Genesis of magnetic anomalies and magnetic properties of archaeological sediments in floodplain wetlands of the Fossa Carolina

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Abstract
Floodplain wetlands are complex systems influenced by many natural and anthropogenic operators. Due to the influence of high and varying groundwater table and high organic contents, geophysical prospection in wetland floodplains quickly reaches the limits of its effectiveness. At the Early Medieval canal Fossa Carolina in southwest Germany, a study design employing magnetometry, drillings, sampling, and in situ rock magnetic measurements was used for environmental magnetic interpretation of magnetic anomalies in magnetograms and sediment layers. This approach offers reliable archaeological interpretation of magnetic anomalies and magnetic properties under the site specific sedimentological conditions of a floodplain wetland. It was also found that man-made magnetic anomalies in the floodplain are due to the genesis of different remanent magnetizations – specifically, greigite (Fe₃S₄) can cause distinct magnetic anomalies in floodplains that can be recognized readily in surface magnetic data.

KEYWORDS
geophysical prospection, magnetic anomaly interpretation, alluvial geoarchaeology, environmental magnetism, greigite, Fossa Carolina

1 INTRODUCTION

Alluvial and semi-terrestrial systems can contain remarkable archaeological record (Brown, 1997). Numerous archaeological and geoarchaeological studies have been carried out in alluvial systems during the last decades (Brown, 1997; Howard, 2003; Needham & Macklin, 1992). Every alluvial archaeological record represents a complex interaction between cultural and geomorphic operators (Needham & Macklin, 1992). To better understand the underlying material structure, the floodplain topography and its genesis must be considered, including all biological, chemical, and physical aspects of specific floodplain wetlands (Brown, 1997; Howard & Macklin, 1999). Various archaeological prospection techniques can contribute considerably to deciphering the complex material structure at all scales (Challis & Howard, 2006; Scollar, Tabbagh, Hesse, & Herzog, 1990). Site-scale magnetic prospecting is one of the most powerful and effective tools in archaeological prospection (Aspinall, Gaffney, & Schmidt, 2008; Fassbinder, 2015; Kvamme, 2009). However, alluvial environments are often considered problematic for magnetometry. Due to the limited depth range of magnetic prospecting the overlying sedimentary cover can offer difficult conditions for signal penetration (Clark, 1992). Also, the choice of instruments can produce different
results (Linford, Linford, Martin, & Payne, 2007). Nevertheless, site-dependent variables are the primary factors for the detection and interpretation of archaeological structures by magnetic prospection (Cuenca-Garcia et al., 2018; English Heritage, 2008). In this case the most important site-dependent variables are rock, sediment, and soil magnetism (Dunlop & Özdemir, 1997; Evans & Heller, 2003; Jordanova, 2017; Liu et al., 2012; Thompson & Oldfield, 1986). A broad understanding of these site-specific variables is necessary for detailed interpretation of significant archaeological structures in magnetograms (Fassbinder, 2015).

Man-made magnetic anomalies have been found at several sites in river floodplains (Weston, 2001), including Fossa Carolina (Zielhofer et al., 2014). So far, the genesis of these anomalies has only been discussed in general terms without considering the physical properties of floodplain sediments. Therefore, the aim of this article is to provide a detailed magnetic investigation of the genesis of magnetic anomalies in the floodplains of Fossa Carolina.

2 | STUDY AREA

In AD 792/793, Charlemagne started to build a navigable connection between the Rhine–Main catchment and the Danube catchment. This canal is called Fossa Carolina and was one of the major hydroengineering projects in Early Medieval Europe. Bridging of the Central European watershed was of high geostrategic relevance, due to the expanding fluvial communication and transportation network of the Franconian Empire at that time (McCormick, 2002; Werther et al., 2018). Nevertheless, the canal was never finished (Kirchner et al., 2018) and only remains of it are visible today (Schmidt et al., 2019; Schmidt, Werther, & Zielhofer, 2018). The post-Carolingian canal filling was reconstructed using excavation, drillings, and sediment analysis (Völlmer et al., 2018; Zielhofer et al., 2014).

