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Methodological Observations on Magnetic Prospecting at Two Hallstatt Period Enclosures in Bavaria

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Abstract
The magnetometer surveys of two Hallstatt earthworks in Bavaria are used to highlight some operational and methodological conspicuous observations that can occur during data acquisition and processing. Two common types of magnetometers are used and compared. The highly sensitive caesium total field magnetometer and fluxgate gradiometer measurements are additionally supplemented by a drone photogrammetry survey. The two archaeological sites have different conditions in terms of land use, crop type, soil type, hydrology and magnetic contrast. There are also different states of the Earth's magnetic field at the respective survey periods. Regarding the detection ability of the instruments, it was found that environmental conditions such as hydrology and soil type are limiting the significance of the results. The other environmental factors, such as the Earth's magnetic field or ground conditions, can be controlled by a skilful and well-thought-out choice of instrument and time of prospecting.

Keywords: magnetogram interpretation; caesium magnetometers vs. fluxgate gradiometers; drone photogrammetry; geophysics on wet and waterlogged soils; solar magnetic storms.

1. Introduction and objective

The structurally representative enclosures of the Hallstatt period (or *Hallstattherrenhöfe* in German) are one of the most spectacular Iron Age earthwork types in Central Europe. The German research into this archaeological feature began in the mid-1970s in Bavaria. Here, more than 200 Hallstatt period earthworks are known nowadays. Like all other archaeological monuments, they are listed in the Bavarian monument inventory.

Aerial archaeology contributed significantly to the rapidly increasing number of new discoveries of Hallstatt enclosures, especially in the years between 1978 and 1982. Since the mid-1980s and until 2002, new enclosures have been detected by aerial archaeology at least every 3 years (Berg-Hobohm 2003). Current distribution maps show that most of them are located on fertile, loess-covered lowland margins and terraces or (more rarely) in the floodplains of larger rivers. Other factors are probably access to watercourses and good conditions for trade through transport favours. The Danube and Isar valleys and their tributaries are the main geographical areas of occurrence in Bavaria (Fig. 1). With regard to the detection and inventory of archaeological monuments, current heritage management practice requires the most reliable, multi-layered conclusions about the characteristics of the archaeological features to be expected in the subsurface and geodetically accurate plans of their layout. The creation of such plans is not always possible with the help of aerial archaeology alone, especially in the case of a thick covering of the archaeological feature, for example by colluvium. Total field and vector field magnetometry are particularly efficient for detecting and drawing up plans of complex and heavily covered Hallstatt enclosures. Helmut Becker carried out the first magnetometer surveys on *Hallstattherrenhöfe* in Bavaria in 1978. Since then, geophysical prospection of this type of archaeological monument has been one of the long-standing research projects of the BLfD's Archaeological Prospecting Group. Moreover, the Hallstatt research and the development of archaeological prospection methods in Bavaria, especially magnetometer prospection, are directly related and have been stimulating each other for years (Stele et al. 2023a).

Today, 45 of the Hallstatt enclosures are documented using magnetometer prospecting. Two of them were surveyed in the 2022 season: the enclosures at Oberstimm (Obs22) south of Ingolstadt and at Hartkirchen (Hkn22) in the lower Vils valley (Fig. 1). These two enclosures shall serve as examples of some methodological conspicuities that prospectors may be confronted with during interpreting magnetic survey data of such archaeological structures.

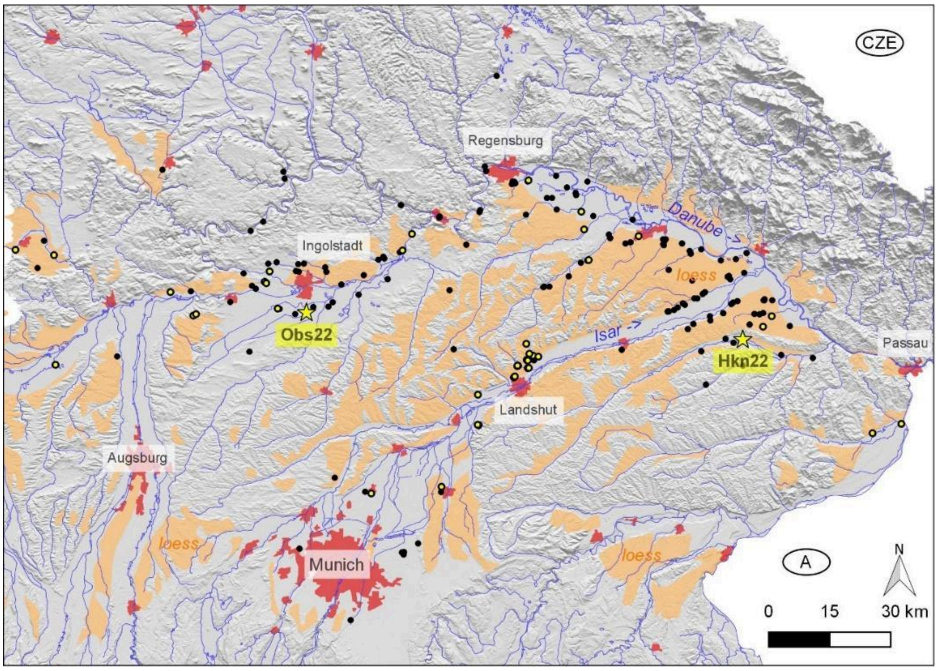

Fig. 1. Distribution of all known Hallstatt period enclosures (black dots) and all geophysically prospected Hallstatt enclosures (black-yellow dots) in Bavaria. The location of the discussed enclosures is marked with black-yellow stars. Background: BAG 500 (soil parent material map): © Bayerisches Landesamt für Umwelt (2011), DGM 50 (50 m res. digital topography model): © Bayerische Vermessungsverwaltung, www.geodaten.bayern.de (2019). Figure credits: Andreas Stele.

