Brazilian Journal of Geology

REFERÊNCIA

CAMINHA-MACIEL, George et al. Evaluation of mafic dyke swarm continuity under the Joaquina dune field with ground magnetic survey. **Brazilian Journal of Geology**, São Paulo, v. 47, n. 2, p. 237-247, abr./jun. 2017. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S2317-48892017000200237&lng=en&nrm=iso>. Acesso em: 5 jan. 2018. Epub June 12, 2017. doi: http://dx.doi.org/10.1590/2317-4889201720170009.

DOI: 10.1590/2317-4889201720170009

ARTICLE

Evaluation of mafic dyke swarm continuity under the Joaquina dune field with ground magnetic survey

Investigação da continuidade do enxame de diques máficos sob as dunas da Joaquina usando magnetometria terrestre

George Caminha-Maciel[1]*, Marcia Ernesto[2], Welitom R. Borges[3], Junior Bresolin[1], Reginaldo Lemos[1]

ABSTRACT: A ground magnetic survey in a Central-East area of the Santa Catarina Island tested the continuity of the Cretaceous mafic dykes beneath the aeolic sediments of the Joaquina plain. Vertical gradient measurements taken in 1880 stations did not detect any magnetic anomaly related to subsurface dykes. Four magnetic profiles located to the north and south of the main area showed the magnetic signature of various dykes some of them already mapped (north profiles), but also some in subsurface (south profiles). These results suggest that the dykes probably were shallow and truncated, and were already eroded along with the crystalline basement.

KEYWORDS: Dyke swarm; Santa Catarina Island; Geophysical mapping; Ground surveys; Magnetic methods.

RESUMO: *Um levantamento magnético terrestre foi realizado numa área do centro-leste da Ilha de Santa Catarina, para verificar a continuidade dos diques em subsuperfície na área das dunas da praia da Joaquina. Medidas de gradiente vertical em 1880 estações não revelaram nenhum sinal relacionado com anomalias magneticas produzidas por diques em subsuperfície. Quatro perfis localizados ao norte e sul da área principal de estudo detectaram a assinatura magnética de vários diques, alguns aflorantes (perfis-norte) mas também alguns em subsuperfície (perfis-sul). Estes resultados sugerem que os diques eram rasos e truncados e foram erodidos juntamente com o embasamento cristalino.*

PALAVRAS-CHAVE: *Enxame de diques; Ilha de Santa Catarina; Mapeamento geofísico; Levantamentos terrestres; Métodos magnéticos.*

[1]Universidade Federal de Santa Catarina – UFSC, Florianópolis (SC), Brasil. *E-mail: caminha.maciel@ufsc.br*

[2]Universidade de São Paulo – USP, Departamento de Geofísica, São Paulo (SP), Brasil. *E-mail: mernesto@usp.br*

[3]Universidade de Brasília – UnB, Brasília (DF), Brasil. *E-mail: welitom@unb.br*

*Corresponding author.

Manuscript ID: 20170009. **Received in:** 01/23/2017. **Approved in:** 03/17/2017.

INTRODUCTION

The Brazilian Atlantic coast is cut by Cretaceous dyke swarms (Marques & Ernesto 2004) associated with the Atlantic opening. The most expressive one is the Ponta Grossa dyke swarm trending mainly NW; the other two are NE trending systems: the Serra do Mar swarm to the north, and the Florianópolis swarm to the south (Fig. 1). In spite of their geodynamical importance, there are very few geophysical investigations (Ferreira 1982, Ussami *et al.* 1991, Stanton *et al.* 2010) on these dykes which could contribute to a better understanding of its subsurface configuration and its role in the geodynamical processes of the eastern Gondwana breakup.

The Florianópolis dyke swarm is more concentrated in Santa Catarina Island (Fig. 1), but also extends to the adjacent continental areas. Dyke outcrops are seen all over the island, but the best exposures are found on the rocky shorelines. In the inner areas, weathering conditions frequently do not allow to infer some important characteristics as the dyke attitude, thickness and length. Furthermore, some parts of the island are covered by recent sediments, hampering the observation of possible lateral continuation of dykes.

In the absence of aeromagnetic data for Santa Catarina Island, a magnetic investigation of the Florianopolis swarm was performed through a ground magnetic survey. However, the island is densely urbanized, limiting this type of investigation. Fortunately, some environmental preservation areas are still available, and one of the largest is the dune field of Joaquina Beach, where this study is concentrated.

GEOLOGICAL SETTING

The mafic dykes cropping out in Santa Catarina Island and adjacent continental area (Florianópolis swarm) are related to the Paraná Magmatic Province (e.g. Marques & Ernesto 2004) of Early Cretaceous age, which preceded the South Atlantic opening. Radiometric ages based on the Ar^{39}/Ar^{40} method yielded ages ranging from 119.0±0.9 Ma to 128.3±0.5 Ma (Raposo *et al.* 1998), slightly younger than the ages for the Paraná Province (134-132 Ma), associating the dyke swarm to the final stages of the rifting at those latitudes. However, a U/Pb age of about 134 Ma was reported for one dyke located on the continental side (Florisbal *et al.* 2014).