The Fossa Carolina is located on a valley watershed between the Altmühl and Swabian Rezat Rivers in Franconia, Bavaria, southern Germany. The valley fills consist of Pleistocene sandy to loamy fluvial sediments. The canal has a length of 2.9 km, as proven by drillings (Kirchner et al., 2018; Zielhofer et al., 2014), archaeological excavation (Werther et al., 2015), and direct-push sensing (Hausmann et al., 2018; Völlmer et al., 2018). Furthermore, extensive multi-disciplinary research has been carried out at the Early Medieval canal over the last decade (Ettel, Daim, Berg-Hobohm, Werther, & Zielhofer, 2014; Hausmann et al., 2018; Kirchner et al., 2018; Linzen et al., 2017; Schmidt et al., 2018; Schmidt et al., 2019; Stele, 2017; Zielhofer et al., 2014). Therefore, the site offers an excellent case study.

Two sections of the Fossa Carolina floodplain were selected for our study: the West–East Section and the Northern Section (Zielhofer et al., 2014) (Figure 1). Both sections are located in the

**FIGURE 1** Study area and type locations in the northern floodplain of Fossa Carolina (ArcTron 3D GmbH, 2009; Bayerische Vermessungsverwaltung, 2012; CCM2, 2008; ESRI Europe Basemap, 2010; LitU-WMS, 2019)
foothills of the Weissenburger Alb of the southern Franconian Jura (Jätzold, 1962) at an elevation of 413 to 420 m above sea level. They are situated in water sensitive areas and covered by bogs, floodplain gley soils, and colluvial deposits (LfU-WMS, 2019; Zielhofer et al., 2014). The sections are divided by the current watershed. Due to construction of the canal the original watershed was relocated 850 m toward the northeast and the West–East Section (Zielhofer et al., 2014; Zielhofer & Leitholdt, 2014). At present, the areas differ slightly in composition and elevation: few remains of the original excavation ramparts of Fossa Carolina have been detected in the Northern Section by LiDAR (light detection and ranging) digital elevation models (DEMs), and the entire structure is clearly visible in the East–West Section (Figure 1).

3 | METHODS

The study design is illustrated schematically in Figure 2. It is based on a sequence and combination of geophysical procedures and on-site methods. Esri geographic information system (GIS) ArcGIS Desktop was used for geodata handling, management, spatial analysis, and mapping (Esri, 2019). For geodetic surveying of spatial data (e.g. magnetic surveys and drillings) a Topcon HiPer II global navigation satellite system (GNSS receiver) was used (Topcon, 2019). The entire workflow comprises magnetometry, identification of drilling sites, drillings, sampling, and in situ rock magnetic measurements. Environmental magnetic interpretation was carried out based on the results of the magnetometry and in situ magnetic measurements (Figure 2).

3.1 | Magnetometry

The magnetometry was carried out with a Bartington Instruments Grad601 dual fluxgate gradiometer. This portable system measures the gradient (1 m) of the vertical magnetic field component. Depending on topography a grid mode of 20 m × 20 m or 40 m × 40 m was used. The vertical gradient was measured at a ±100 nT range with a traverse spacing of 0.5 m and an interval of 0.25 m along each traverse (Bartington & Chapman, 2004; Bartington Instruments, 2019a).

Raw gradiometer data were processed with Geoplot 3.0 (Geoscan Research, 2019). Individual traverses were moved against each other to reduce spatial inhomogeneities (destaggering). Additional statistical treatment of the traverse data smoothed the magnetograms (zero mean traverse). By interpolation, the grids were transformed from 0.25 m × 0.5 m to 0.25 m × 0.25 m spatial resolution and integrated into the GIS for further analysis.

3.2 | Drilling campaigns

Based on the results of the magnetometry, drilling locations were defined using a GNSS receiver. The magnetic anomalies that indicate canal structures were sampled with two core transects of three cores each using a closed 50 mm polyethylene inliner (Figure 3).

