may exhibit one single anomaly due largely to the permanent moment.

On the one hand, ground magnetic surveys are used to detect clandestine waste landfills. On the other, they are frequently applied jointly with other techniques to monitor the evolution of authorized sanitary landfills.

Magnetic surveys allow the detection of perturbations in the earth magnetic field caused by buried ferromagnetic objects like tools, drums and metallic waste in general. It is worth mentioning, that drums can contain very contaminating fluids. Magnetometry is one of the six techniques suggested by the US Environmental Protection Agency (Benson et al. 1984) to be used in environmental monitoring studies. This method is usually applied in Europe to determine the existence and location of drums containing dangerous substances (e.g. Dahlin and Jeppson 1995). The magnetic properties of steel drums have also been studied taking into account laboratory and field magnetic measurements (Ravat 1996).

This paper presents the first results of a ground magnetic survey applied to the study of sanitary landfills. A pilot case was chosen, considering the available knowledge about the cessation of operations, and the interest of the local authorities in verifying the existence of anomalies indicative of possible dangerous pollutants.

Background

The study area corresponds to the actual municipal sanitary landfill. It is located approximately 3 km southward of the town of Gualeguaychú, in the southeastern part of Entre Ríos province, Argentina (Fig. 1). This zone has an extensive road and railway network. There are many towns, but the most important one is Gualeguaychú. This town has a population of 80,000 inhabitants, and is the centre of numerous commercial, industrial and agricultural activities.

The activities in the sanitary landfill were suspended 4 years ago. The environmental protective works (if any) undertaken during the operation time are unknown. Nowadays, the operation of the waste deposit is carried out by the Municipal Urban Hygiene Enterprise, which solicited an evaluation of the actual state of the old sanitary landfill.

As part of the environmental study, a ground magnetic survey was carried out to determine the existence of anomalies that could indicate the presence of objects of long degradation or of potentially dangerous solid waste. It is important to mention that resistivity studies were also carried out in the same landfill (Sainato et al. 2004).

Geologic setting of the study area

This region forms part of the Chaco-Paranense plain. The most important outcropping formations are described as follows.

Lower Plio–Pleistocene Salto Chico Formation: This formation (Rimoldi 1963) is composed mainly of white and yellowish coarse and fine sandstones in the base, which gradually turn reddish at the top. Silt and clay layers of green colour and coarse and fine conglomerates are intercalated throughout the sequence (Iriondo 1980).