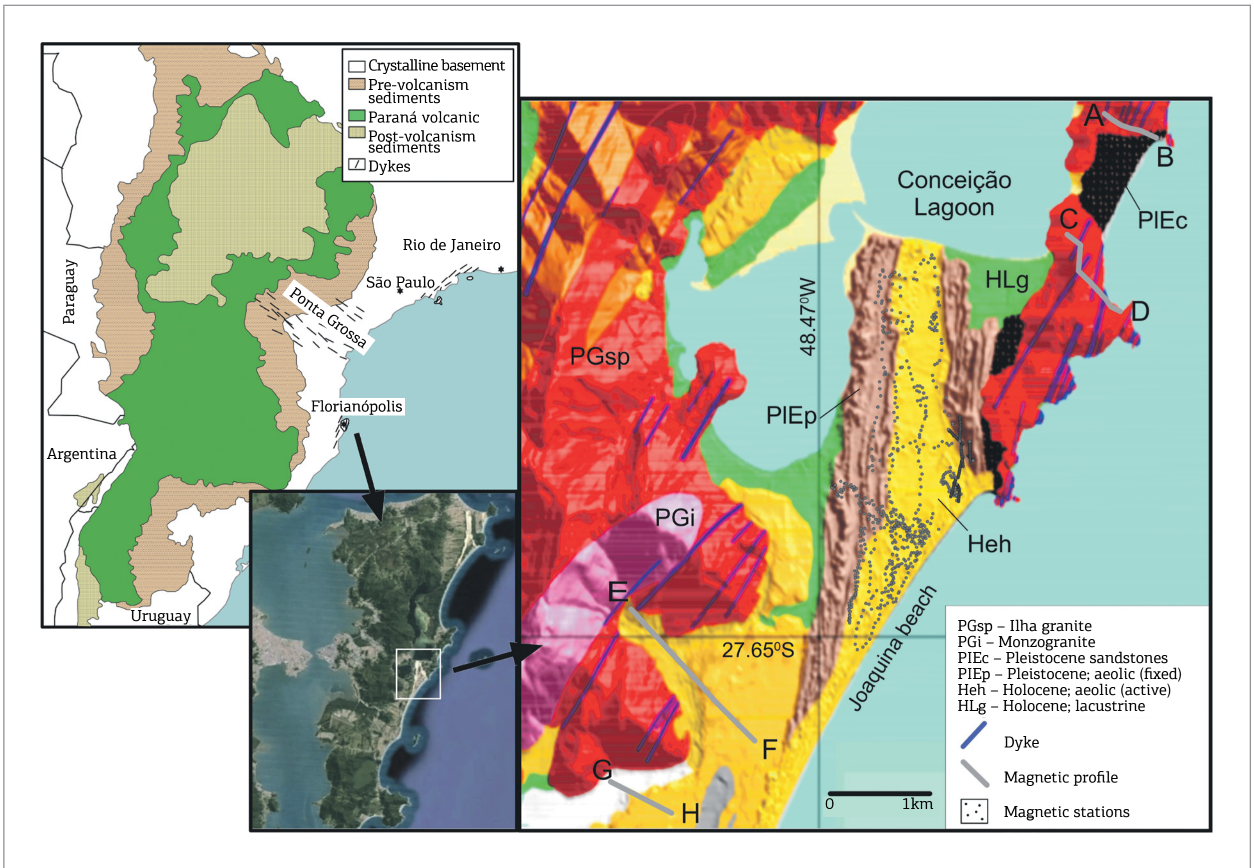

Figure 1. Sketch map of the Paraná Magmatic Province (left) indicating the main dyke swarms. The Santa Catarina island (center) indicating the study area. Geological map (Tomazzoli & Pellerin 2015) of the study area (right) indicating the magnetic profiles and magnetic stations over the Joaquina beach.

Chemically, the dikes are mainly basalts with similar composition to the one of extrusive rocks of the Paraná Province (Marques *et al.* 1993). Paleomagnetic studies on these dykes (Raposo *et al.* 1998) showed that they have stable remanent magnetizations of normal and reversed polarities.

The Florianópolis dykes crosscut vertically or sub-vertically the Late Proterozoic granitic rocks, and they generally appear truncated, although some can be traced for some kilometers (Tomazzoli & Pellerin 2015). They trend mainly N30-55°E, but a smaller group trending N15-45°W eventually cuts the NE group, as seen in Joaquina Beach. Their thicknesses vary from centimetres to 60 m.

Quaternary sediments are deposited in the low areas of the island, forming the coastal plains; aeolic sedimentation forms dune fields on the eastern side — the largest one is in the area of Joaquina Beach, where dunes are as high as 40 m.

GROUND MAGNETIC DATA: ACQUISITION AND PROCESSING

The magnetic data was acquired using a single unit of proton GSM-19 Overhauser Gradiometer (GEM Systems). The gradiometer measures the variation (vertical gradient – VG) of Earth's total magnetic field in two sensors located 50 cm vertically apart; the lower unit being ~200 cm high. The total magnetic intensity (TMI) can also be obtained from one of the sensors.

A gradiometric survey was performed all over the dune field of Joaquina Beach (Fig. 1), and measurements were taken in 1,880 magnetic stations, forming lines with different orientations and avoiding relief and wildlife barriers. No base station measurements were necessary for the VG data as they are normally free of diurnal variations — both sensors experience the same temporal variations, therefore being automatically eliminated in the gradient.

VG and TMI measurements were taken along four profiles with general W-E trend — two to the north and two to the south of Joaquina Beach (Fig. 1). In North profiles (Mole beach, A-B profile; Gravatá trail, C-D profile), stations were equally spaced (5 m) along the existent trails in a downhill direction. South profiles (E-F and G-H profiles, to the north and south of the Pedrita Quarry, respectively) were taken on plain terrains, offering easier conditions but showing more human interference. For each profile, a magnetic base station was visited repeatedly at least at the beginning and the end of the survey. A variation curve was constructed for each base station and was used to correct the TMI data for the diurnal variation.

It is also common in magnetic surveys to eliminate the trends of the global magnetic reference field (IGRF). However, in the present case, these trends are negligible as the survey area is small and profiles are short-length. Similarly, the regional components which represent long-scale trends, usually related to long-wavelength and/or deep crustal features, were not considered.