3.3 | Magnetic susceptibility measurements

Volume magnetic susceptibility measurements were carried out with a Bartington Instruments MS3-Meter-MS2C sensor configuration to localize magnetically conspicuous layers in the core profile (Dearing, 1999). The closed inliners were passed through the loop of a MS2C-sensor and measurements were carried out with a spatial resolution of 2 cm and a susceptibility accuracy of ±2 × 10⁻⁶ SI (Bartington Instruments, 2019b). After mass anomalies (κ peaks) were identified in the cores, anomalies were sampled and their stratigraphic location determined by comparing the set of cores in the transects. Prior to their further analysis with a variable field translation balance (VTFB), the original samples were analysed for mass specific susceptibility (χ) and frequency dependent susceptibility (χfd%) with a Bartington Instruments MS3-Meter-MS2B sensor configuration (Bartington Instruments, 2019; Dearing, 1999; Dearing et al., 1996).

3.4 | Variable field translation balance (VTFB)

Field dependent and temperature dependent magnetization measurements (Krása, Petersen, & Petersen, 2007) were carried out on all samples with apparent mass anomalies. Hysteresis loops and backfield curves with the key points saturation magnetization (Ms), saturation remanent magnetization (Mr), coercivity force (Bc), and coercivity of remanence (Bcr) were estimated which allows a differentiation of
magnetic properties of mass anomaly producers (Day, Fuller, & Schmidt, 1977; Dunlop, 2002a, 2002b; Evans & Heller, 2003; Roberts, Tauxe, Heslop, Zhao, & Jiang, 2018). In addition, the shape of hysteresis loops and backfield curves allows a first magnetomineralogic typification (Fabian, 2003; Tauxe, Bertram, & Seberino, 2002; Tauxe, Mullender, & Pick, 1996). From temperature dependent magnetization measurements ($M/T$) Curie temperatures and crystallographic phase transitions of magnetic minerals can be inferred which allows identification of remanence carriers in the sample (Dunlop & Özdemir, 1997; Hanesch, Stanjek, & Petersen, 2006; Moskowitz, 1981). Visualization, analysis and interpretation of VFTB measurements were supported by the RockMagAnalyzer 1.0 software designed by Leonhardt (2006).

4 | RESULTS AND DISCUSSION

4.1 | Magnetometry results

Discussion of magnetometry results focuses on sections where significant anomalies point toward the ancient canal of Fossa Carolina with accompanying structures (Figure 3). Smaller anomalies are not considered. The anomalies described in the following have also been partially detected by superconducting quantum interference device (SQUID) and caesium magnetometer systems (Berg-Hobohm, Linzen, & Faßbinder, 2014; Linzen & Schneider, 2014; Zielhofer et al., 2014).

Several linear remanence-based anomalies of varying intensity are detected in the magnetograms (Figure 3). The three most prominent anomalies are located in the Northern Section. Over a distance of about 250 m, they are aligned in a north-south direction and are separated into several segments. In contrast to the two northern linear anomalies, the southern anomaly has lower intensities in its southern part and changes its course in the south-western part several times. In areas of high magnetic intensity, all three anomalies have a dipolar north-south alignment. The course of these intensive dipolar anomalies do not follow the Fossa Carolina, which lies about 15 m east between two clearly defined excavation ramparts (Zielhofer et al., 2014). In the fluxgate data of the Northern Section, Fossa Carolina is represented only by a weak positive (maximum 2 nT) linear anomaly which runs parallel to the three earlier-mentioned, intensive, dipolar anomalies.

In the West-East Section, the course of the canal can be detected clearly as a weak (~2 nT) positive linear anomaly between two excavation ramps. With a width of up to 5 m, the anomaly is particularly prominent in the western part. It is accompanied by weak negative linear anomalies in the north as well as in the south, where it follows the
outlines of a current drainage ditch. The northern negative anomaly for the most part follows the positive anomaly indicating Fossa Carolina. The intensity of the Fossa Carolina anomaly increases at the point where the entire structure changes to an east-northeast direction, then it decreases considerably until it disappears entirely in the southern part of the Northern Section.