2. Survey methods, instruments and data handling

Two different types of magnetometers were used to record and document the two Hallstatt earthworks. The carried Geometrics G858 duo-sensor caesium total field magnetometer (G858, Geometrics 2024) was used in grid mode to survey the enclosure at Hartkirchen (Fig. 2A). This highly sensitive instrument works uncompensated and is ready for use after a short warm-up phase. We are using the G858 in areas with little magnetic disturbance, primarily to document older archaeological features or in cases where low magnetic contrasts are to be expected. The most important operating parameters for the G858 are shown in Tab. 1.

As the ditches of Hkn22 could not be detected using magnetometry, but were visible in the fine ground relief on-site, drone photogrammetry was additionally used in Hartkirchen to produce a high-resolution digital surface model (DSM) of the site. For this purpose, we applied a DJI Inspire 2 drone equipped with a Zenmuse X4S camera offering a 20 Megapixel resolution. The enclosure at Hartkirchen was covered through an automatic flight plan in 40 m altitude resulting in a 1.1 cm resolution of the photos. The overlap of the parallel trajectories was 70% and the overlap between the single photos was set to 80%. This guarantees ideal data for a photogrammetric data processing executed afterwards in Agisoft Metashape (Agisoft 2024). Due to strong wind conditions during the survey, the flight traces were tilted towards the main wind direction. The data processing to gain the DSM included all standard steps like e.g.

alignment of the photos, creation of a dense point cloud, positioning of ground control points in RTK accuracy and calculation of DSM. The resulting DSM has a resolution of 2 cm.

Instrument	*Sensor type*	*Number of sensors; spatial resolution*	*Sample rate*	*On-site sensor resolution (5m std)**	*On-site sensor resolution (5s std)**	*Maximum survey progress per day*
Geometrics G858	Optical pumped caesium total field magnetometer	2; 0.1 x 0.5 m	10 Hz	0.567 nT	0.024 nT	1.6 ha
Sensys MXPDA	Fluxgate gradiometer with a ΔZ gradient of 0.65 m	5; 0.01 x 0.5 m	100 Hz	0.202 nT	0.150 nT	3.5 ha

*The respective sensor resolution is given as standard deviation (std) for a 5-minute measurement (5m std) and for the 5 seconds after the 3rd second (5s std). For further details on measurement and calculation of sensor resolution, see Stele et al. 2023b.

Tab. 1. The most important operating parameters for the magnetometers used

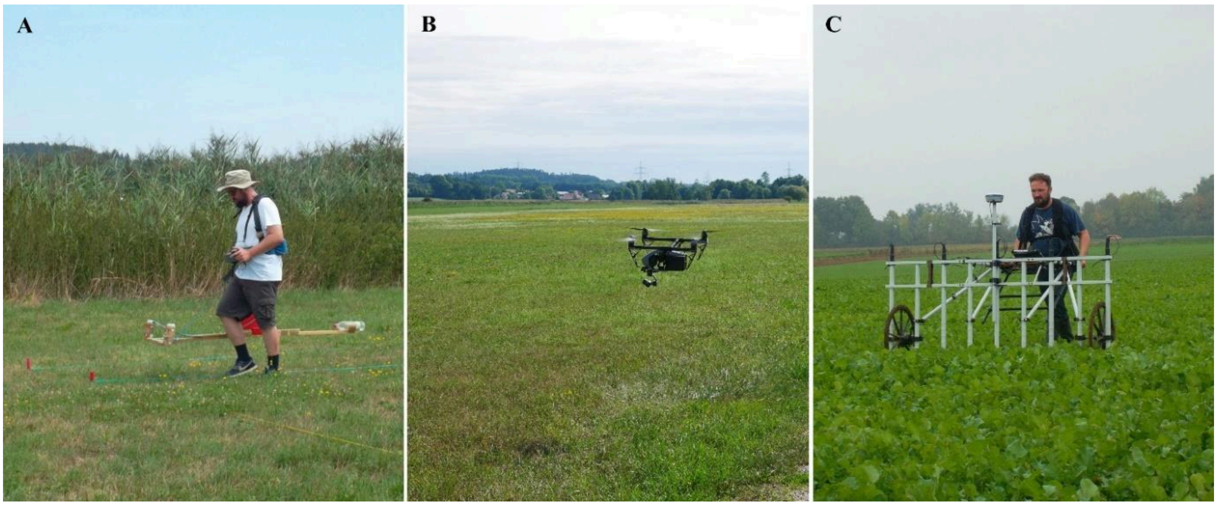

Fig. 2. Prospection instruments used: Geometrics G858 duo-sensor total field magnetometer during the survey in Hartkirchen (A); DJI Inspire 2 drone for the photogrammetric survey in Hartkirchen (B); five-channel Sensys MXPDA fluxgate gradiometer with a wheeled frame during the survey in Oberstimm (C). Figure credits: Tatjana Gericke and Roland Linck.