Other useful processing tools are frequency filtering, linear field transformations (pseudogravity and reduction to the pole – RTP) and the use of magnetic derivatives. Frequency filtering brings the problem of defining a set of cut-off frequencies, which is a multiple solution problem; it also varies for different profiles in a survey, and even along a single profile; those choices are highly critical for short-length data. Linear transformations, particularly RTP, aim to show the magnetic anomaly as if it was originated by a monopolar central field (like gravity field); they are meant to minimize interpretation ambiguities due to the dipolar nature of magnetic fields. However, they present two drawbacks: they are ill defined near the equator, and the magnetization should be induced only — any remanence may cause distortions in the interpreted bodies. Therefore, they are not useful in the present processing. The so called magnetic derivatives are derivatives from total intensity values (scalar field) or from some magnetic vector component (usually estimated from TMI data), and are helpful in enhancing some aspects of an anomaly, related to the possible causative body properties.

In this paper, we used the analytic signal (AS), the total horizontal derivative (THDR) and the Tilt angle, as described in Table 1. Some of these derivatives, particularly AS, are little influenced by the magnetization direction (Maunde *et al.* 2013, Verduzco *et al.* 2004). The Florianópolis dykes have strong and variable natural remanent magnetization directions, including normal and reverse polarities (Raposo *et al.* 1998). These magnetizations can generate VG higher than 1,000nT/m, as observed over a dyke outcrop in Galheta Beach.

The AS curve has maxima over magnetic bodies and their edges. The THDR and Tilt angle curves were used as

Table 1. Magnetic derivatives applied to the 2D profiles.

Analytic Signal	$AS = \sqrt{\left(\frac{\delta T}{\delta x}\right)^2 + VG^2}$
Total Horizontal Derivative	$THDR = \sqrt{\left(\frac{\delta T}{\delta x}\right)^2}$
Tilt Angle	$Tilt = arctan\left[\frac{VG}{THDR}\right]$

AS: analytic signal; THDR: total horizontal derivative; T: total magnetic intensity; VG: vertical gradient (Verduzco *et al.* 2004).

auxiliary tools for qualitative interpretation, as the data were not previously RTP transformed, which could bias quantitative estimates based on those derivatives.

RESULTS

The VG data over the Joaquina dune area (Fig. 2) showed no magnetic anomalies or significant magnetic contrast that could be interpreted as borders of a magnetic body. Most of the area showed VG near zero, and the maximum VG (~5 nT/m), in some particular points, does not show any geometric pattern that could be related to any geologic feature of interest. Also, there are no long-wavelength features associated with deep bodies, as can be seen, on the 100 m VG upper continuation (Fig. 3). There are some very weak variations, probably associated to the sedimentary topography in the area.

The northern profiles (Figs. 4 and 5) are noisy due to some unavoidable cultural interference (electric power lines, concrete pipe lines, metallic garbage bins etc.), and geological noise generated by variable relief and also rolled rock blocks. The magnetic curves display several anomalies not easily interpretable, although some of them clearly correspond to mapped dykes, as seen on Fig. 1. When the interpretation was straightforward a vertical arrow indicates the dyke anomaly in the AS curves. If resolution was not sufficient for reliable interpretation, the anomaly was coded as BR (below resolution). The Gravatá profile (Fig. 5) clearly cut some mapped dykes (Fig. 1) in a zone where the survey line changed direction. Coincidently, the magnetic curves are noisy in this area, which may be due to the proximity of various dykes.

The south profiles (Figs. 6 and 7) were the most favorable ones for the magnetic investigation, as they are in an open and plain area. We found several anomalies probably related to dykes in subsurface corresponding to the continuation of those observed on the geological map (Fig. 1). Between the two profiles, the Pedrita quarry exposes three dykes, two of which are 60 m thick.

DISCUSSION AND CONCLUSIONS

In this reconnaissance survey, we aimed to identify magnetic anomalies possibly associated to non exposed dykes, which could represent the continuation in subsurface of the geologically mapped bodies close to the Joaquina Beach area. No quantitative interpretation or modeling was performed, but only estimations of location of possible bodies based on the shape and maxima of AS curves.

Some of the magnetic anomalies were clearly interpretable as dykes, some of which correspond to the continuation of dykes already mapped. On the other hand, other anomalies were not easily resolved, and further studies would be necessary to better define these signal sources (e.g. higher resolution ground magnetic surveys, additional geophysical methods, etc.). Some of these "non-resolved" anomalies may correspond to narrow dykes (less than 10-5 m wide), which could not be properly detected in our 5 m spaced magnetic stations.

The gradiometric survey over the Joaquina Beach dunes revealed the inexistence of any magnetic anomalies, as could be expected if at least some of the dykes had subsurface continuation. Considering that usually VG enhances near-surface, small or weakly magnetized bodies, we can confidently say that there are no significant magnetic finite sources beneath the Cenozoic sediments in the area. Conversely, the presence of dykes beneath the shallow sediments in the south and north profiles is a reality. However, it must be considered that these profiles are located very close to the granitic bodies cut by dykes, and therefore it is reasonable to expect that the sources should be associated with intrusions in a shallow granitic basement.

Unfortunately, there is no published information about the thickness of the sedimentary column in the Joaquina area, nor about its basement lithology. However, although deep, any existing magnetic source signal would be detected on the surface via the magnetic anomalies they generate. Therefore, we conclude that the dykes in the area are all short and truncated. Particularly, it is really surprising that thick dykes like those in Pedrita Quarry show no continuation in the Joaquina plain. Therefore, it is reasonable to admit that the dykes are actually shallow structures, and were removed by erosion along with the host granitic bodies. As an example, one may refer to the model proposed by Valentine & Krogh (2006) for shallow dykes and sills intruded in pre-existing structures beneath a basaltic volcanic centre. A more detailed and specific geophysical work should be carried out for such an investigation.