4.2 Mass anomaly detection

For further analysis of the depth and characterization of the linear anomalies, the coordinates of the anomalies were measured. Several closed inliners were drilled from central areas of the linear anomalies. Volume magnetic susceptibility was measured at all inliners and compared with sedimentological and geoarchaeological findings from Zielhofer et al. (2014) for the cross-sections O and QP (Figures 4 and 5).

Results for cross-section O with the location of the boreholes in the concerned magnetogram are shown in Figure 4. Here, the ferrimagnetic mass anomalies are situated at a depth of 3.5 to 4 m in an organic backfill of the central canal area. They have relatively high \( \kappa \) values of up to \( > 350 \times 10^{-6} \) SI (core O, Figure 4). The sandy alluvial and colluvial sediment matrix (represented by core O1) have weak to moderate volume susceptibilities that rarely exceed \( 200 \times 10^{-6} \) SI. Moderate volume magnetic susceptibilities are also found in the pond sediments situated above the canal fillings (upper parts of cores O and O3). Thus, the combination of sedimentary data and volume magnetic susceptibility have a distinct pattern where only individual thin layers of organic canal fills have exceptional \( \kappa \) peaks. These peaks represent ferrimagnetic layers, which are responsible for the linear anomaly in the West–East Section. The two layers with the strongest signals (mass anomaly samples in Figure 4) were, therefore, used for VFTB measurements.

The volume magnetic susceptibility of sediments from the QP cross-section in the Northern Section of Fossa Carolina are shown in Figure 5. In core QP4 only the fossil soil has slightly elevated \( \kappa \) values of \( > 200 \times 10^{-6} \) SI. Thus, QP4 represents the weak and moderate magnetic sediment matrix of the Northern Section. Canal fillings in the Northern Section are represented by core QP1. Similar to core O (Figure 4), several organic canal fill layers have \( \kappa \) peaks that indicate ferrimagnetic behaviour with \( \kappa \) values of \( > 550 \times 10^{-6} \) SI. The sandy alluvial sediments have typical alternating of weak and moderate magnetic layers. The upper canal fills with pond sediments also only have weak to moderate \( \kappa \) values, while volume magnetic susceptibility increases again in the upper colluvial sediments.

Core QP2 (Figure 5) from the central of the intensive, dipolar anomaly has an entirely different pattern. With values exceeding \( 45000 \times 10^{-6} \) SI, a mass anomaly at a depth of 1.35 to 1.55 m has the highest volume magnetic susceptibility of all samples. At a depth of

**FIGURE 4** Cross-section O of the West–East Section with magnetogram (20 m × 20 m) and drilling locations (top). Simplified stratigraphy (cf. Zielhofer et al., 2014) with matched MS2C-volume susceptibility (\( \kappa \), SI units) measurements on the closed inline cores (dots = measurements, line = spline interpolation of the measurements) (below)

**FIGURE 5** Cross-section QP of the Northern Section. Simplified stratigraphy (cf. Zielhofer et al., 2014) with matched MS2C-volume susceptibility (\( \kappa \), SI units) measurements on the closed inline cores (dots = measurements, line = spline interpolation of the measurements)
2.30 m below ground, this strongly ferrimagnetic layer is duplicated by strata with maximum $\kappa$ values of $15 \times 10^{-6}$ SI. Interbedded are sandy alluvial sediments with moderate $\kappa$ values between 80 and $150 \times 10^{-6}$ SI. The upper colluvial sediments also have moderate maximum volume magnetic susceptibility of $200 \times 10^{-6}$ SI. For further analysis of the mass anomaly remanence carriers, samples for VFTB measurements and mass specific and frequency dependent susceptibilities were taken from the layers with (extremely) high $\kappa$ peaks in QP2 and QP1 (Figures 4 and 5).

4.3 | Magnetic properties of mass anomaly samples

Hysteresis loops for all mass anomaly samples in Figure 6 have high-field slopes that indicate the presence of paramagnetic minerals. After the high-field slope corrections of hysteresis loops (not shown), analysis of the coercivity curves (Figure 7) and thermomagnetic measurements (Figure 8), the mass anomaly samples can be divided in to three groups (see also Table 1) as follows.