The region around Ingolstadt is considered as magnetically turbulent due to the industrial and former military infrastructure; therefore, the stable, wheeled five channel magnetic gradiometer Sensys MXPDA (MXPA, Sensys 2024) was used to survey the Obs22 Hallstatt enclosure (Fig. 2C). The real-time measurements of the five 0.65 m gradient fluxgate sensors were calibrated to zero before the survey, they do not need a further compensation during the measurement. We performed the survey in grid and Global Positioning System (GPS) mode using the Real Time Kinematic Antenna Stonex 900A. Like all fluxgates, the MXPDA is subject to a certain temperature drift, but it offers an excellent survey progress and a reasonable sensor resolution for archaeological prospection (Tab. 1).

The survey data of the grid mode of both magnetometers were processed using Geoplot 4 (Geoscan Research 2024). The processing included filtering (Zero Mean Grid for G858; Zero Mean Traverse and Low Pass Filter for MXPDA), geometric corrections (Destagger) and interpolation of the data to 0.25 x 0.25 m magnetograms. The GPS mode data of the MXPDA were filtered in MonMX (using Moving Median Filter with 25 m window), converted to an ASCII file in MAGNETO and interpolated to a 0.25 x 0.25 m magnetogram in Quantum GIS (QGIS 2024; Sensys 2024). The analysis, spatial combination and visualisation of all survey data was also carried out in QGIS.

3. Results and discussion

3.1 Observations in Oberstimm

As already known from numerous aerial photographs, the Hallstatt period enclosure consists of three ditches and clear gateway situation in the south of the earthwork. The total extent of the Hallstattherrenhof is about 90 m (East-West direction) by 76 m (North-South direction); the area within the inner ditch is about 0.3 ha. Fig. 3 shows the respective survey areas in Oberstimm, the results of the magnetometer prospection, an interpretation plan of the site and the superimposition with other geodata.The outer two enclosure ditches are open to the North-North-West, obviously to the former course of the creek or the former edge of the terrace. The inner ditch is only opened in the area of the gate; otherwise, it completely encloses the inner area of the earthwork. North of this entrance are two parallel rows of post pits marking a gatehouse. Near to the southwestern post pit of the gatehouse, a linear structure runs parallel to the ditches towards the west. It is most clearly visible on some aerial photographs and can be interpreted as a palisade track belonging to the gatehouse. The exit/entrance runs through this gateway, towards the south, and the outer two ditches had to be crossed by a bridge. In the northern interior of the enclosure, in the northwestern and northeastern corners respectively, two anomalies exist, which can be interpreted as so-called Hüttenlehmgräber (daub graves in English) due to their thermoremanent characteristics. The fillings of the southeastern, inner ditch should also be seen in this context: here the daub backfill exhibits even more pronounced thermoremanent behaviour (Fig. 3B). Such observations can often be made within large Hallstatt earthworks or in their ditches. It is assumed that after destruction, remains of the burnt exterior plaster of the houses were disposed of in ditches or larger pits inside some bigger Hallstatt enclosures (Fries-Knoblach 2023). Perspectively, such archaeologically well-dated Hallstatt period daub graves could be used in the future to better understand younger palaeomagnetism and to improve the archaeomagnetic dating method (Stele et al. 2023a).