ACKNOWLEDGMENTS

We thank Edison Tomazzoli for valuable discussions and Luana Florisbal for the help in fieldwork preparation. Comments of two anonymous referees greatly improved the manuscript. This work has been funded by CNPq (grant 308475/2015).

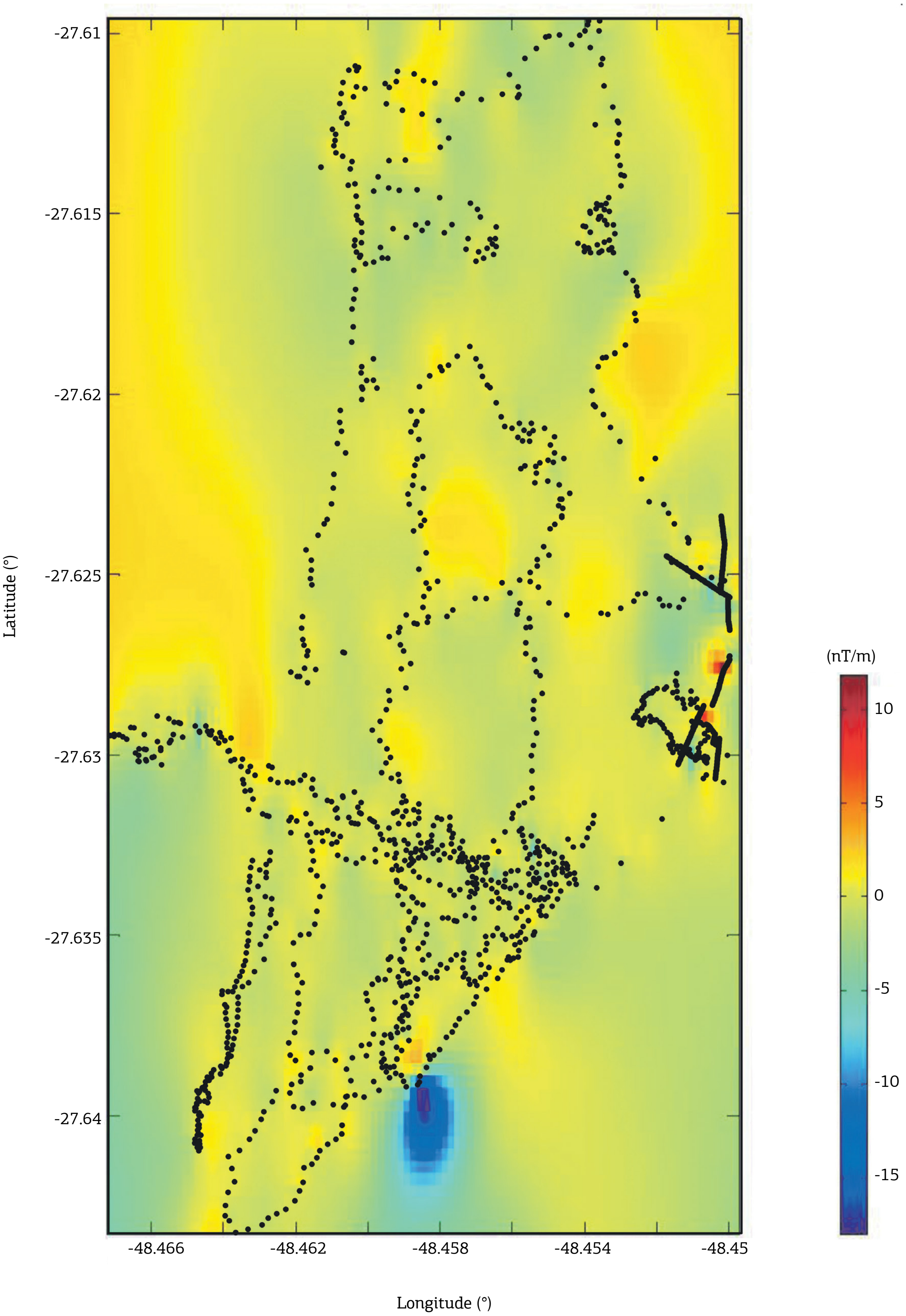

Figure 2. Vertical gradient (VG) over the Joaquina dune field, drawn in Mirone software (Luis 2007). Black dots are the magnetic stations.