1. The first group consists of samples 2 and 4 from the linear, intensive, and dipolar anomaly in core QP2. Both samples are entirely saturated at 200–250 mT and have high $M_s$ and mass $\chi$ (Figure 6(E, F) and Table 1). The $\chi_{\text{tot}}$ value and its ratio with $\chi$ indicate superparamagnetic (SP) enhancement as a result of burning (Dearing, 1999). Hysteresis measurements point to the magnetite type with only sample 2 having a potbellied hysteresis loop shape parameter (Fabian, 2003). The values of $B_C$ and $B_{CR}$ are relatively low, which indicates soft magnetic material and, thus, high magnetic viscosity of the remanence carrier. Hysteresis and coercivity ratios of both samples indicate vortex state, a mixture of different magnetic grains (Day et al., 1977; Dunlop, 2002a; Roberts et al., 2017). The thermomagnetic measurements in Figure 8(Q–X) and the calculated dominant magnetic phase transitions have marked differences (see also Table 1). The heating cycle of sample 2 (Figure 8(R)) has a magnetization increase between 150 and 250 °C. This range demarcates the Curie temperature which could point to titanomagnetite ($\text{Fe}_2\text{TiO}_4$) (Dunlop & Özdemir, 1997; McElhinny & McFadden, 2000; Soffel, 2002). The heating curve for sample 2 then decreases to zero magnetization at 600 °C. The heating curve for sample 4 (Figure 8(V)) has a convex shape until it rapidly reaches zero magnetization at 560–630 °C (see second derivative in Figure 8(W)). The calculated dominant phase transition (Table 1) points to Curie temperature of magnetite ($\text{Fe}_3\text{O}_4$) as the dominant remanence carrier (Dunlop & Özdemir, 1997; McElhinny & McFadden, 2000; Soffel, 2002).

![FIGURE 6](image1)

**FIGURE 6** Magnetic hysteresis loops of mass anomaly samples without high-field slope correction are shown and assigned to the respective core column (cf. Figures 4 and 5). For each case, hysteresis and coercivity ratios are shown in the lower right-hand corner. Definitions of magnetic hysteresis parameters and ratios as well their limitations are discussed by Roberts et al. (2018)

![FIGURE 7](image2)

**FIGURE 7** Backfield demagnetization curves of mass anomaly samples. The sample number is on the left side of each curve (cf. Figures 4 and 5) with the group membership (see text) behind the number of sample. The curves reflect classification of samples into three groups. Backfield demagnetization curves, associated hysteresis parameters and ratios and their limitations are discussed by Roberts et al. (2018)
There are two notable abnormalities in the $M/T$ measurements. The cooling and heating curves for both samples are similar (Figure 8(S) similar to Figure 8(T) and Figure 8(W) similar to Figure 8(X)) and the cooling curves are weaker than the heating curves (Figure 8(Q, U)). This indicates that there was little thermally-induced transformation throughout the thermomagnetic experiments and, thus, that the samples have been heated to above 700 °C prior to the $M/T$ measurements.
2. The second group consists of sample 10 from core O (Figure 4) and sample 6 from core QP1 (Figure 5). They have relatively low mass specific magnetic susceptibilities and measurable proportions of SP content (Table 1; (Dearing et al., 1996)). They reach \( M_s \) at 230 and 280 mT (Figure 6(A, C)). In contrast to samples from group 1, they have relatively low \( M_s \) and much higher \( B_C \) and \( B_{CR} \). The hysteresis loop shape for both samples is distinctly potbelly shaped (Fabian, 2003). The ratios \( M_{BS} \) and \( B_{CR}/B_C \) indicate the dominance of high coercivity single domain (SD) particles. The heating cycles for both samples (Figure 8(B, J)) have three temperature dependent magnetic phase transitions. The first transition is marked by a bend in the heating curve with an increase of magnetization at 100 °C, demarcation the Curie point of goethite (FeOOH) (Dunlop & Ozdemir, 1997). The then following steady magnetization increase ends abruptly at 350 °C, which is indicative for a maximum unblocking or alteration temperature of greigite (Fe3S4) (Skinner, Erd, & Grimaldi, 1964) as the dominant solid magnetic carrier (Table 1). The coercivity remanence \( B_{CR} \) for sample 8 is high (Figure 6(D) and Table 1), which indicates probably SP enrichment (Rowan & Roberts, 2006; Rowan, Roberts, & Broadbent, 2009).

