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Anomalies of the Earth's total magnetic field in Germany – the first complete homogenous data set reveals new opportunities for multiscale geoscientific studies

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SUMMARY

Anomalies of the Earth's total magnetic field reveal important information about crustal structures. For the first time, a homogenous map of anomalies of the Earth's total magnetic field for the whole of Germany is available. The map is based on 50 shipborne, airborne and ground surveys, which were conducted between 1960 and 1990 and complemented by 17 new surveys after German reunification. The map, with a grid spacing of 100 m, consistently images the entire anomaly pattern in Germany at an altitude of 1000 m a.s.l. related to the DGRF 1980, epoch 1980.0. Because of these reference parameters and consideration of new data, the resolution of this map is higher than any previously published map. The homogenized and complete data set enables the distinction of different magnetic anomalies and – by observing their vector character – the identification of magnetic sources from different stages of the geological history. Since the map images the superposition of magnetic source anomalies from different depths and therefore combines long- and short-wavelength spectrums within one data set, it offers new insights into crustal structures. Not only regional tectonic units, such as the Variscan terranes in south and central Germany, or the extent of old Scandinavian crust under North Germany, as a relict of the collision between Baltica and Avalonia are imaged, but also details of local structures such as the volcanic areas of the Vogelsberg and the Eifel region. Therefore, the new data set can be used for work on modern topics in geosciences that cover both fundamental and applied research – for example, the structural and petrophysical characterization of the crust, its rheology and geodynamic evolution, or even hydrocarbon exploration. The gridded data is available as an electronic supplement to this paper.

Key words: Magnetic anomalies: modelling and interpretation; Composition of the continental crust; Crustal structure; Europe.

1 INTRODUCTION

Many topics with actual relevance in fundamental and applied geosciences deal with regional crustal structures, for example, fundamental research concerning the evolution of the Earth's topography controlled by coupled deep earth and surface processes, and increasing exploration for natural resources – especially hydrocarbon and the growing interest in alternative renewable energies, for example, geothermal energy. During the last years this cutting-edge research has resulted again in an increased demand for spatial gravity and magnetic anomaly data that describes the structure, the rheology and physical properties of the Earth's crust.

Until now, no homogenous, high resolution, magnetic data set for Germany was available that covers the whole region. The most recent compilation by Wonik (1992) was based on a 5000 m grid. It images anomalies at an altitude of 3000 m and therefore focuses consequently on large-scale structures. This is in contrast to the high-resolution data sets of other European countries, such as France (BRGM 1980), Finland (Korhonen *et al*. 2002), Italy (Caratori Tontini *et al.* 2004) and Great Britain (Chacksfield *et al.* 2006) and also Australia (Milligan & Franklin 2004) or North America (Bankey *et al.* 2002).

To overcome this handicap, after German reunification, the first homogenous map of the anomalies of the Earth's total magnetic field (ΔT) for Germany was compiled (Leibniz Institute for Applied Geophysics 2010). Compared to the work by Wonik *et al.* (2001), the present compilation is improved by: (i) the additional consideration of unpublished ground-based and airborne data, (ii) a grid spacing of 100 m to preserve information in the short-wavelength range that is recorded by the more recent airborne surveys and (iii) a common reference level of 1000 m altitude, thus reducing the low-pass effect of upward continuation. Hence, the new compilation closes the gap between 'global-scale maps', for example, the World Digital Magnetic Anomaly Map 2007 (Korhonen *et al.* 2007) and 'local maps of high resolution' (typically terrain clearance less than 100 m and line distances of some 100 m). The new map for Germany enables the interpretation of structural features with extents between some kilometres up to some 100 km. Its information content is consistent with that of regional geological maps, that is, the geological map of Germany (BGR 1993), the most recent digital geological map of Europe (Asch 2005) or the geological map of the world (CGMW 2010). Quantitative applications of the new compilation comprise (amongst others) the following.

(1) Forward modelling of the structure and physical properties of the entire crust, with consideration of the complete spectrum of wavelengths.
(2) Basin modelling, that is, estimation of the depth to the magnetic basement.
(3) Estimation of Curie depths as proxy for the thermal properties of the Earth's crust.

2 DATABASE

For the present compilation, 67 shipborne, airborne and ground surveys, which were conducted between 1961 and 2008, were combined (Table S1).