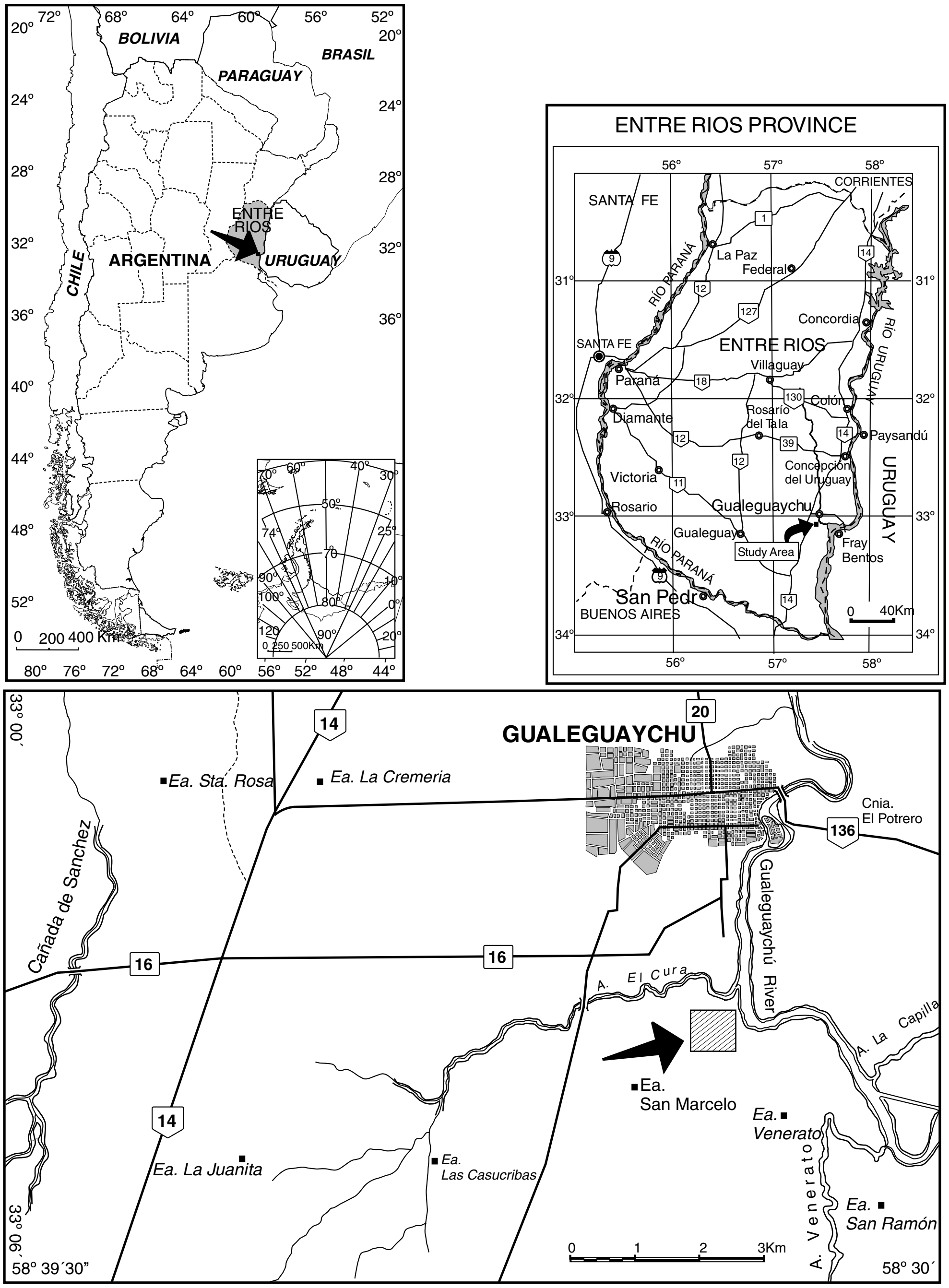

Fig. 1 Location map of the studied sanitary landfill (indicated by an *arrow* and a *shaded area*). It is located approximately 3 km southward of Gualeguaychú

A fluvial origin was proposed for this formation. Bossi (1969) suggested that it is of lower Plio–Pleistocene age.

Middle-Upper Pleistocene Punta Gorda Group: It corresponds to most part of the sedimentary cover in Entre Ríos. This group is composed mainly of brown, yellow and greenish silts and clays containing calcareous concretions, formed in lacustrine and eolian environments (Iriondo 1980). It has a thickness of 20–40 m, and constitutes the substratum of the sanitary landfill studied here. It was assigned a Middle-Upper Pleistocene age.

Holocene La Picada Formation: This unit is composed of brown medium to fine quartzose sandstones at the top, and of yellowish brown silts and clays at the base. It corresponds to the alluvial fills of previous fluvial valleys formed before the deposition of these sediments.

It is worth noting that the substratum of the sanitary landfill does not show any relevant characteristics, which could indicate the existence of susceptibility contrasts at intermediate depths. Therefore, the anomalies detected during the present ground magnetic survey would be exclusively caused by the different magnetic properties of the buried objects in the waste deposit.

Methodology

The ground magnetic survey was made using a Geometrics proton magnetometer. The total magnetic field and the magnetic vertical gradient were measured on 284 stations along 6 profiles, 3 trending approximately N–S, 2 trending approximately E–W, and 1 trending approximately 45°N–45°W (Fig. 2). The distance between the stations was 2 m. The profiles are between 50 and 150 m long (Fig. 2). The location of 2–5 stations along each profile was determined using GPS. The rest of the stations was situated along straight lines connecting the stations located by GPS along each profile. The 2-m distance between stations was determined using a non-magnetic tape measure. The magnetic vertical gradient measurements were completely noisy and could not be modelled or interpreted. They were discarded.