3. The third group consists of samples 8 (core QP1) and 12 (core O). Stratigraphically, these samples were situated below the samples from group 2 and are, thus, also part of the canal fillings (Figures 4 and 5). Although they have different hysteresis and backfield parameters, they have a similar thermomagnetic behaviour (Figure 8(E-H, M-P)). Both heating curves decrease rapidly at 300 °C to 400 °C, which demarcates greigite as the dominant remanence carrier (Table 1). During the heating cycle greigite transforms entirely to magnetite. However, the greigites in samples 8 and 12 have different particle size distributions, as indicated by different hysteresis and coercivity ratios (Figure 6(B, D); Sample 8 is already saturated at 250 mT, while sample 12 reaches saturation at 300 mT). Also, \( B_{CR}/B_C \) for sample 8 is high (Figure 6(D) and Table 1), which indicates probably SP enrichment (Rowan & Roberts, 2006; Rowan, Roberts, & Broadbent, 2009).

### Magnetic anomaly interpretation: an environmental magnetic perspective

The magnetic properties of the various mass anomaly samples responsible for the linear magnetic anomalies in magnetograms at Fossa Carolina originate not only from different natural remanent magnetization (NRM), but also from different post-depositional genetic processes (Evans & Heller, 2003; Liu et al., 2012). The linear, intensive, and dipolar anomaly originates in a 40 cm thick layer of black, reddish-brown and red layers at a depth of 1.35 to 1.55 m. The highest \( \chi \) values occur in a brown to reddish-brown, layer with a high allochthonous, ferrimagnetic titanomagnetite fraction. The high viscosity of the soft magnetic titanomagnetite and magnetite triggered the orientation of the remanence carriers in the soft water-soaked sediments toward Earth’s magnetic field vector, thus causing intensive dipolar anomalies. In areas with simple positive magnetic anomalies, we assume that these layers are not under the influence of ground water (south of the Northern Section in Figure 3).

In natural environments titanomagnetite formation can occur in two forms:

i. **Primary formation of titanomagnetite** can only take place in magmatic rocks (Schmincke, 2010; Schön, 2011).

ii. **Secondary formation** can take place due to weathering in soils on basaltic rocks (Fassbinder & Bondar, 2013; Jordanova, 2017).

There are no basaltic rocks or their weathering products in the river basin of the Swabian Rezat (ArcTron 3D GmbH, 2009; Schmidt-Kaler, 1976). Therefore, the magnetic mass anomalies of the group 1

### Table 1

| Sample number | 2 | 4 | 10 | 6 | 12 | 8 |
|---------------|---|---|----|---|----|---|
| Group (explained in the text) | 1 | 1 | 2 | 2 | 3 | 3 |
| \( \chi \times 10^{-6}m^3/kg \) | 47.4 | 38.2 | 0.3 | 0.2 | 0.1 | 0.2 |
| \( \chi_{fd\%} \) | 4.2 | 6.6 | 3.7 | 2.8 | 2.6 | 5.4 |
| \( M_s \) (e-005 Am²/kg) | 140 | 131 | 6.1 | 8.5 | 1.5 | 0.8 |
| \( M_{BS} \) (e-005 Am²/kg) | 20.1 | 18.7 | 31.4 | 34.5 | 23.8 | 11.5 |
| \( B_C \) (mT) | 6.8 | 6.4 | 19.1 | 47.1 | 50.9 | 38.4 |
| \( B_{CR} \) (mT) | 21.9 | 571 | 348 | 359 | 467 | 434 |
| \( M/T \) transition heating cycle (°C) | 279 | 397 | 420 | 456 | 574 | 548 |
| \( M/T \) transition cooling cycle (°C) | 178 | 597 | 420 | 456 | 574 | 548 |

Explanation of the abbreviations in the first column: \( \chi \), mass specific magnetic susceptibility; \( \chi_{fd\%} \), frequency dependent magnetic susceptibility; \( M_s \), saturation magnetization; \( M_{BS} \), saturation remanence; \( B_C \), coercivity; \( B_{CR} \), coercivity remanence.