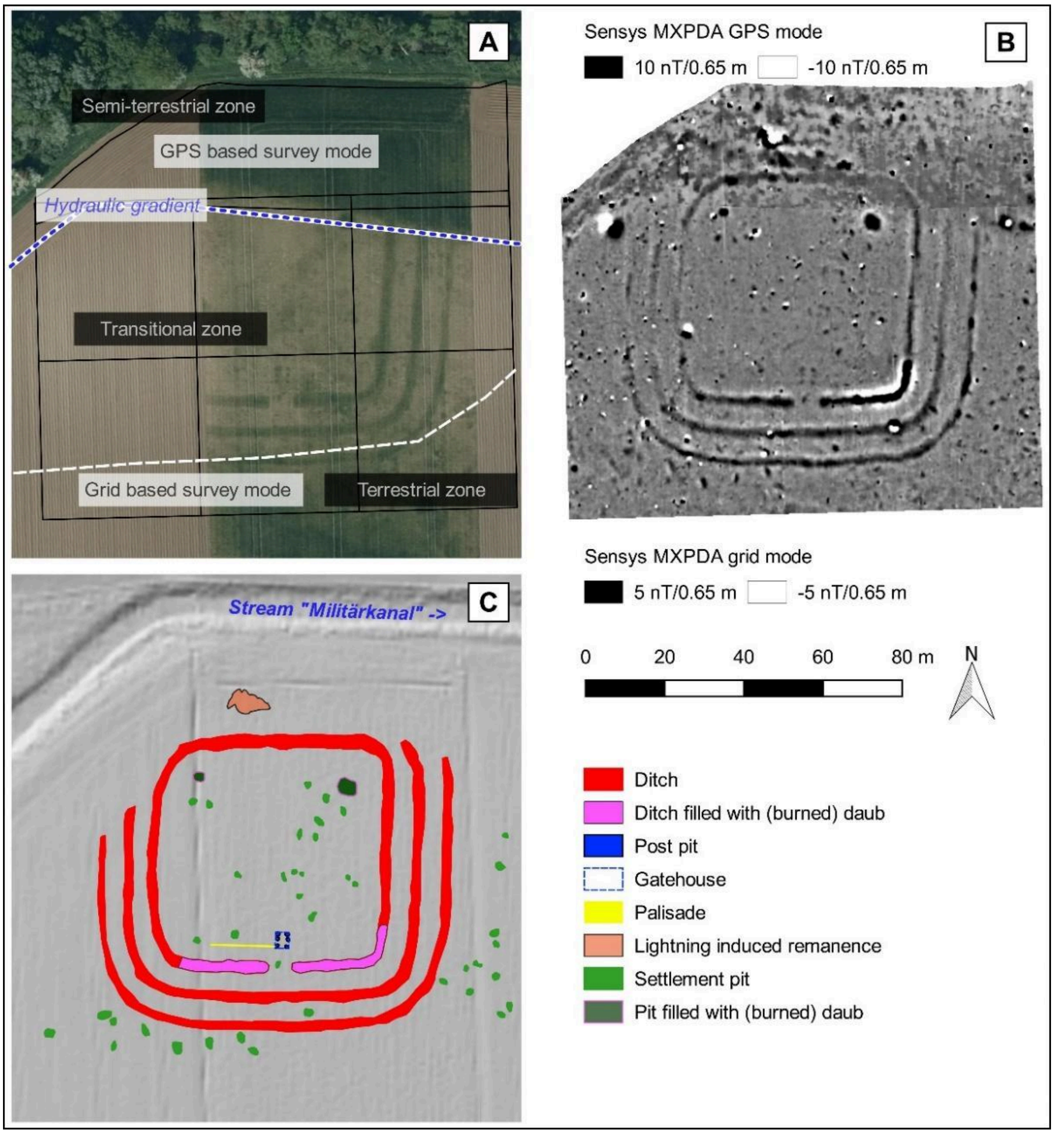

Fig. 3. Prospecting results in Oberstimm: Magnetometer survey and the aerial photography supported soil hydraulic interpretations are shown in A. In B, the merged magnetograms from grid and GPS mode of the MXPDA gradiometer are visualised. In C, the archaeological interpretation of the magnetic survey is shown. Magnetic survey parameters: Sensys MXPDA 5 channel gradiometer, measurement point density 1 x 50 cm, interpolated to 25 x 25 cm. Background: DOP 2018 (digital orthophoto from 2018) and DGM 1 (1 m res. digital topography model): © Bayerische Vermessungsverwaltung, www.geodaten.bayern.de. Figure credits: Andreas Stele.

The Obs22 enclosure is located on a Würm glaciation era low terrace and consists of meltwater gravel. Due to its location close to a stream, semi-terrestrial, waterlogged soils in the north and terrestrial soil areas in the south of the survey area can be sharply separated using the magnetograms and aerial photographs (Fig. 3A). However, there appears to be a transition zone with temporally waterlogged soils that can only be identified by the anomalies marking ditches. While these anomalies appear positive in the terrestrial zone, in the transition zone they are blurred and gradually become negative. This can be explained by a soil water flow leaching of magnetic particles from the ditch fills due to the change of pH conditions during the seasons and field crop rotation (Cunningham et al. 2001). As a result, the surrounding natural soil exhibits higher magnetic susceptibilities than the ditch fill. Therefore, the ditches partly show up as negative anomalies. Nevertheless, this does not apply to the inner ditch, which appears as a clear positive anomaly in semi-terrestrial areas. Presumably, its ferrimagnetic fills are situated above the subsoil hydraulic gradient and are not affected by the leaching processes (Fig. 3B).

The numerous positive magnetic anomalies in the semi-terrestrial zone could be settlement pits as well as spots of magnetic iron oxide or iron sulphide enrichment in peat or organic-rich soil lenses. Their formation could be related to the partly anthropogenically induced translocation processes explained above: i.e. the magnetic particles are "washed out" in the transition zone, transported into the semi-terrestrial zone and enriched there. A clear archaeological interpretation of such structures in waterlogged soils is therefore fraught with great uncertainty. These structures were therefore not included in the corresponding interpretation plan in Fig. 3C.

In contrast to archaeological features in the semi-terrestrial zone, an anomaly that can be attributed to a lightning strike (LIRM or Lightning Induced Remanence Magnetization) is well identifiable in the north of the survey area (Fig. 3B). Most of the ferrimagnetic aggregate (fulgurite?) seems to have been eroded by the plough because the anomaly does not have a typical star-shape anymore (Fassbinder 2015).

During the processing of the MXPDA data from Oberstimm, a methodological aspect was noticed that concerns the wheeled frame. After filtering the data, more or less regular noisy tracks became visible in the grid-based data (Fig. 4). These noisy tracks are particularly easy to recognise in a trace plot (Fig. 4B). They run parallel to the measurement direction and correspond spatially with the tractor tracks in the field. When driving on dry and relatively hard tractor tracks, strong vibrations of the instrument were also recognised during the data acquisition. The noisy tracks are as wide as the instrument swath and are obviously caused by vibrations generated by the wheeled, unamortised MXPDA rack.