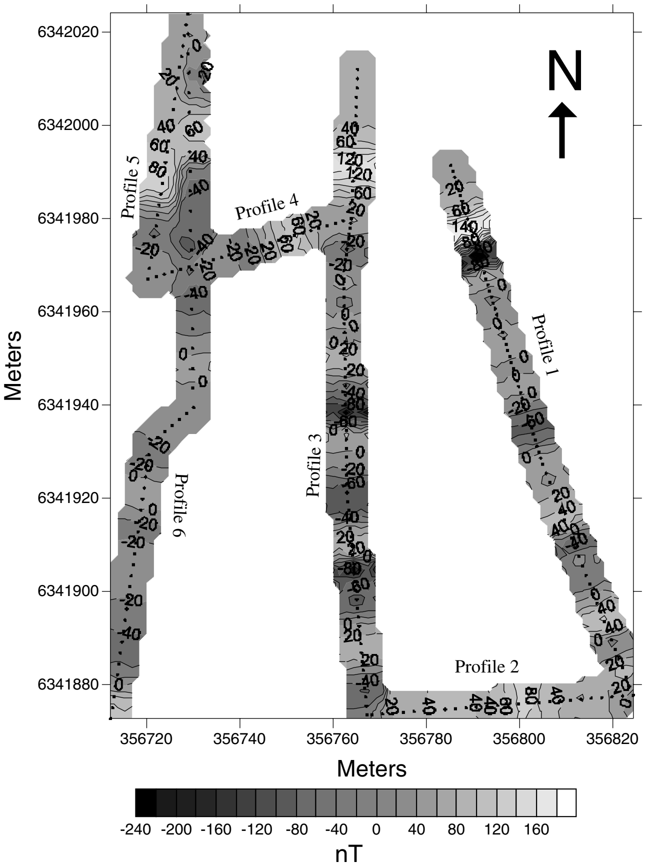

Fig. 2 Contour map of the detected anomalies (UTM coordinates). Each *dot* corresponds to a measured station. The magnitude of the anomalies decreases to the south

The measured values of the total magnetic field were corrected considering the diurnal variation of the earth's magnetic field. The location of the base station was determined using GPS (outside of the landfill at 33°03.052′S–58°32.036′W). The diurnal magnetic variation was recorded through the measurement of the total magnetic field in the base station approximately every 45 min. The value of the International Geomagnetic Reference Field was subtracted from the corrected data. The total magnetic field in Gualeguaychú has an intensity of 23,256 nT, an inclination of −35.4° and a declination of −7.2°. The resulting anomalies were plotted in a contour map (Fig. 2). A 2.5 D modelling was carried out along the profiles using the software Geomodel 2.01 (Cooper 2000) (Figs. 3, 4, 5, 6). A 2D model corresponds to a cross-section whose bodies are assumed to extend to infinity out of the plane of the section. A 2.5 D model is a cross-section in which an end correction is applied to the bodies to account for a limited extent out of the plane of the section.

The existence of induced and permanent magnetizations was taken into account in the models. The parameters used for each modelled body along each one of the presented profiles are shown in Table 1. In addition, Euler's deconvolution was applied along the modelled profiles in order to estimate the depths to the

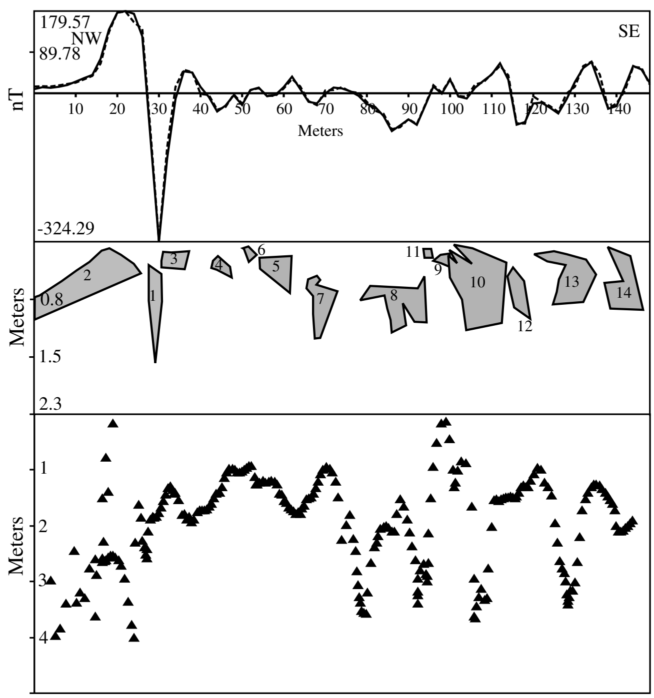

Fig. 3 Comparison of the measured and modelled anomalies along profile 1. *Solid (dashed)* line: measured (calculated) anomaly. See Table 1 for the parameters considered for each numbered modelled body. *Solid triangles* correspond to Euler's solutions. *Meters*: indicate depth below the surface