The most comprehensive surveys were carried out by the Prakla-Seismos Company between 1965 and 1971 (BGR 1976), which cover the northern (1, numbers refer to Table S1 that gives more detailed information, including references), central (2) and southern parts (3) of western Germany. These surveys were flown at 700, 1000 or 1500 m altitude, with respect to the depths of the magnetic source bodies. Because the original data was not available any more, 73 maps of scale 1:100 000 were digitized along the flight lines and the contour lines.

Additional measurements in the following years concentrated on the German border with former Czechoslovakia (now the Czech Republic). In 1977, an aeromagnetic survey in the area of Passau (4) was carried out. Additional ground data was collected in the Upper Palatinate region in preparation for the German Continental Deep Drilling Project (Kontinentales Tiefbohrprogramm) (5). Between 1988 and 1993, ground magnetic surveys in the Bavarian Forest (6) were conducted.

Between 1961 and 1990 magnetic observations in the former German Democratic Republic (7–44) were carried out, but never published. For this new project, one homogenous data set, referred to the epoch 1980.5 and 1000 m a.s.l., was made available by Geophysik GGD mbH. This data set consists of 38 shipborne, airborne and ground surveys. Data from Poland and the Czech Republic was used to improve the precision of anomalies in the border areas.

Although between 1976 and 1990 the Wendland area (45) in Central Germany was covered by several ground surveys, after German reunification a lack of data along the former border between the German states became obvious. Therefore, the Leibniz Institute for Applied Geophysics contracted out several helicopter borne surveys in this area (46–55).

To complete the database of a homogenous map of ΔT for the whole of Germany, surface measurements were realized in the area around Schwarzenbek between 1993 and 1995 (56) and an aeromagnetic survey over the Isle of Fehmarn (57) was flown in 1996, followed by some local surveys along the German/Dutch border in 2000 (58–61). In 2007/2008 the last gaps in northwest Schleswig-Holstein and in the area of the East Frisian Islands were closed (62, 63) and additional surveys were conducted in Saarland (64) and the northern foreland of the Harz Mountains (65).

The German part of the North Sea is covered by a 2 km grid, whose origin is unknown (66). To complete the map in the Bavarian Alps, data that was collected within an Austrian–German cooperation project, was included (67).

3 DATA PROCESSING

Data processing aimed to generate a homogenous map of ΔT with a common reference level for all the different data sets. Following parameters were chosen

(i) As the three main surveys were flown by Prakla-Seismos Company at 700, 1000 and 1500 m a.s.l. a common altitude of 1000 m was chosen. Downward continuation of the data erased problems but does not improve the resolution. Upward continuation acts as a low-pass filter, reducing the information content of the data.
(ii) As geomagnetic reference field, the DGRF1980 was chosen. In 1980 the MAGSAT satellite offered the first opportunity to determine the complete terrestrial magnetic field and to identify all the anomalies related to the Earth's crust. Reference fields for the epoch 1980.0 are considered to be more precise than any other epoch (Wonik *et al.* 2001).

Due to these constraints, the data set (2) derived from the survey flown in 1000 m a.s.l. served as a reference data set of highest priority within the data processing.

Data processing for all surveys followed the workflow set below (software OASIS montaj, Geosoft Ltd.). In practice an individual solution for each data set had to be often found in detail, which depended on the information provided with the data.

(1) The *original geomagnetic reference field* was calculated and added to the anomaly data.
(2) The *secular variation* was corrected. With respect to the three surveys (1–3), secular variations between 1967.5 and 1980.0 were calculated by fitting the data from European observatories to a polygon of the second degree (Wonik 1992). Using this approach, regional variation of the secular variation was considered. All other surveys are of local character. Therefore, secular variation can be assumed to be constant for each single survey area, without spatial variation. The correction of the secular variation was carried out together with processing step 5.
(3) As a *new geomagnetic reference field* the DGRF1980, epoch 1980.0, was calculated and subtracted, with respect to the exact position and height of each single observation.
(4) For surveys that were not measured at the height of 1000 m, *field continuation* was calculated with the OASIS montaj software whenever undulation of the topography was low. For some areas with rough topography, for example, the Harz Mountains and the Bavarian Forest, an algorithm developed by Grauch (1984) was used for field continuation between an irregular surface and the horizontal plane at 1000 m a.s.l.
(5) *Merging adjacent surveys* was carried out manually. For each gridpoint within the overlapping area of the survey under examination and the already processed part of the entire map, the differences of the anomalies were calculated. Then the survey under examination was shifted by the mean of the differences. Primarily, this mean value reflects the secular variation. Therefore, the mean of the

differences was always compared to data of magnetic observatories to check its reliability. To a minor amount it is also affected by other differences between the surveys (e.g. discrepancies in the original measurements due to the distribution of observation points and/or the lateral resolution of the surveys, data processing and interpolation of the data).