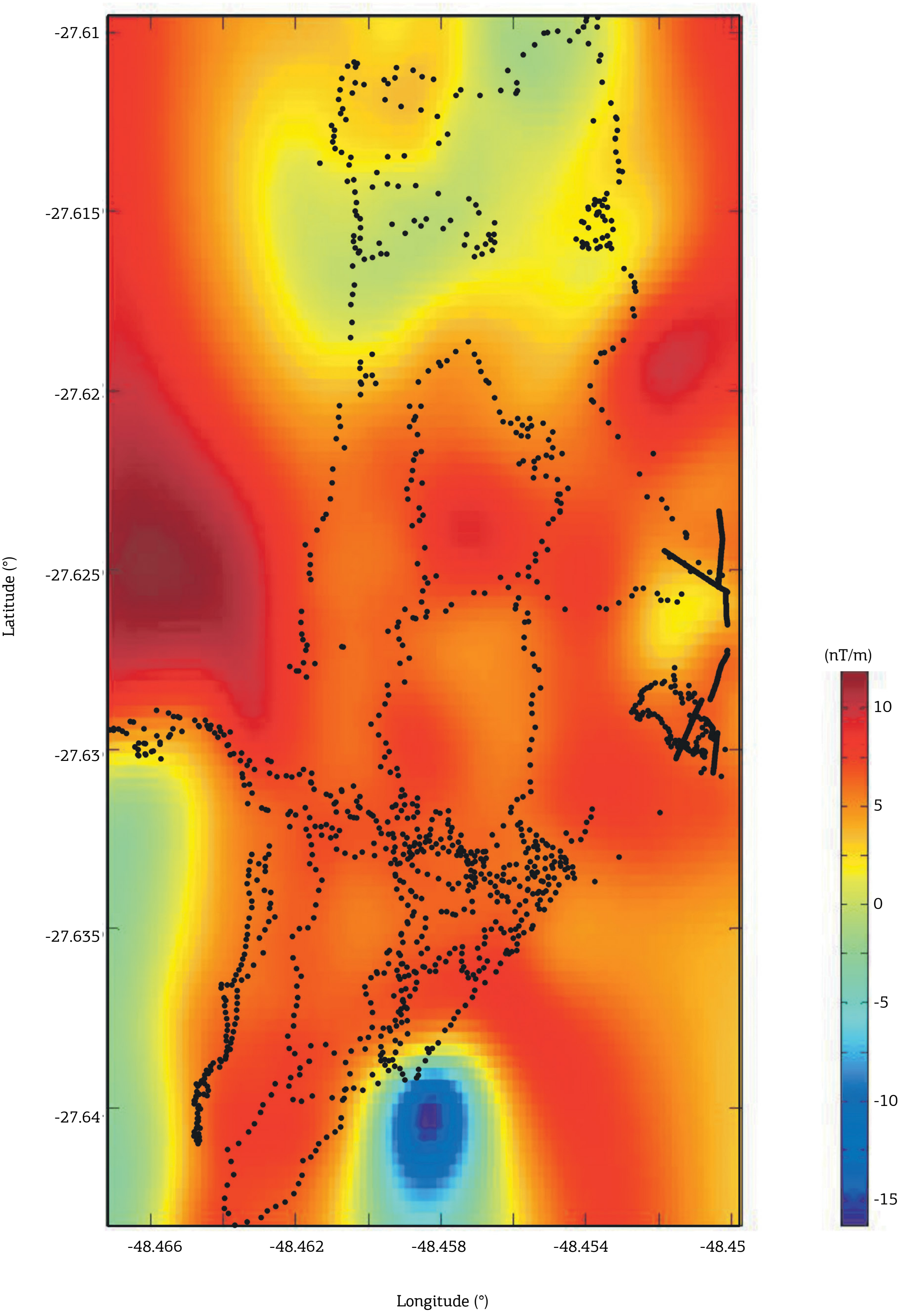

Figure 3. Upper continuation (at 100 m) of VG over Joaquina dune field, drawn in Mirone software (Luis 2007). Black dots are the magnetic stations.