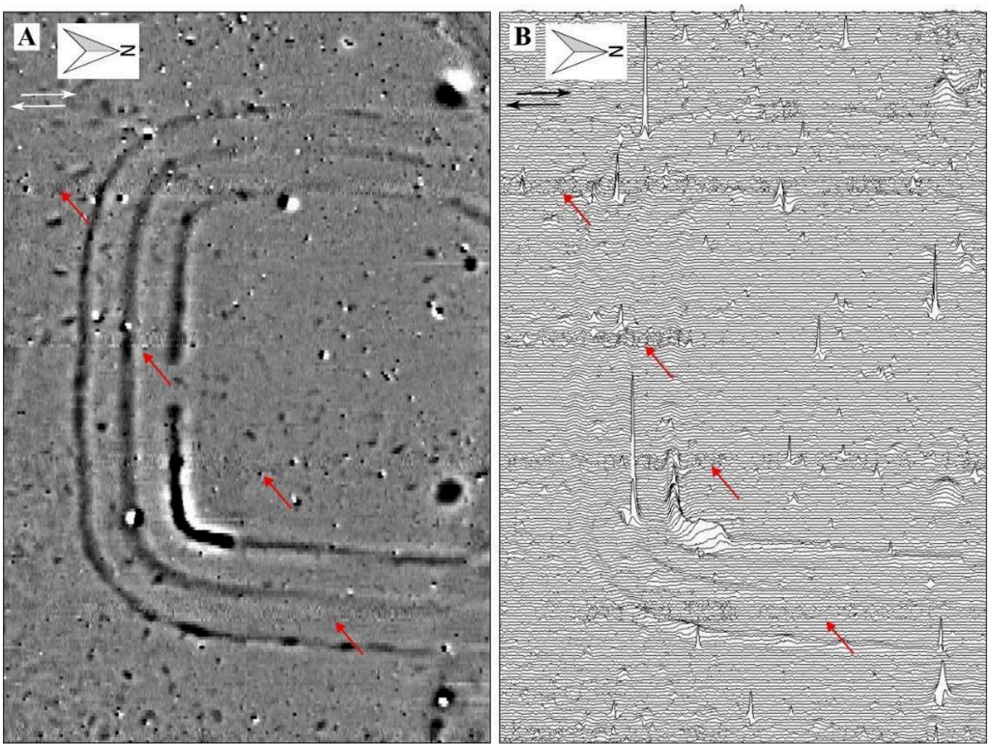

Fig. 4. Shade plot (A; ±7nT, positive=black/negative=white) and the corresponding trace plot (B; resolution 1.7) of the grid based MXPDA data in Oberstimm. The noisy tracks are marked with red arrows. Black and white arrows indicate the direction of walking during data acquisition. Figure credits: Andreas Stele.

3.2 Observations in Hartkirchen

The Hkn22 Hallstatt period enclosure near Hartkirchen is entirely located in semi-terrestrial soil areas, they consist of Pleistocene and Holocene river deposits as well as Holocene bogs from the (sub-)soil. Despite extreme drought at the time of the survey, bog soil vibrated under the foot. It can therefore be assumed that although the bog is drained, but the peat at the site has not been extracted.

There is no evidence of enclosure ditches in the Hkn22 magnetogram and only some very weak negative anomalies in the northwest trace their course (Fig. 5B). Therefore, structures that draw ditches and paleochannels were added from aerial image rectification and drone photogrammetry-based DSM to the interpretation plan (Fig. 5C). Due to the permanent water-logged soil conditions, there are several reasons why the ditches are not visible in the magnetogram. The explanation is more complex compared to the Obs22 enclosure. (1) The first reason could be the already discussed leaching of the magnetic particles from the backfills of the ditches; (2) the second reason may be the dissolution of ferrimagnetic particles in the waterlogged bog soil (Williams 1992); and (3) the third reason might be the re-oxidation of ferrimagnetic particles into antiferromagnetic or paramagnetic compounds under anoxic conditions (Schwertmann and Taylor 1989). After all, the interaction of the three reasons is obvious (compare e.g. with Gimson 2019). Finally, the initial lack of enrichment of magnetic particles in the ditch fillings is also possible.

The results in Fig. 5 show that Hkn22 is an earthwork with two ditches, at which the inner ditch is enclosing a plateau of approx. 0.4 hectares. The ditches have rounded corners and were probably once filled with water, as they have a connection to the palaeochannels in the south of the enclosure. Therefore, the entrance to the Hallstattherrenhof was probably once situated in the north. However, this interpretation is uncertain, as there is now a modern stream, whose dredging has destroyed the northeastern part of the earthwork. Inside the enclosure plateau, between the trenches and outside, a large number of positive anomalies are visible, which could possibly represent settlement pits. A lot of metal scrap (i.e. dipolar anomalies) is spread over the entire area with a concentration in the southern outer ditch. Assuming this scrap being modern, it can be supposed that the trenches were open for a very long time. Furthermore, the ditches are still visible in the DSM today, which suggests that the site has never been ploughed (Fig. 5A).