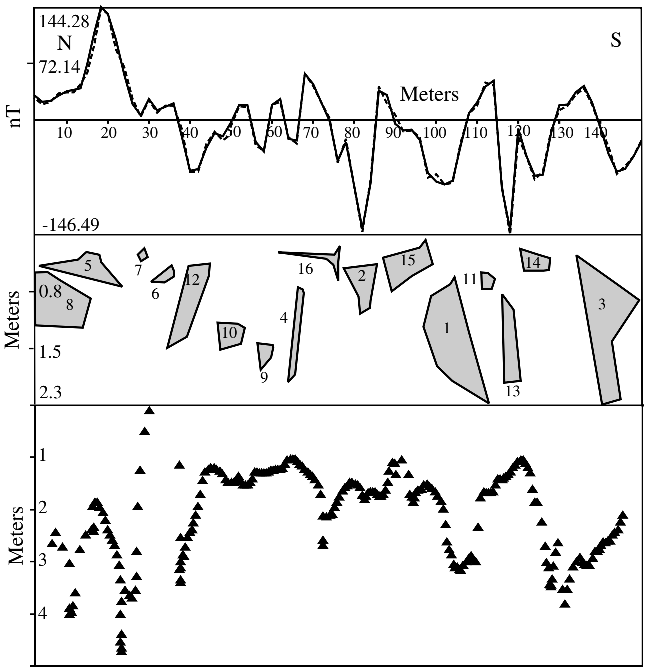

Fig. 4 Comparison of the measured and modelled anomalies along profile 3. *Solid (dashed)* line: measured (calculated) anomaly. See Table 1 for the parameters considered for each numbered modelled body. *Solid triangles* correspond to Euler's solutions. *Meters*: indicate depth below the surface

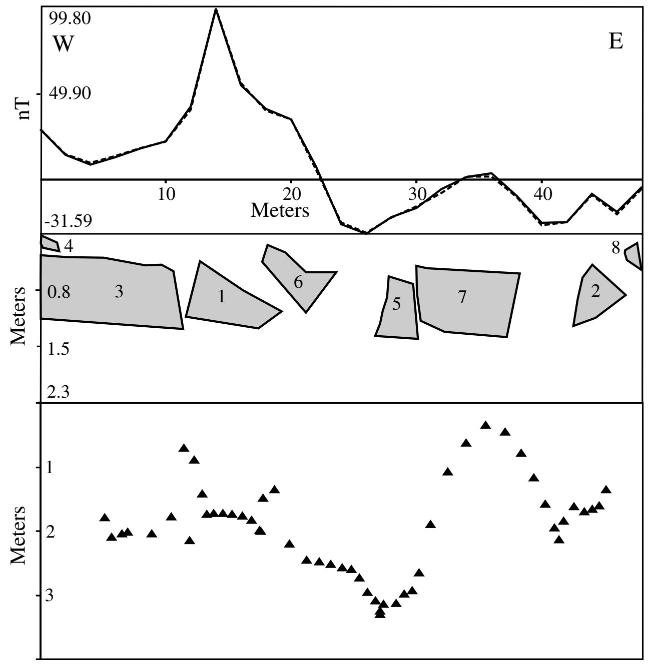

Fig. 5 Comparison of the measured and modelled anomalies along profile 4. It is worth noting that the interpretation along this profile should be regarded with care because of its west–east orientation (anomalies due to induced magnetization can not be displayed). *Solid (dashed)* line: measured (calculated) anomaly. See Table 1 for the parameters considered for each numbered modelled body. *Solid triangles* correspond to Euler's solutions. *Meters*: indicate depth below the surface

sources, using the software Euler 1.0 (Cooper 2001) (Figs. 3, 4, 5, 6). The first and the second vertical derivatives of the residual magnetic field were also calculated (Fig. 7) with the aim of sharpening the detected anomalies.

Results and discussion

The magnitude of the detected anomalies indicates that the studied solid waste landfill is of a domestic character (Fig. 2).

Although an exact determination of the shape, size, location and depth of the buried bodies is not possible due to the inherent limitations of the magnetic method and lack of another constraining data, good estimations were made, which are useful for the objectives of the present study.

The parameters defining the permanent magnetization of the modelled bodies along each profile vary over a wide range (Table 1). As it was mentioned above there is a great uncertainty about the orientation and the magnitude of the permanent moment of a buried object (Breiner 1973). As a result of this uncertainty, the value of a magnetic anomaly associated with a buried body may vary considerably, making the quantitative analysis of the data difficult (Benson et al. 1984). However, it is worth noting that we were not able to fit the measured and calculated anomalies through our modelling considering only the existence of induced magnetizations. Taking into account these limitations, our models should be regarded with care, and considered only as an estimation of the average depths, sizes and susceptibilities of different sectors (bodies) in the landfill containing ferrous metals in varying amounts and/or with different physical properties.