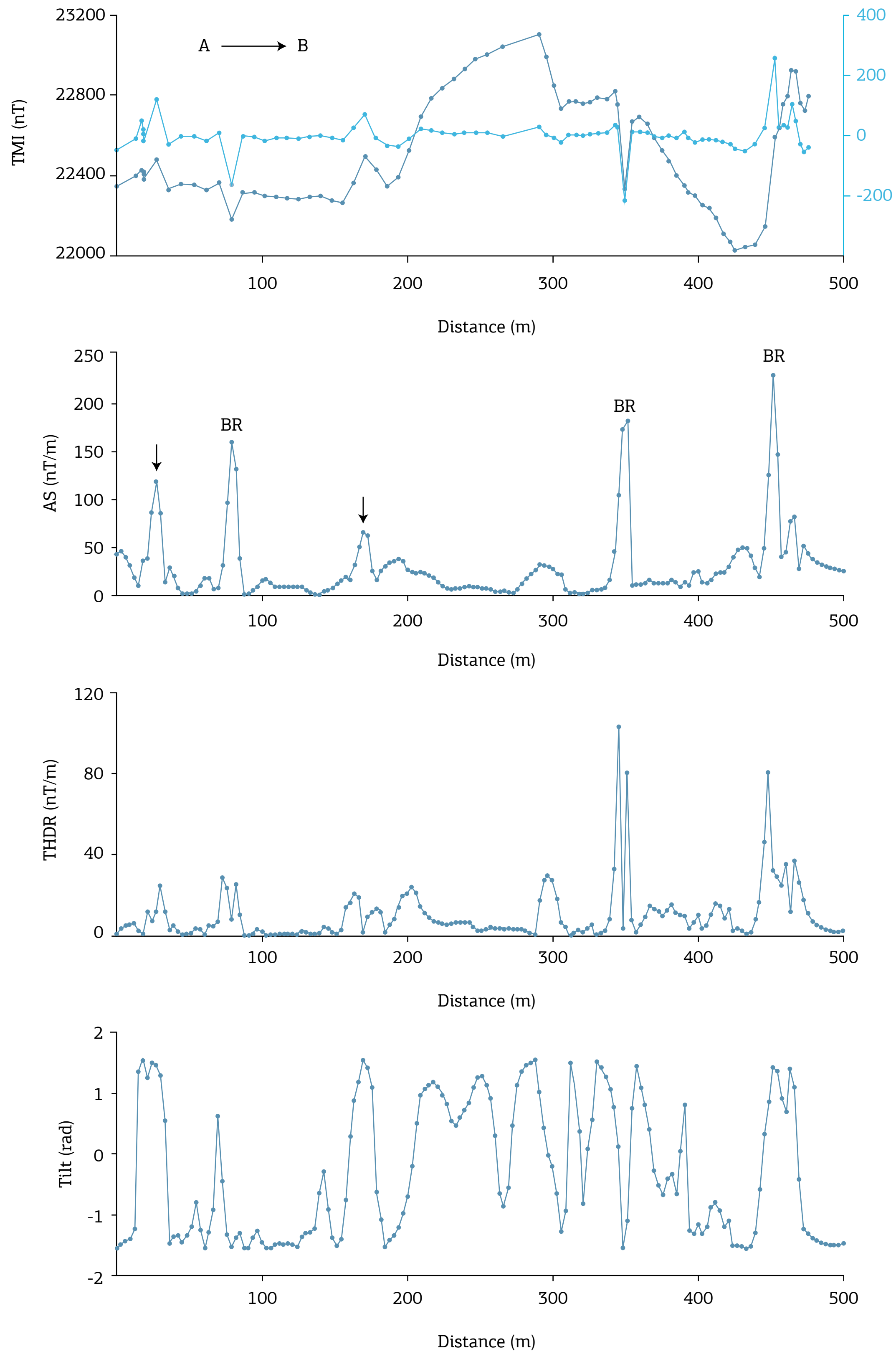

Figure 4. Magnetic curves for the Mole profile (A-B). From top to bottom: total magnetic intensity (TMI), vertical gradient (VG), analytic signal (AS), total horizontal derivative (THDR), tilt angle (Tilt). Arrows on the AS curve indicate anomalies clearly related to dykes; BR means below resolution for reliable interpretation.

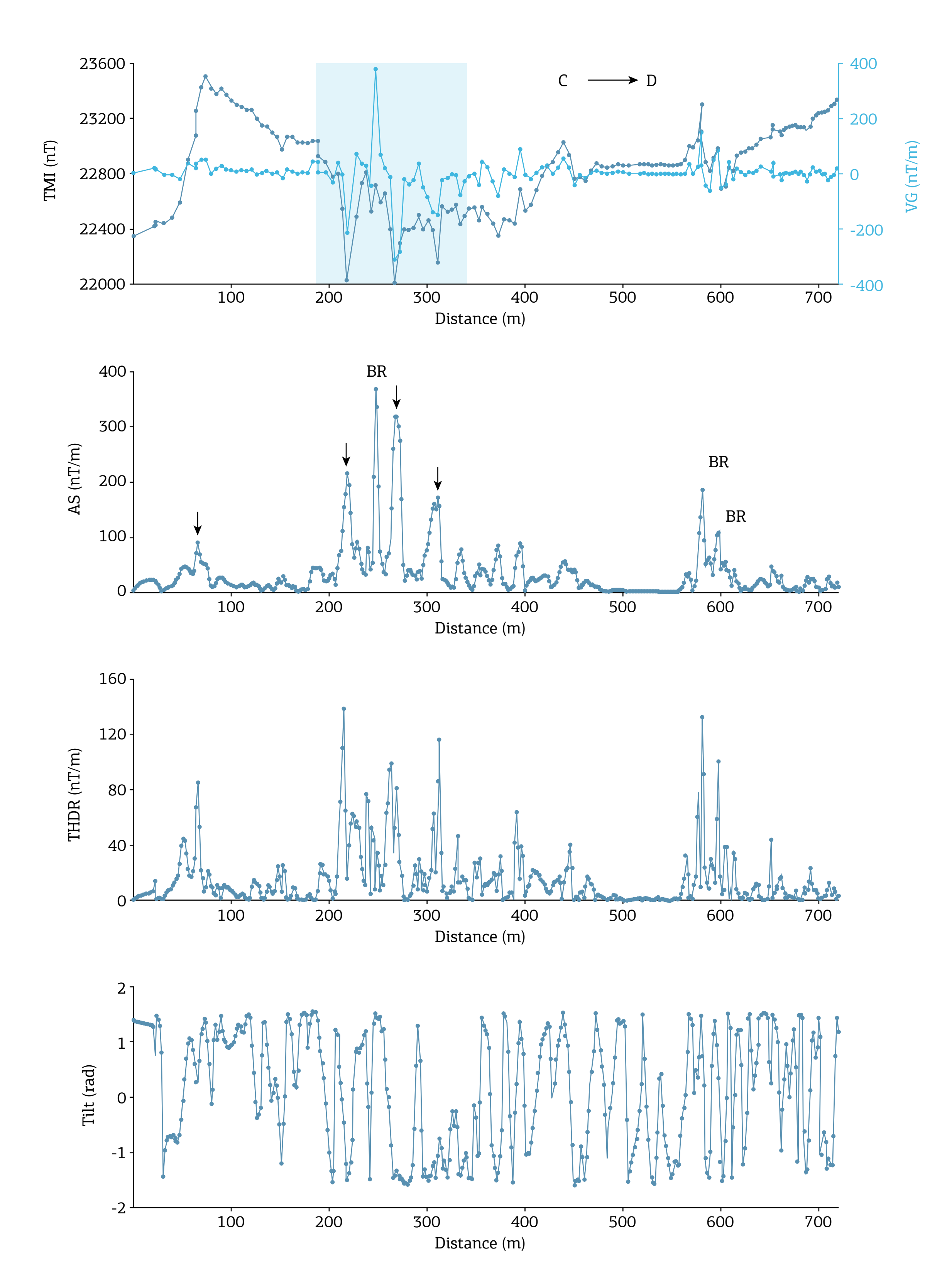

Figure 5. Magnetic curves for the Gravatá profile (C-D). From top to bottom: total magnetic intensity (TMI), vertical gradient (VG), analytic signal (AS), total horizontal derivative (THDR), tilt angle (Tilt). Arrows on the AS curve indicate anomalies clearly related to dykes; BR means below resolution for reliable interpretation. Shaded area in the TMI curve indicates the profile change in direction.