After adding this constant shift the differences between both data sets – the new data under preparation and the already processed part of the map – were recalculated. Discrepancies of ±5 nT were accepted. Wherever differences greater ±5 nT occurred during quality control, it was decided which data set was the more reliable by considering the original data. The corresponding gridpoints in the data set of lower quality were then eliminated.

The resulting map (Fig. 1) images reliable information for most wavelengths. Nevertheless, for very local studies of highest resolution the original data sets should still be used. Some local artefacts, which were included in the original data, as provided by third parties, could not be removed, for example, an apparent west–east lineament in the Austrian data. Also the very long wavelength part might be affected by the merging procedure, so that the use of satellite data might be more appropriate if the research target is related to very low frequency anomalies of low amplitudes.

4 FEATURES

The segmentation of the European crust is mainly due to the Caledonian and Variscan Orogenies. In Germany, from north to south, three different tectonic units can be distinguished (e.g. Walter 2007): (1) the Caledonides (with a Cadomic basement), (2) the German Variscides that comprise the Rhenohercynian Zone, the Saxothuringian Zone and the Moldanubian Region as main constituents, but also the Mid German Crystalline High (MGCH) and the Northern Phyllite Zone (NPZ) and (3) the Alpine system with the Molasse Basin (MB) in southern Germany and the Alps.

These tectonic segments are partially displayed by the magnetic anomaly pattern (Fig. 1), since each unit is characterized by its own geological history, petrographic composition and metamorphic grade. In northern Germany long-wavelength anomalies indicate deep-seated relicts of old Scandinavian crust below the sedimentary cover. The Rhenohercynian Zone is associated with predominantly negative anomalies, whereas the Saxothuringian Zone and the MGCH are clearly separated from the Rhenohercynian to the north and the Moldanubian to the south by their strong positive anomalies. The region of the MB, north of the Alps, is again dominated by anomalies of large wavelengths, that is, sources below the Molasse sediments.

One of the most prominent features of the new map is the broad belt of positive anomalies that runs from southwest Germany towards northeast with a significant change of its strike east of about 12°E, towards the Sudetes Mountains (Fig. 1). This belt consists of various separate anomalies that represent sources in the middle and shallow crust (magnetically multilayered crust), as evidenced by the spectrum of different wavelengths, which is fully preserved due to the reduced reference altitude. This line of positive anomalies correlates with the Saxothuringian Zone and especially with the MGCH to the north of it. Because of the complex lithological compositions of the MGCH and the Saxothuringian Zone (e.g. Oncken 1997), an unequivocal distinction between the units, based on the magnetic anomalies alone, is not possible. However their magnetic signature traces the Rheic suture through Germany (Kroner *et al*. 2008). Towards the east – that is, in the northern part of the Bohemian Massif (south/southeast of Leipzig) – the character of the magnetic anomaly pattern changes. More high-frequency anomalies occur that image magnetic sources which belong to a significantly different structural complex.

The position of the Variscan deformation front in northern Germany (border between units 1 and 2 in Fig. 1) is still a matter of debate, which is to some extent stirred by different interpretations of deep, cored boreholes. Consequently, the most recent interpretation published by Guterch *et al.* (2010) differs in detail from the geological overlay used here, as defined by the European Geotraverse Project (Berthelsen *et al*. 1992; Burollet *et al.* 1992). The magnetic anomalies might be used to define the rather schematically plotted borders between the different Variscan units more precisely, for example, by 3-D forward modelling.

5 APPLICATIONS

The new ΔT map for Germany images anomalies of different wavelengths at a resolution and completeness that was not available before. Therefore the new data set can be used to work on both fundamental and applied research, and also on a wide spectrum of wavelengths. In the following examples, some future applications are listed that are appropriate to recent developments in Earth Sciences and have only become methodically feasible with the more precise and homogenized data set, since specific tasks are directly linked to the main tectonic units in Germany. These are easily identifiable in the new magnetic map (Fig. 1).