It can be observed in Fig. 2 that, in general, the magnitudes of the detected anomalies decrease to the south—southeast. Landfilling operations normally involve the deposition of waste in cells, in a geometric and ordered way. The southern part of the surveyed area corresponds to the older cells of the sanitary landfill. Therefore, it could be interpreted that such a distribution of the magnetic anomalies is generated by dense ferrous metallic objects, which are more deeply buried to the south, due to a progressive dynamic sinking by compaction. The resulting depressions are naturally filled with a non-magnetic cover, through the eolian deposition of sediments coming from positive areas. Such sediments correspond to reworked quaternary cover (silts, loess, eolian Holocene sandstones). This natural cover is obviously deposited over the previous

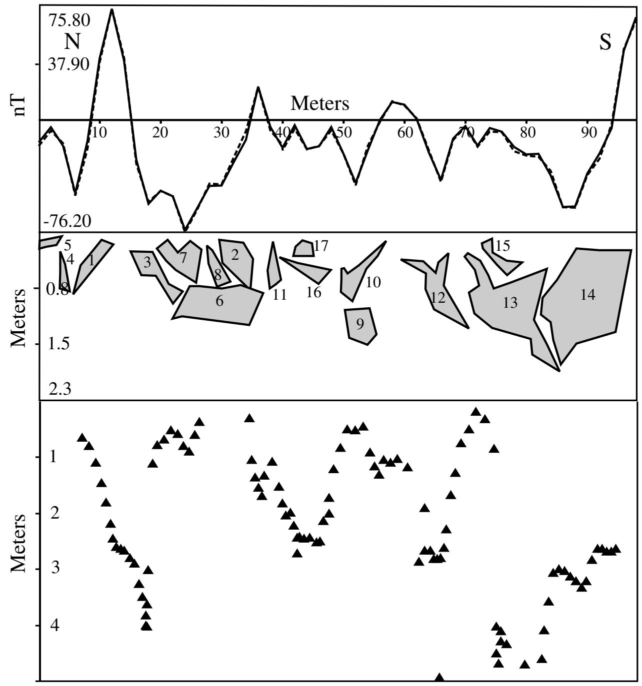

Fig. 6 Comparison of the measured and modelled anomalies along profile 6. *Solid (dashed)* line: measured (calculated) anomaly. See Table 1 for the parameters considered for each numbered modelled body. *Solid triangles* correspond to Euler's solutions. *Meters*: indicate depth below the surface

sediments emplaced over the waste during the operations (classic covering system of landfills). This sinking effect is usually observed in anthropological deposits. One can arrive at a similar conclusion through the observation of the models proposed along profiles 1, 3 and 6 (Figs. 4,6).

The modelling of the different profiles (Figs. 3, 4, 5, 6) allowed to estimate an average depth of the buried bodies of nearly 0.8–1 m, with maximum depths of 2.3 m. These results were confirmed applying Euler's deconvolution. Considering a structural index of 1 (thin prism), most of the solutions are at depths ranging between 1 and 2.5 m (Figs. 3, 4, 5, 6). It is worth noting, that in Euler's deconvolution no particular subsurface model is assumed. Hence, Euler's results are independent of the proposed models. In general, greater depths were derived from the Euler deconvolution than from the forward modelling. This difference could be explained considering that the solving of Euler's equation requires the horizontal and vertical gradients of the potential field data, which are calculated in the frequency domain (see Gunn 1975). Magnetic data are reduced to the pole before the gradients are calculated, and in such reduction the existence of permanent magnetization is not considered. This last fact introduces errors and uncertainties in the calculation of the solutions. However, the obtained depth is consistent with the information given by the workers of the sanitary landfill and with the results of the resistivity investigations (Sainato et al. 2004). The workers reported a maximum depth of 2 m and said that shallower sectors could exist. Such depths were confirmed "in situ" through observations in the neighbouring active area of the landfill. Sainato et al. (2004) determined the existence of a surface variable resistive layer 2–3 m thick. This layer is underlain by a more conductive zone (resistivity between 3 and 6 ohm m) related to the existence of contamination near the phreatic level (located between 2 and 3 m depth). They suggested that the contamination plume would not extend deeper than the phreatic level.

The first and second vertical derivatives of the anomaly permitted a better identification of the location of the edges of the causative bodies (Fig. 7). These derivatives enhance the short wavelength components of the field, and remove the long wavelength ones. They help to resolve closely spaced, even superposed anomalies. Compared to the residual magnetic field, the vertical derivatives reflect sources closer to the surface. The second vertical derivative accentuates the edges of structures, thus sharpening anomalies and exaggerating discontinuities, facilitating the location of boundaries within shallow depths (Fig. 7). It is important to remark that the west–east structures shown in Fig. 7 could probably be artefacts due to the distribution of measurement points.