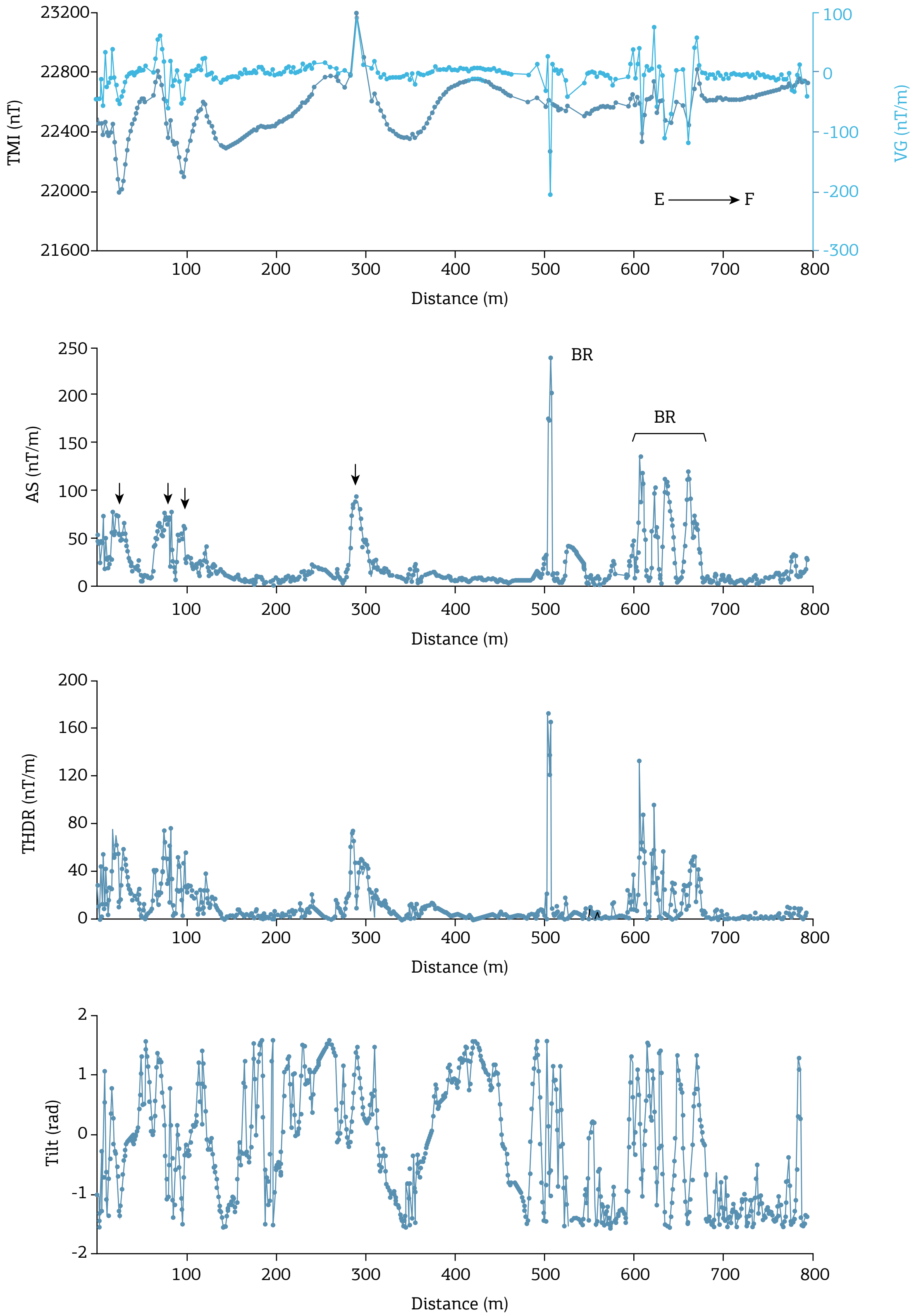

Figure 6. Magnetic curves for the south profile E-F. From top to bottom: total magnetic intensity (TMI), vertical gradient (VG), analytic signal (AS), total horizontal derivative (THDR), tilt angle (Tilt). Arrows on the AS curve indicate anomalies clearly related to dykes; BR means below resolution for reliable interpretation.

