Magnetic data – in Archaeological Prospection

*Guidance on '**Archaeology to Precision Agriculture (PA)**' data exchange via API platforms and Ecosystem Services (online GIS platforms)*

Part one: Descriptions

Magnetic data in archaeology (see Schmidt *et* al. 2015) are generally derived from three forms of field-based instrument:

- *Single loop* field instrument with an active coil sensor, which measures and maps variation in soil magnetic susceptibility directly in the first 10cm of the topsoil.
- *Magnetometers* with passive sensors of either vector (e.g. fluxgate) or scalar (e.g. caesium vapour) type, which measure and map variations in magnetic flux density. Sensor configurations in archaeology typically target features *c*. 1m–2m below ground level, although deeper anomalies can be detected, particularly if large and strongly magnetized (von der Osten-Woldenburg, 2011).
- *Electromagnetic induction* (transmitter-receiver) instrument with active coil sensors which evaluate soil magnetic susceptibility (volume specific) through the in-phase signal response in multi-depth volumes depending on coil configuration. In archaeology, coil configurations typically target anomalies *c*. 1m – 2m below ground level (see also ipaast EMI Data Guidance.

Data Types – common to archaeological prospection

Magnetic data types relating to three workflow stages: collection, processing, interpretation:

- ASCII text file – as collected raw (unprocessed) in the field or exported post-processed: tabular format delimited text file either fixed-width or with comma-, tab- or space-separated values; sometimes accompanied by a header file recording instrument specific survey parameters
- Grid data – 2D raster format file derived from field data where a matrix of cells visualize the numeric data using a colour legend, typically greyscale; the attribute represented by each cell can be either the unprocessed magnetic data (raw) in original collection pattern (un-interpolated e.g. 0.25m x 1m), or the processed magnetic value, usually interpolated in an even and/or finer resolution (e.g. 0.25m x 0.25m or 0.125m x 0.125m)
    - Grid data are sometimes supplemented with image format files (e.g. jpeg, tiff, etc.) after processing. Image enhancements include clipping or stretching the range of values on a different scale to enhance contrast and make features of interest more visible; supplementary image format files are often georeferenced (e.g. geotiff, etc.)

Common Data Derivatives

- Archaeological interpretation – 2D vector format file of individual features, or sets of features, overlaid and interpreted from the processed grid data as represented geometrically by points, lines or outline polygons.
    - Interpreted features are typically classified according to set categories relating to some, or all, of the following:
        - Geophysical signal response (high/low magnetic value)
        - Archaeology – feature type (wall, ditch, etc.)
        - Archaeology – potential (probable, possible etc.)

        - Geology and/or pedology
        - Modern activity (agriculture, utility, infrastructure, military, disturbance, sporting, leisure, etc.)
- Other classed/clustered data (e.g. management zones, etc.).
- Vectorised interpretation classifications and features might be alternatively represented either individually or collectively, as image format files (e.g. jpeg, tiff, etc.) usually georeferenced (e.g. geotif, etc.).

Vocabulary – common to archaeological prospection

(Thematic tags, term lists, thesauri)

Basic description or interpretation of geophysical anomaly

- Magnetic anomaly: positive (+) / strong / enhanced; negative (-) / weak / decreased; ferrous, geological, overwhelming disturbance, etc.

Classification of soil characteristics

- Customized descriptions: fills (possible / probable, linear / discrete), areas (texture, highlights), cultivation (trends), drains (possible / probable), boundaries (former / modern), trackways (former / modern), etc.

Archaeological interpretation by response and form

- General classification (archaeology (possible / probable), modern structure, etc.)
- Detailed classification (wall (possible / probable), ditch (possible / probable), pit (possible / probable), kiln (possible / probable), etc.

Event description

- FISH Event Types Thesaurus (non-intrusive/geophysical/insert type)
    - http://purl.org/heritagedata/schemes/agl_et/concepts/145134

Part Two: Recommendations to increase interoperability

Identifiers – recommended

Unique identifier for published dataset (e.g. as provided by an open access digital repository)

Data structure – recommended

Core attributes of (above) data types

Critical information for inclusion

- Raw data – minimum required attribute fields in order: X, Y, V, TS, H-DOP, V-DOP, where:
    - attribute one is X the first locational co-ordinate (Latitude/Easting)
    - attribute two is Y the second locational co-ordinate (Longitude/Northing)
    - attribute three is V the measured magnetic value (nT, ppt or dimensionless unit SI)
    - attribute four is TS the GNSS time stamp
    - attribute five is H-DOP the horizontal quality of the locational GNSS measurement
    - attribute six is V-DOP the vertical quality of the locational GNSS measurement

Note: In non-GNSS integrated surveys, the minimum required attributes are one, two and four (X, Y, V)

Note: In GNSS integrated surveys, inclusion of the Z attribute (height above ellipsoid/ODN), would provide (with X and Y) a supplementary dataset for terrain modelling to aid visualisation and interpretation

- Raster data. Processed grid or image data – a grid matrix of cell (pixel) rows and columns where each cell contains the numeric magnetic value; the extent is defined by a bounding box
    - A supplementary, georeferenced version of this grid file, in an image file format where each magnetic value is represented by a colour value (e.g. geotiff, etc.), might be useful for non-specialists

- Vector data. Vector interpretation – geophysical or archaeological features or areas of interest as represented by line or polygons each of which is linked to a database element or row which describes its essential attributes such as line start, line length, line bearing, polygonal area, as well as any additional data; extent is defined by a bounding box

Data processing – recommended

Relating to instruments typically used to collect magnetic data in archaeology (see above)

Single loop sensor instrument (direct magnetic susceptibility)

- Raw file – tabular with X,Y,V where V is the magnetic susceptibility value in ppt or dimensionless SI units.
- No processing required – uncorrected, volume specific magnetic susceptibility can be usefully mapped.