A very important point to be evaluated is the magnitude of the magnetic anomalies. In this study, the highest values were of the order of 180 nT. The magnetic anomaly that would be produced by a drum buried in the studied area can be estimated and compared with the measured one. Taking into account the normal dimensions of the 55 gallon drums (length approximately 90 cm, diameter approximately 60 cm, thickness approximately 1 mm), the maximum depth of this sanitary landfill (around 2 m), the intensity of the total magnetic field (23,256 nT) and an average apparent bulk susceptibility of 110 SI for the drum (Ravat 1996); an anomaly of more than 400 nT would be expected. It is worth noting that in this calculation the possible existence of permanent magnetization was not considered. This simplification is supported by the investigations carried out by Ravat (1996), who determined that the permanent magnetizations are very small in comparison to the respective induced magnetization in most drums (Königsberger ratios ~0.1). If we use the nomograms of Breiner (1973) and of Benson and others (1984) to estimate the mass of the body causative of the measured anomaly (maximum 180 nT), we obtain a value of 3.6 kg. The weight of 55-gallon steel drums is between 18 and 23 kg (Benson et al. 1984; Ravat 1996). From these nomograms, we can estimate the anomalies that would be generated by a 55-gallon drum buried at different depths. If it is buried at 1 m depth, the anomaly

Table 1 Parameters used in the modelling of each body along the different profiles

	Susceptibility (SI)	Strike length (m)	Permanent magnetization		
			Declination (°)	Inclination (°)	Intensity (nT)
Profile 1					
Body 1	0.25	1	180	80	1,500
Body 2	0.50	1	0	−60	800
Body 3	1.00	0.5	–	–	–
Body 4	0.63	0.5	0	70	1,000
Body 5	0.38	0.5	–	–	–
Body 6	0.88	0.7	–	–	–
Body 7	0.13	1	0	50	100
Body 8	0.25	1	0	40	500
Body 9	0.38	0.3	0	−50	4,200
Body 10	0.19	1	–	–	–
Body 11	0.25	0.2	0	−50	4,200
Body 12	0.25	1	0	90	700
Body 13	0.63	0.5	–	–	–
Body 14	0.25	1	–	–	–
Profile 3					
Body 1	0.13	1	0	40	400
Body 2	0.25	0.5	0	40	1,700
Body 3	0.15	1	–	–	–
Body 4	0.25	1	0	0	500
Body 5	0.75	1	–	–	–
Body 6	0.25	1	–	–	–
Body 7	0.38	1	–	–	–
Body 8	0.38	0.5	–	–	–
Body 9	0.88	1	0	40	1,300
Body 10	0.13	1	0	0	500
Body 11	0.63	0.5	–	–	–
Body 12	0.13	1	0	90	400
Body 13	0.25	1	0	40	1,100
Body 14	0.13	1	0	60	1,200
Body 15	0.13	0.5	0	90	500
Body 16	0.25	0.5	0	90	1,900
Profile 4					
Body 1	0.13	1	0	−60	1,800
Body 2	0.50	1	0	−50	50
Body 3	0.13	1	35	−50	1,000
Body 4	0.63	0.5	0	−90	800
Body 5	0.25	1	–	–	–
Body 6	0.13	1	0	−90	500
Body 7	0.13	1	120	−60	100
Body 8	0.13	0.5	60	−60	1,200
Profile 6					
Body 1	0.38	1	–	–	–
Body 2	0.13	0.5	–	–	–
Body 3	0.25	1	0	60	700
Body 4	0.25	1	180	50	1,000
Body 5	0.13	0.5	0	30	1,000
Body 6	0.13	1	0	60	500
Body 7	0.13	0.5	0	30	900
Body 8	0.25	0.5	0	40	500
Body 9	0.25	0.3	0	40	200
Body 10	0.25	0.5	0	90	800
Body 11	0.13	0.5	0	90	1,000
Body 12	0.25	0.5	0	90	600
Body 13	0.25	0.5	0	90	400
Body 14	0.25	1	80	50	400
Body 15	0.11	0.5	180	20	600
Body 16	0.13	0.3	180	90	1,200
Body 17	0.25	0.3	180	90	600