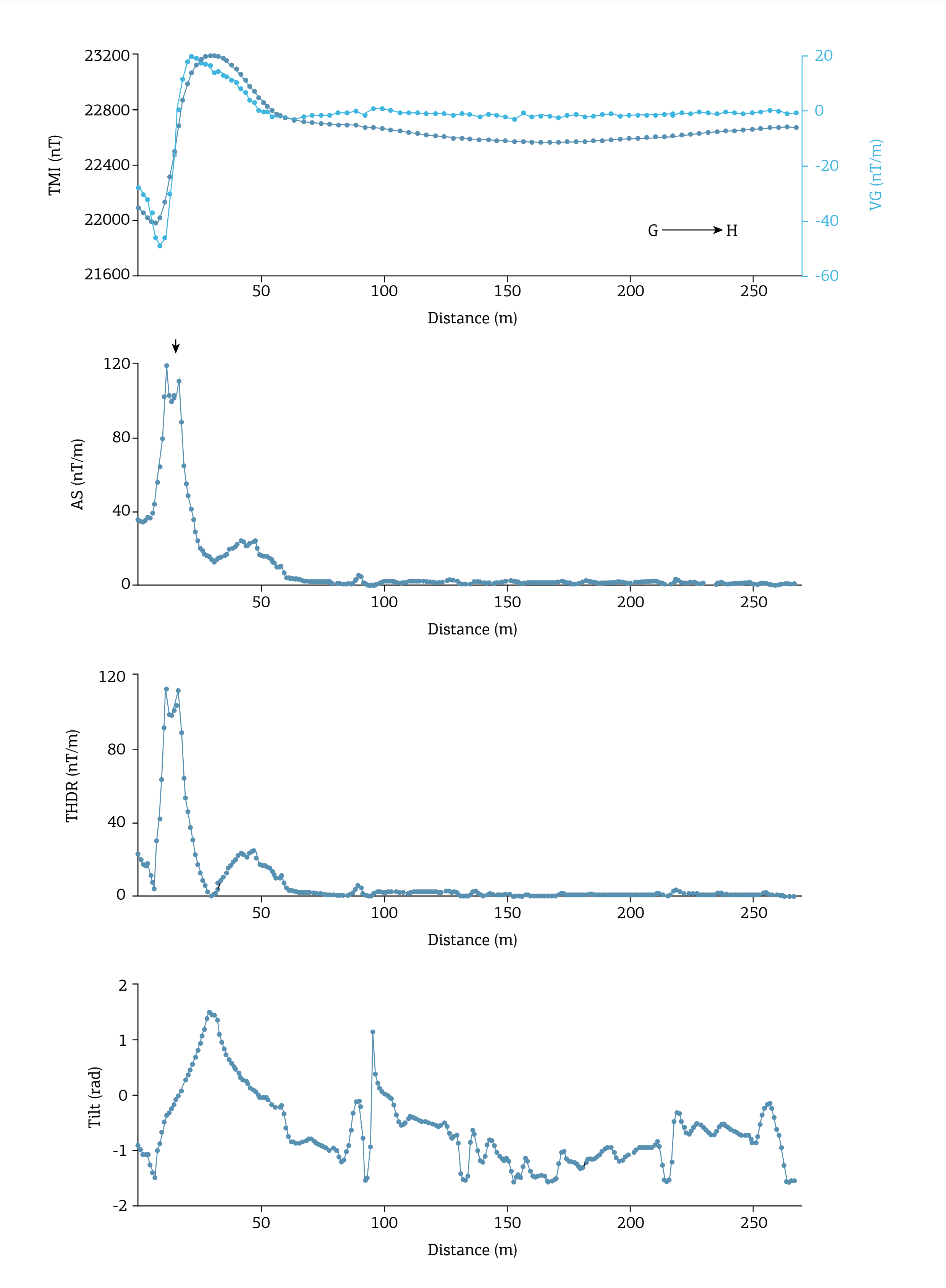

Figure 7. Magnetic curves for the south profile (G-H). From top to bottom: total magnetic intensity (TMI), vertical gradient (VG), analytic signal (AS), total horizontal derivative (THDR), tilt angle (Tilt). The arrow on the AS curve indicate anomaly clearly related to dyke.

REFERENCES

Ferreira F.J.F. 1982. Alinhamentos estruturais magnéticos da região centro-oriental da bacia do Paraná e seu significado tectônico. *In*: IPT – INSTITUTO DE PESQUISAS TECNOLÓGICAS DO ESTADO DE SÃO PAULO. *Geologia da Bacia do Paraná*. São Paulo: IPT, p.143-166. (Publ. Especial 12).

Florisbal L.M., Heaman L.M., Janasi V.A., Bitencourt M.F. 2014. Tectonic significance of the Florianópolis Dyke Swarm, Paraná-Etendeka Magmatic Province: a reappraisal based on precise U-Pb dating. *Journal of Volcanology and Geothermal Research*, **289**:140-150.

Luis J.F. 2007. Mirone: A multi-purpose tool for exploring grid data. *Computers & Geosciences*, **33**(1):31-41.

Marques L.S., Bellieni G., De Min A., Piccirillo E.M. 1993. O enxame de diques da Ilha de Santa Catarina: resultados geoquímicos preliminares. *In*: Congresso Brasileiro de Geoquímica, 4. *Resumos*, p.3-4.

Marques L.S., Ernesto M. 2004. O magmatismo basáltico na Bacia do Paraná. *In*: Almeida, F.F.M.; Mantesso-Neto V., Bartorelli A., Carneiro C.D.R.; Brito Neves, B.B. (Eds.). *Geologia do Continente Sul-Americano*. São Paulo: Beca Produções Culturais, p.245-263.

Maunde A., Bassey N.E., Raji A.S., Haruna I.V. 2013. Interpretation of ground magnetic survey over Cleveland dyke of north Yorkshire, England. *IRJGM*, **3**(5):179-189.

Raposo M.I.B., Ernesto M., Renne P.R. 1998. Paleomagnetism and 40Ar/39Ar dating of the Early Cretaceous Florianópolis dike swarm (Santa Catarina Island), Southern Brazil. *Earth and Planetary Science Letters*, **108**(4):275-290.

Stanton N.S.G., Schmitt R.S., Maia M., Galdeano S. 2010. Mesozoic rifting structures between Campos and Santos basins, Cabo Frio, Brazil: magnetic and structural analysis. *Trabajos de Geología*, **30**(30):253-260.

Tomazzoli E.R., Pellerin J.M. 2015. Unidades do mapa geológico da ilha de Santa Catarina: as rochas. *Geosul*, **30**(60):225-247.

Ussami N., Kolisnyk A., Raposo M.I.B., Ferreira F.J.F., Molina E.C., Ernesto M. 1991. Detectabilidade magnética de diques do Arco de Ponta Grossa: um estudo integrado de magnetometria terrestre/aérea e magnetismo de rocha. *Revista Brasileira de Geociências*, **21**(4):317-327.

Valentine G.A., Krogh K.E.C. 2006. Emplacement of shallow dikes and sills beneath a small basaltic volcanic center – the role of pre-existing structure (Paiute Ridge, southern Nevada, USA). *EPSL*, **246**(3-4):217-230.

Verduzco B., Fairhead J.D., Green C.M., Mackenzie C. 2004. New insights into magnetic derivatives for structural mapping. *The Leading Edge*, **23**(2):116-119.

Available at www.sbgeo.org.br