5.1 Multiscale studies: crustal segmentation

In the Earth Sciences, a move from static description to an understanding of the dynamic evolution of processes in the Earth's crust or specific tectonic and geological regimes is evident. EarthScope activities, for example, aim for a deeper understanding of the structure, deformation and evolution of the North American continent. In this context, the gravity and magnetic database is also complemented to improve the characterization of the crust and to constrain geodynamic parameters (Ravat 2004). A similar project in Europe is TOPO Europe, which deals with the interaction of processes inherent in the deep Earth with surface processes, which together shaped the topography of Europe (Cloething *et al.* 2009). To image the condition of the crust on a regional scale with complete spatial coverage, potential field methods are the only appropriate methods. They allow the delineation of even old basement structures on continental scales, for example, the Precambrian basement structure of the continental United States, which has strongly influenced later Proterozoic and Phanerozoic tectonics (Sims *et al.* 2005). The precondition is a consistent and accurate data set that covers the entire spectrum of wavelengths to image both shallow and deep structures (Ravat 2004).

With respect to the Variscan basement in Germany, the source(s) for the magnetic anomalies that are associated with the MGCH are still a matter of debate (Kroner *et al.* 2008). Since anomalies in eastern Germany are now tied to those in western Germany in the new data set, without loss in resolution and are complemented by additional surveys in the former border-area, consistent quantitative modelling is now possible and sections of single lineaments of the MGCH can be traced with higher accuracy. In particular, comparison of magnetic anomalies and Bouguer gravity could enhance knowledge about the lithological and physical composition of the crust. With a quantitative, multiscale interpretation of the magnetic