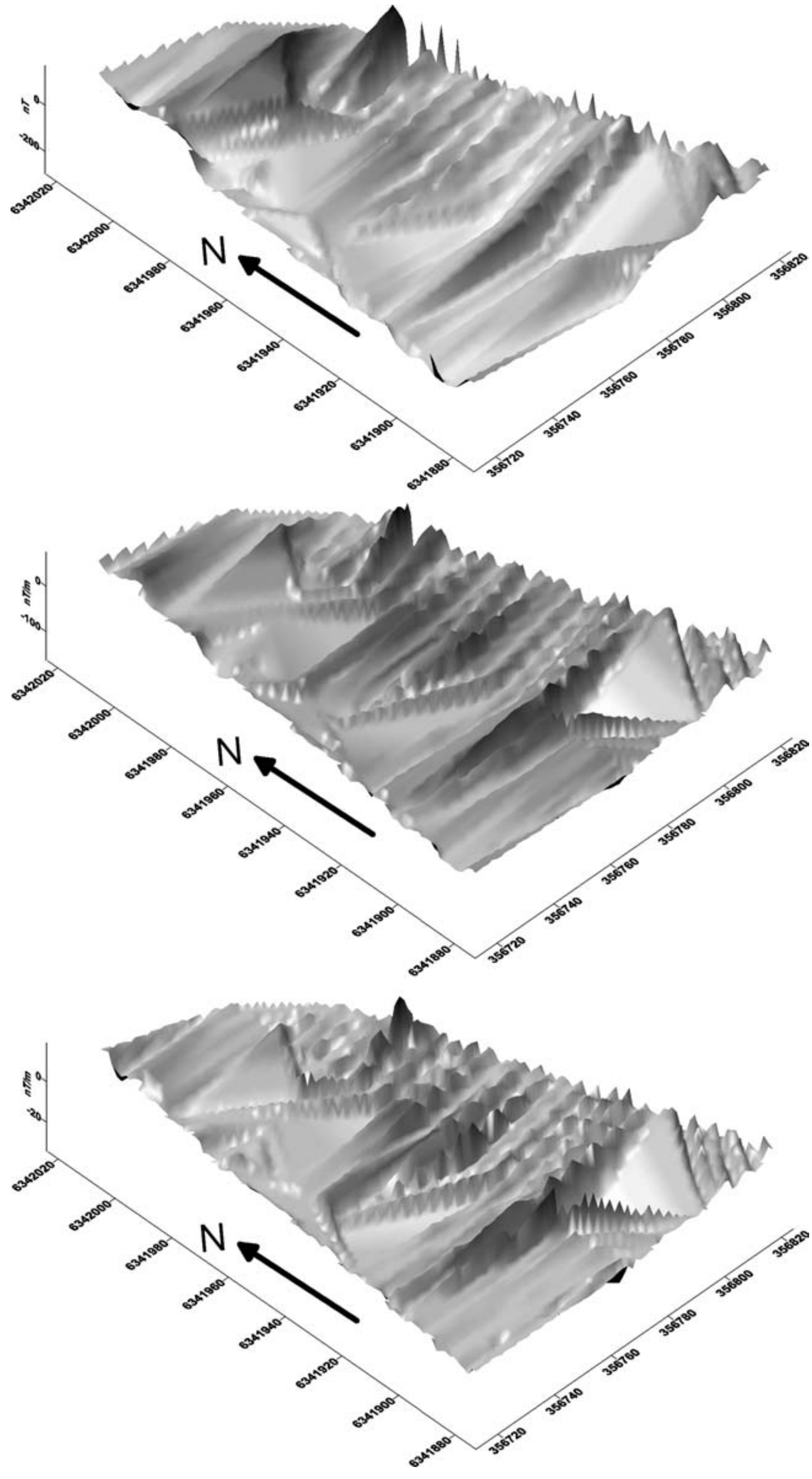

Fig. 7 *Up*: surface map of the measured anomaly. *Middle*: surface map of the first vertical derivative. *Down*: surface map of the second vertical derivative. A sharpening of the anomalies can be observed in the second vertical derivative map

would be of approximately 1,000 nT; if it is buried at 1.5 m depth, the anomaly would be of approximately 300 nT. These values would suggest that drums are not present in the studied area.

Ravat (1996) measured an anomaly of more than 340 nT produced by a drum located at 2.43 m vertical distance of the magnetometer in an inducing field of 54,000 nT. He applied equivalent source and 3D modelling methods, and compared the observed and best-fit computed anomalies. He determined that at most source-to-observation distances applicable to environmental investigations, the equivalent source method is able to approximate the observed anomalies of steel drums better than 3D modelling methods, supporting the above made calculations.