In the northwestern corner of the Hkn22 earthwork, some post pits can be reconstructed to a rectangular house plan. The size of this house is ~9 x 17 m or ~150 square meters. With regard to its size, its location within the enclosure and the shape of the post pit positions, it can be interpreted as a residential house. Zeeb (1993) documented a very similar finding during excavations in Baldingen (Swabia, Western Bavaria).

Examining the entire magnetogram of the Hkn22 earthwork (Fig. 5B), irregular stripes are noticeable. These irregularities prevent a correct statistic adjustment of the measured values of the individual grids during the filtering of the total field magnetic data. The product is an unsystematic noise; therefore, it is neither instrument noise nor an operator error. Jörg Fassbinder observed very similar patterns during his measurements in Wörth a. Main (Franconia, north-west Bavaria) and a few other places worldwide (such as Saqqara, Egypt). He considers the source of these unsystematic disturbances to be the magnetic solar storms. Recently, this thesis can be qualitatively tested by considering the measurements of the total intensity of the Earth's magnetic field (F) during the survey period in Hartkirchen.

Fig. 6 shows that at the time of the survey and on the days before and after, increased intensities of the total field were detected by the geomagnetic observatory in Fürstenfeldbruck (FUR; linear distance: about 130 km south-southeast of Hartkirchen).

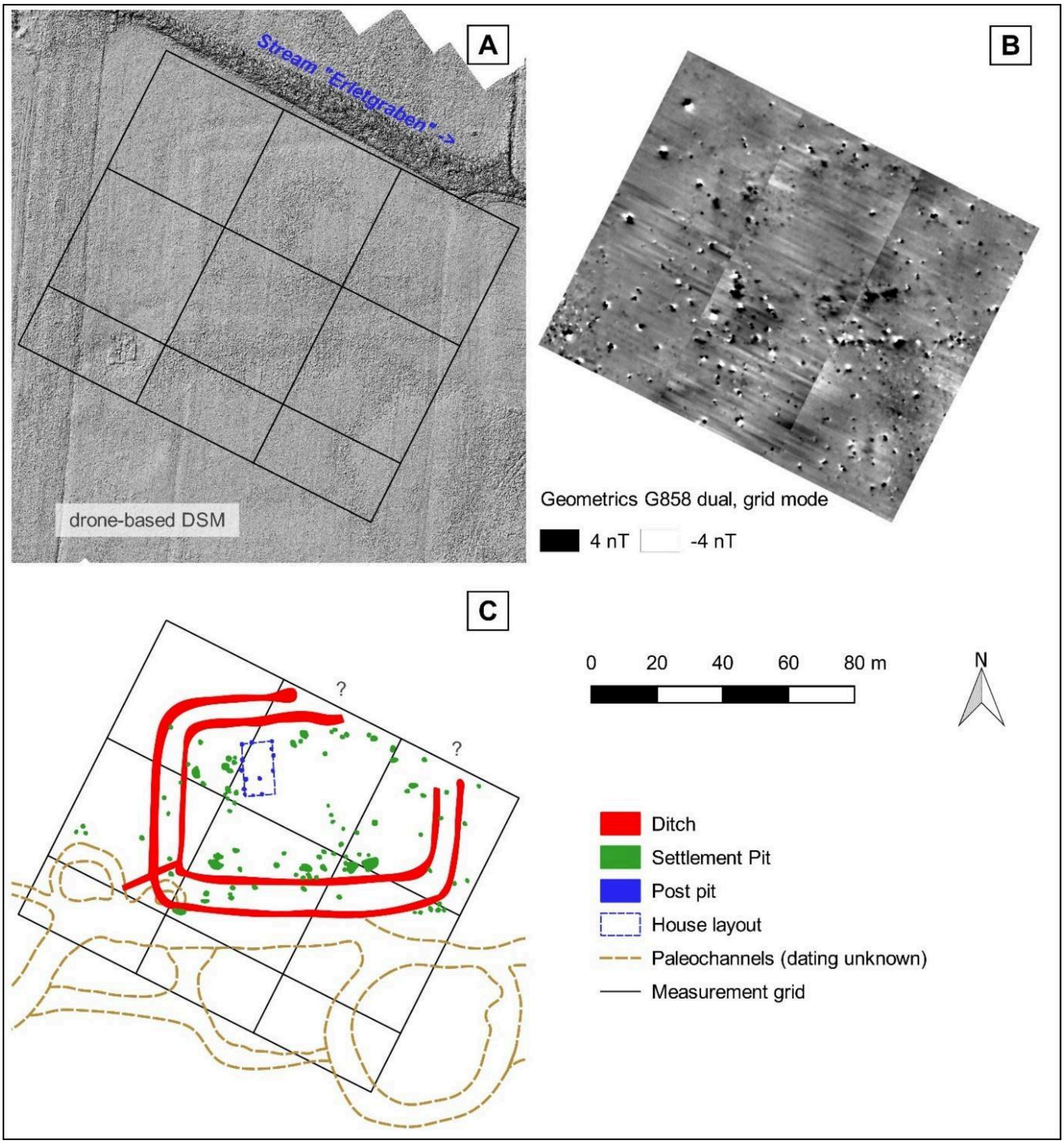

Fig. 5. Prospecting results in Hartkirchen: the interpretation plan in C is based on the drone based DSM (A), magnetometry (B) and aerial photography (not shown) results. Magnetic survey parameters: Geometrics G858 dual caesium total field magnetometer, measurement point density 25 x 50 cm, interpolated to 25 x 25 cm. Figure credits: Andreas Stele, Roland Linck and Helmut Becker.