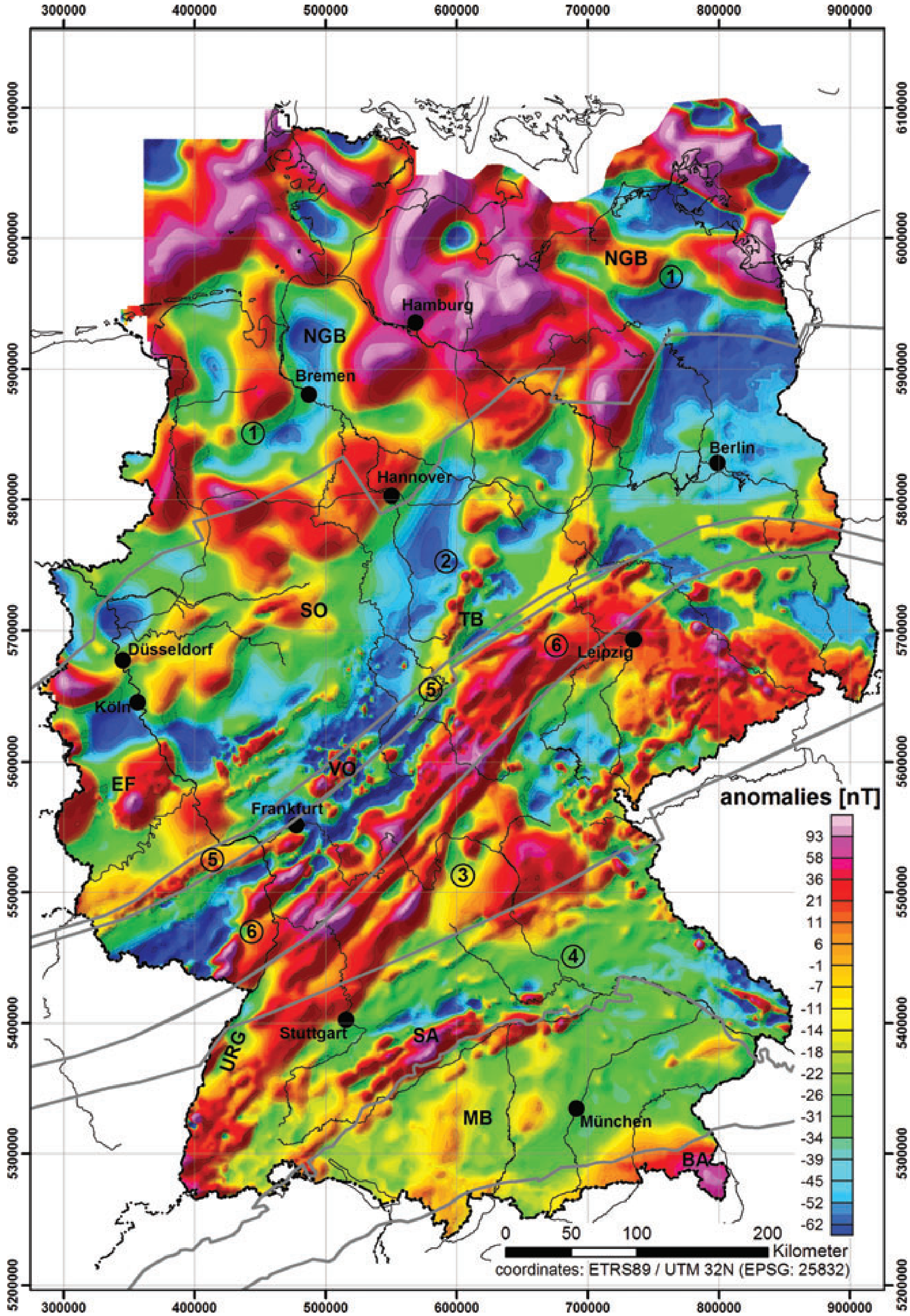

Figure 1. Anomalies of the Earth's total magnetic field in Germany (DGRF 1980, epoch 1980.0, reference altitude 1000 m). Illumination parameters: 310° declination, 35° inclination. Table S1 summarizes the data sets that were used in this compilation. 1, Caledonian Basement; 2, Rhenohercynian Zone; 3, Saxothuringian Zone; 4, Moldanubian Zone; 5, Northern Phyllite Zone (NPZ); 6, Mid German Crystalline High (MGCH); BA, Berchtesgaden anomaly; EF, Eifel; MB, Molasse Basin; NGB, North German Basin; SA, Swabian Alb; SO, Soest anomaly; TB, Thuringian Basin; URG, Upper Rhine Graben; VO, Vogelsberg. Tectonic lineaments after Berthelsen *et al*. (1992) and Burollet *et al*. (1992).

anomalies that considers both induced and remanent magnetization, new information (for more local anomalies the vector character of induced anomalies is now better resolved) about the evolution of a tectonic segment can be derived, which can be interpreted further in terms of tectonic processes or varying stress fields. As the German territory is now fully covered by the magnetic data, data from border-zone areas in France or the Czech Republic can complete the anomaly pattern and expand such studies for a more continental scale. Hence, Variscan structures in these countries, such as the Vogues Mountains or the Bohemian Massif, can be included in the discussion.

5.2 Regional scale: basin modelling

Currently a re-evaluation of potential hydrocarbon reservoirs in Germany is being undertaken by companies. The corresponding decision-making processes also consider potential field data. Key areas for the hydrocarbon exploration are the MB in southern Germany, the Upper Rhine Graben (URG) area in southwest Germany, the Thuringian Basin (TB) and especially the area of the North German Basin (NGB; Fig. 1).

Due to its position approximately east of the former intra-German border, data quality within the TB has been improved by this new compilation. Although the basin itself was completely covered by the data collected in East Germany before German reunification, modern investigations concerning its structure and evolution can now consider a more complete and homogenous data set, especially since gaps along the intra-German border have been closed by additional surveys and the East German data has been tied to the West German data.

The key area for hydrocarbon exploration in Germany is the NGB. It is part of the intracontinental Central European Basin and extents from west to east over entire North Germany. Its basement is formed by Caledonian rocks, originated from the collision between Gondwana and Avalonia (late Cambrian to Devonian, e.g. Walter 2007; Krawczyk *et al.* 2008). The broad positive anomaly of maximum 250 nT in central North Germany (Fig. 1) is envisaged to image old Scandinavian crust of high (normal polarized remanent) magnetization which is a relict of the collision between Baltica and Avalonia and located at depths around 10–15 km. The present-day structure of the NGB and regional differences in the basin evolution are the result of a differentiated subsidence history since Late Carboniferous/Early Permian (Walter 2007). Late Carboniferous/Early Permian crustal extension was accompanied by intense magmatism. Consequently, up to 2000-m-thick volcanic series of Lower Permian age were deposited, especially in the northeastern part of the basin – well imaged by magnetic anomalies of medium wavelengths. Sediment thicknesses (Permian, Mesozoic and Cenozoic) reach a maximum of 10 km (Franke *et al.* 1996; DEKORP-BASIN Research Group 1998). The basin was partly inverted during the Upper Cretaceous/Early Tertiary and has potential for both geothermal energy and hydrocarbons.