Consequently, the magnitudes of the detected anomalies (see Figs. 2, 3, 4, 5, 6) and also the characteristics of the modelled bodies (see Table 1) are not indicative of the existence of buried drums in the studied area.

Conclusions

The magnetic method was adequate to the objectives of this survey. Large buried bodies of very high magnetic susceptibility were not detected. This fact is consistent with a domestic sanitary landfill. The existence of buried drums, which can contain dangerous pollutants, was discarded. The depth of the metallic objects decreases to the north, as a consequence of the natural progressive sinking effect.

Acknowledgements We wish to thank Intendencia de la Ciudad de Gualeguaychú, CONICET, Buenos Aires University and IAA. C. Prezzi gratefully acknowledges the support of Alexander von Humboldt Fellowship. We thank the Gravity Group of the Institut für Geowissenschaften of the Christian Albrechts Universität for helpful discussion. G. Cooper provided free access to Geomodel 2.01 software. Suggestions by reviewer G.Gabriel are gratefully acknowledged.

References

Aristodemu E, Thomas-Betts A (2000) DC resistivity and induced polarisation investigations at a waste disposal site and its environments. J Appl Geophys 44:275–302

Benson R, Glaccum R, Noel M (1984) Geophysical techniques for sensing buried wastes and waste migration. Report for the U.S. Environmental protection Agency. PB84-198449. EPA –600/7-84-064, p 233

Bossi G (1969) Geología y estratigrafía del sector sur del Valle de Choromoro. Acta Geológica Lilloana 10 (2):17–64, Tucumán

Breiner S (1973) Applications manual for portable magnetometers. Geometrics Sunnyvale, USA, p 58

Carpenter P, Kaufmann R, Price B (1990) Use of resistivity soundings to determine landfill structure. Ground Water 28:569–575

Carpenter P, Calkin S, Kaufmann R (1991) Assessing a fractured landfill cover using electrical resistivity and seismic refraction techniques. Geophysics 56:1896–1904

Cooper G (2000) Geomodel 2.01 for Windows 95/98. License No 0005GM11UK

Cooper G (2001) Euler 1.00 for Windows

Dahlin T, Jeppson H (1995) Geophysical investigations of a wastedeposit in Southern Sweden. In: Proceedings of the symposium on the application of geophysics to ingineering and environmental problems. Copyright 1995. EEGS, pp 97–105

Gunn P (1975) Linear transformations of gravity and magnetic fields. Geophys Prospect 23(2):300–312

Iriondo M (1980) El Cuaternario de Entre Ríos. Revista de la Asociación de Ciencias Naturales del Litoral, Santa Fe, Argentina 11:125–141

Meju M (2000a) Environmental geophysics: the tasks ahead. J Appl Geophys 44:63–65

Meju M (2000b) Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: model development with a genetic diagnosis approach. J Appl Geophys 44:115–150

Pellerin L (2002) Applications of electrical and electromagnetic methods for environmental and geotechnical investigation. Surv Geophys 23:101–132

Piratoba Morales G, Fenzi N (2000) Environmental impact of the deposit of solid waste of the "Aura" Belém-PA (Brazil). In: 31st international geological congress, Rio de Janeiro, Brazil, vol 53A, p 4218

Ravat D (1996) Magnetic properties of unrusted steel drums from laboratory and field-magnetic measurements. Geophysics 61(5):1325–1335

Rimoldi H (1963) Aprovechamiento del Río Uruguay en la zona de Salto Grande. Estudio geológico-geotectónico para la presa de compensación proyectada en el Paso Hervidero (provincia de Entre Ríos). 1as. Jornadas Geológicas Argentinas Anales 2:287–310, Buenos Aires, Argentina

Robinson H, Gronow J (1995) A review of landfill leachate composition in the UK. In: Institute of Waste Management proceedings, January 1995, IWM, Northampton, pp 3–8

Sainato C, Favetto A, Pomposiello C (2004) Estudios geoeléctricos de un relleno sanitario de Gualeguaychú, Pcia. de Entre Ríos. XXII Reunión Científica de la Asociación Argentina de Geofísicos y Geodestas, Buenos Aires, Argentina, pp 196–197

Staton R, Thyne G, McCray J (2004) Temporal changes in leachate chemistry of a municipal solid waste landfill cell in Florida, USA. Environ Geol 45:982–991

US EPA (1988) Criteria for municipal solid waste landfills, case studies on groundwater and surface water contamination from municipal solid waste landfills. US EPA Office of Solid Waste, EPA/530-SW-88-040