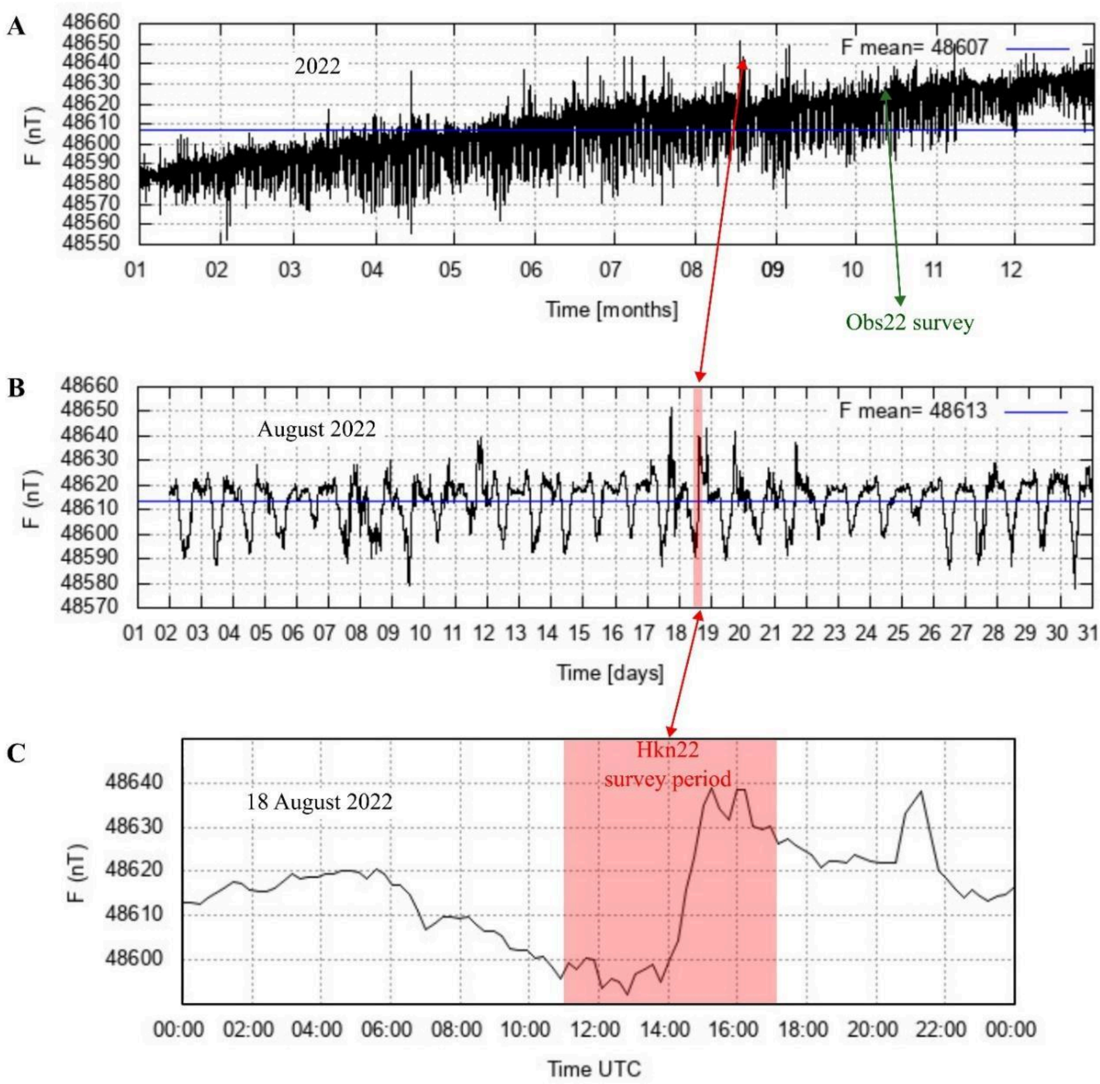

Fig. 6. Date and period of the magnetic survey in Hartkirchen (red markings) and Oberstimm (dark green) entered in the yearly (A), monthly (B) and daily (C) magnetograms of the total intensity of the Earth's magnetic field (F). Declination near Fürstenfeldbruck and Munich is around 90', that means 1°30' East or 1.5° East. Time is given in universal time [UT], that means CET - 1 hour or CEST - 2 hours. Data resolution is 1 minute. The Munich Earth Observatory is part of University Munich (FUR 2024). Figure credits: Andreas Stele, FUR.

3.3 Discussion

Using the observations in Oberstimm and Hartkirchen, implications for future choices of a suitable instrument and data interpretations will be discussed in the following. Of course, such implications cannot only concern magnetic surveys of Hallstatt enclosures, but may well have general validity for earthworks or ditch structures. The results in Hartkirchen indicate that in the area of waterlogged soils, the detection of such findings can be strongly inhibited due to a lack of magnetic contrasts, even despite a good state of preservation of the archaeological feature. It is therefore quite possible to establish the rule that magnetic particles are washed out of permanently in waterlogged soils or that there is no initial accumulation of magnetic iron oxides at all.