*Calculated dominant thermomagnetic phase transition is shown (calculating method: second derivative) (see also Figure 8).
samples must have been produced by an allochthonous/anthropogenic influence. This is supported by the fact that sediment colours and magnetic properties of these layers show clear signs of fire exposure. The findings of Zielhofer et al. (2014), that the titanomagnetite/magnetite layer, which produces the intensive dipolar anomaly, correlates stratigraphically with the construction of Fossa Carolina, and the fact that these intensive anomalies in the SQUID data of Linzen and Schneider (2014), which show that the same remanence carriers are found in the entire northern part of the canal, support the interpretation of the mass anomalies as anthropogenically introduced/influenced and burned materials. Additional (geo) archaeological research is necessary to determine the source and specific characteristics of this material.

Greigite-generated mass anomalies (groups 2 and 3), which partially follow the course of the canal and of the canal fills, is supported by the fact that samples 6 and 10 have similar magnetic behaviour as the SD greigites found by Faßbinder and Stanjek (1994). Hall, Cisowski, and King (1997), and Roberts et al. (1998). The characteristics of sample 12 are comparable to those reported by Jelinowska et al. (1998). The magnetic properties of sample 8 relate to genetic processes, which we interpret to be similar to those described by Rowan et al. (2009). All layers with greigite-generated mass anomalies may have undergone post-sedimentary remagnetization: These highly coercive SD greigites were generated as secondary/authigenic formations under highly organic, anaerobic conditions after deposition of the organic rich canal fills. Thus, the organic canal fills offered the necessary conditions for producing mass anomalies due sulphidic remanence carriers and the sediments acquired their stable chemical remanence magnetization (CRM) (Snowball, 1997). These findings are similar to those of Stanjek, Fassbinder, Vali, Wägele, and Graf (1994) in gley soils, where the environmental conditions were similar to those in the canal fills. Also, the hysteresis and coercivity ratios of the greigite in the canal fills point at differences in the domain state of the dominant solid FeS magnetic phases. For a correct domain state diagnosis, further analyses such as FORC diagrams or scanning electron microscopy/transmission electron microscopy (SEM/TEM) observations are necessary (Chang et al., 2014; Roberts et al., 2019). Should these methods deliver uncertain results, methods such as X-ray diffraction could also be used (Linford, Linford, & Platzman, 2005).

In order to make such magnetic and non-magnetic analyses possible in the future, we recommend the use of closed polyethylene inliners when drilling/sampling, because they allow longer storage of the samples without any changes in the magnetic mineralogy during the storage (Stele, 2017). Samples for in situ magnetic measurements should be then taken from the inliner immediately before analysis. This sample preparation approach prevents the oxidation of possible ferrimagnetic iron sulphides in the samples.

5 CONCLUSIONS

At the Fossa Carolina in southern Germany a workflow comprising magnetometry, identification of drilling sites, drillings, sampling and rock magnetic measurements was used to interpret magnetic anomalies. The approach offers a reliable estimate of:

- the depth of magnetic mass anomalies;
- differentiation between natural and anthropogenically induced structures; and
- genetic processes leading to the production of mass anomalies.

Our results indicate that secondary/post-sedimentary processes in the canal fillings produced magnetic anomalies in the Fossa Carolina. Greigite-generated mass anomalies in deeper sediment layers can cause detectable anomalies in near-surface magnetic surveys with a 1 m fluxgate at a depth of up to 3.5 m. There is also strong evidence that titanomagnetite/magnetite-generated mass anomalies at Fossa Carolina were anthropogenically introduced. Evidence of greigite in organic-rich canal fills in a European Watershed means that these processes can be expected in palaeochannels or active channels in middle European floodplains with similar characteristics.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this article.

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