Re-evaluation of the hydrocarbon potential will include basin modelling. Complementary gravity, magnetic and seismic data provide fundamental information to derive information about the depth to the basin basement, its internal structure, as well as its geodynamic and thermal evolution. As reservoirs are often bound to individual subbasins or isolated troughs (Walter 2007) and the reservoir depths are between 1000 and 5000 m (gas reservoirs of Permian age: 3000–5000 m, oil reservoirs of Jurassic/Cretaceous age: 1000–2000 m) the potential field data must also image the short to medium wavelength spectrum. With the new compilation of the magnetic data this demand is fulfilled. Along the former intra-German border, the consideration of new magnetic data that was collected, especially after 1990, significantly changed the anomaly pattern between Schleswig–Holstein and Mecklenburg–Vorpommern.

5.3 Regional scale: applied rheological and petrophysical studies (geothermal proxies)

The petrophysical parameter that controls ΔT is the magnetization of the rocks. Above the Curie temperature rocks lose their ferromagnetic magnetization. The Curie depth is a proxy for the thermal condition of the Earth's crust, which is one of the main parameters that controls geodynamic processes. Therefore, enhanced knowledge about thermal conditions is crucial to quantitatively understand many geoprocesses and rheological physical parameters in general. In applied geosciences, the geothermal condition of the crust is the subject of increasing interest regarding the use of geothermal energy. As direct access to *in situ* data is often limited, only proxy data (such as Curie depths) can be used to determine the thermal structure.

Areas in Germany which are suitable for geothermal exploration are the NGB, the URG and the MB. The MB was formed by the collision of the African–Adrian Plate with the European Plate. This triggered the uplift and northward migration of the Alps and as a consequence a asymmetric foreland basin developed north of the Alps that was filled by Eocene, Oligocene and Miocene sediments, for example, conglomerates and sandstones (Walter 2007). The basement of the MB is composed of Variscan crystalline basement with some Permo-Carboniferous troughs and a 500–1000-m-thick Mesozoic unit. Consequently, this area is dominated by long-wavelength anomalies of the Earth's total magnetic field bounded by a belt of local anomalies in the north that is caused by near surface crystalline rocks of the Swabian Alb. In the southeast a strong positive anomaly (*ca.* 95 nT, Fig. 1) images the northern extent of the Berchtesgaden anomaly – the source of this is still unknown.

As the magnetic anomalies in Germany are already tied to those of the Alps, the MB can be analysed as regarding Curie depth distribution. Methodological approaches to estimate the Curie depth are based on the analysis of the radial power spectrum. Bansal *et al.* (2010) found for the MB increasing Curie depths from west to east and from north to south. This result correlates with the general distribution of heat flow density, which shows slightly decreasing values from west to east – although only sparse heat-flow data is available. Hence, Curie depths could be an appropriate proxy for the thermal structure of the crust in Germany but require further investigation.

5.4 Local scale: young volcanic structures

In addition to the discussed examples, which represent applications in the long to medium wavelength range, the new map also preserves information on the short wavelength scale. The most prominent examples are the famous young volcanic regions of the Eifel or the Vogelsberg, both located in central western Germany (Fig. 1). The complex geological structure of the Vogelsberg is well imaged by clusters of alternating local positive (max. 850 nT) and negative anomalies (min. –525 nT). Therefore, the map offers opportunities to quickly correlate the magnetic anomaly pattern with near surface geological structures. Even on this scale the vector character of the anomalies is imaged and enables qualitative interpretations: The anomaly close to Soest must be caused by a magnetic body of strong remanent magnetization, otherwise the positive part (*ca.* 85 nT) of the anomaly to the north of the main minimum (*ca.* –40 nT) cannot be explained with respect to the inclination of the current Earth magnetic field at this latitude (Fig. 1).

6 CONCLUSION

With this new map of the anomalies of the Earth's total magnetic field a homogenous data set for entire Germany is available that offers a broad potential for future applied and basic studies. The gridded data is available as an electronic supplement to this paper. The map, which is available as GIS-based version, can be updated at any time, as and when significant new surveys become available in the future. For instance, a new airborne survey that covers the German part of the North Sea is desirable. In summary, the first step towards dynamic modelling and process evaluation is available.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Magnetic data sets considered for the compilation of a complete and homogenous map of anomalies of the Earth's total magnetic field for the whole of Germany.

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