The processes appear to be different in temporarily waterlogged soils, as the results from Oberstimm show. In the immediate vicinity of watercourses, magnetic particles from ditch and pit backfills are probably only washed out along hydraulic gradients. In terrain sections between the hydraulic gradient and the watercourse, magnetic particles can be secondarily enriched. Investigations at the early medieval Fossa Carolina (Franconia, central Bavaria), for example, have shown that magnetic iron sulphides, such as greigite, can be enriched in archaeological findings in these areas. In such transitional zones, the thermoremanence is also easier to recognise, because the elementary magnets of soft magnetic remanence carriers of the thermoremanent mass anomaly rotates in the main direction of the Earth's magnetic field. In this state, they generate the typical intense anomaly with a negative part in the north and a positive part in the south (Stele et al. 2019).

When selecting an instrument platform, it should be considered that wheeled racks on rough surfaces could shock the magnetometers, which in turn can generate noisy data. Although this noise can be filtered out, the speed of the data acquisition should be adapted to the roughness of the ground surface, if necessary, especially when using vehicle-towed systems. Carried systems offer the chance to generate quieter and cleaner data in this respect, but the operator should also avoid vibrations of the magnetometers during the data acquisition.

Unlike gradiometers, caesium total field magnetometers have the ability to record the change in the daily variation of the total intensity of the Earth's magnetic field. This fluctuation can already be measured during five minutes and causes the low 5m std resolution value of the G858 instrument compared to the MXPDA (Tab. 1). Regarding the MXPDA gradiometer probes, the diurnal variation is not reflected in the 5m std resolution due to the much lower sensitivity of the instrument. The small difference between the 5s std and the 5m std is attributable to the temperature drift of the tested gradiometer probe.

Long-term geomagnetic observatory measurements indicate that the intensity of the Earth's magnetic field tends to increase in the future (FUR 2024; see e.g. Fig 6A). This in turn leads to more intensive and more frequent interactions between the magnetic solar storms and the Earth's magnetic field. The example from Hartkirchen shows that such interactions can massively disturb the data acquisition utilizing high sensitive magnetometers for archaeological prospecting. Now, the influence of magnetic solar storms on the archaeological magnetometry can only be understood qualitatively and very superficially. Further comparisons and experiences in this field of research are crucially. It is understandable that nobody likes to publish and discuss noisy magnetograms. However, such magnetograms and their comparison with observatory data are necessary in order to understand the degree of the magnetic solar storms impacts and whether an archaeological magnetometer survey with high sensitive total field magnetometers makes sense or not. We are currently countering such impacts by monitoring the space weather forecasts (e.g. from ASWFC 2024). In the case of forecasting a geomagnetic warning, we do not use sensitive total field instruments, but rely on more stable gradiometers. Alternatives to the operation of gradiometers during a magnetic storm would be the application of a caesium base measurement synchronised in time with the caesium survey instrument or the use of three-axis fluxgates (Gavazzi et al. 2016; Stele et al. 2023b), which offer a reliable sensor resolution and a total field output.

4. Conclusions

We used magnetic surveys of two different Hallstatt enclosures to outline the methodological and instrumental issues that prospectors may be confronted with. The environmental parameters in particular have an influence on the magnetometric detectability of these (and similar) archaeological findings. The location and hydrological situation of a site are the main determining factors. In permanently waterlogged soils, leaching and dissolution processes can lead to a complete lack of magnetic contrasts. Therefore, in the case of Hartkirchen, drone photogrammetry had to be used to complete the documentation of the site. Sections of the landscape that are constantly (ground) waterlogged, remain problematic for magnetometer prospection, no matter how sensitive the instrument is utilized. In transition zones between terrestrial, temporarily waterlogged and permanently waterlogged soils, the scenario is more variable. As the results in Oberstimm show, a weakening or strengthening of magnetic contrasts in such areas depends on the position in relation to the hydraulic gradient.

The state of the Earth's magnetic field during the high sensitivity total field magnetic survey can also be counted among the determining environmental factors because its short-term changes can have negative and irreversible effects on the survey results. As the strength of the Earth's magnetic field increases, this problem becomes more and more relevant. The influence of the extra-terrestrial magnetic storms on archaeological magnetometer surveys should be therefore deeper investigated. The development of alternative approaches to uncompensated and unshielded, highly sensitive caesium magnetometer surveys should be promoted. At present, there is nothing else to do, but rely on space weather forecasts and use a gradiometer in the event of a geomagnetic warning. In this regard, perhaps the ultra-light and flexible three-axis fluxgate magnetometers can offer a balanced solution between sensitivity, stability and data quality in the future.

Ultimately, the choice of the instrument is crucial and the good news is that all magnetometers currently used in archaeological surveys show sufficient sensitivity to detect most types of archaeological structures. There are differences in survey progress and sensitivity to infrastructural, object-specific or extra-terrestrial sources of interference. The scope and capabilities of the respective instruments can best be assessed and implemented by experts. As long as experts are involved in geophysical surveys, there is a chance of obtaining high-quality data. Only the latter allows geophysical measurements to be placed in a meaningful archaeological context.

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