Fluxgate Gradiometer (magnetic flux density – vector instrument type example)

- Raw – tabular with X, Y, V where V is the graded magnetic flux density value in nT
- Processing required to make it useful (gradiometer):
    - Recommended minimum: data correction to optimise signal-to-noise ratio in function of survey targets (e.g. destriping, despiking)
    - Re-sampling: interpolation between inline and crossline sampling to even appearance

Caesium Vapour Magnetometer (magnetic flux density – scalar instrument type example)

- Raw – tabular with X, Y, V where V is the magnetic flux density value in nT
- Processing (1) – *Total field intensity (TMI) configuration*
    - Recommended minimum: account for the influence of diurnal ambient magnetic field variations
    - Re-sampling: interpolation between inline and crossline sampling to even appearance, followed by low pass filter for smoothing
- Processing (2) – *Vertical gradiometer configuration*
    - Recommended: 'pseudo-gradient' calculation of processed TMI data to model vertical gradient data (see Roseveare, 2018, 4.3.1). Also useful for targeted signal analysis such as separation of shallow and deep magnetic signals.
    - Re-sampling: interpolation between inline and crossline sampling to even appearance

Electromagnetic Induction (magnetic component of the signal – magnetic susceptibility)

- See ipaast EMI Data Guidance for further details.

Metadata standard – recommended

For minimum metadata requirements, the BonaRes Metadata Schema for soil surveys is recommended (see Appendix 1 metadata ipaast template for a list of mandatory metadata elements). In addition, IPAAST-CZO recommends the following core elements (Schmidt and Ernenwein, 2011, Section 5.3) for inclusion with geophysical datasets:

Geophysics Metadata		See Appendix 1 metadata ipaast template for full definition
(All survey techniques and data types)		
Duration/Collection date	Mandatory	Date (ISO 8601)
Survey type	Mandatory	Character String (Controlled List Value): tbd
Instrumentation	Mandatory	Character String (Free text)
Area surveyed	Mandatory	Character String (Free text)
Method of coverage	Mandatory	Character String (Controlled List Value): Gridded/Line/Non-gridded/Scanning/etc.
Line separation (cross-line) in metres	Mandatory	Decimal / Numerical
Reading interval (in-line) in metres	Mandatory	Decimal / Numerical
Additional remarks/notes e.g. weather	Mandatory	Character String (Free text)

Metadata for specific techniques		
Magnetometer Surveys		
Magnetic north	Mandatory	Decimal / Numerical (Degrees)
Instrument drift value	Mandatory	Decimal / Numerical

Additional Metadata for specific data type (See above)		
Survey Methodology (for raw datasets)		
Data grid layout	Mandatory	Character String (Free text)
Data grid size	Mandatory	Character String (Free text)
Resolution	Mandatory	Character String (Free text)
Survey direction	Mandatory	Character String (Free text)
Line sequence	Mandatory	Character String (Free text)
Sampling position (if applicable)	Mandatory	Character String (Free text)
Data processing (for processed datasets)		
Processing history list	Mandatory	Character String (Free text)
Archaeology (for Interpretation datasets)		
Monument type	Mandatory	Character String (Controlled List Value): tbd
Monument period	Mandatory	Character String (Controlled List Value): tbd
SM /Heritage List number	Mandatory	Decimal / Numerical

Part Three: Scope Notes and Schema – to encourage exchange

Scope Note 1

Applications of magnetic data in precision agricultural management decisions

Magnetic data can identify areas of changing soil mineralogy. For example, magnetic sensors are sensitive to the presence or absence of iron oxides, which in turn are relevant to soil nutrient balance. This can be undertaken at various levels: single loop magnetic susceptibility meters target courser changes in the topsoil, while fluxgate gradiometers and total field sensors (as found in caesium vapour systems) target deeper, cut futures within the subsoil or natural bedrock. Depending on configuration, caesium vapour instruments have reduced instrument noise levels which can be advantageous for evaluating a range of soil properties for analysis, thereby potentially aiding in the classification of soils and the creation of managements zones. Magnetic information on mineralogy could also be linked usefully to non-geophysical survey types such as geochemical data (e.g., gamma-ray instruments, optical sensors) – see Scope Note 2 below.

Certain types of instruments such as fluxgate gradiometers or caesium vapour magnetometer, also record remnant magnetic signals, which can assist in the detection of buried, brick field-drain systems. Magnetic data such as susceptibility values can also inform on soil erosion and redistribution, particularly when combined with topographic information (e.g. Jordanova et al., 2014) and/or time-lapse (repeat) survey.

Magnetic survey works well in saline environments where EMI survey (often used in agriculture to measure apparent electrical conductivity for soil mapping) has issues.

Limitations
Magnetic data can be detrimentally affected by overwhelming ferrous disturbances from proximity to both surface iron (fences, vehicles) and buried metal objects. Additionally, fluxgate gradiometer data are limited by high pass filtering inherent to gradiometric survey mode, which supresses background soil responses that are of potential interest in soil analysis.

Magnetic anomalies:

- interpreted ditch and pit features will most likely retain moisture, as potentially reflected in increased plant growth
- interpreted ditch and pit features will most likely contain concentrations of iron oxides from topsoil in-filling, which could be indicative of increased levels of mineral nutrients such as phosphates (see Scope 2 below)
- interpreted wall, surface and area of compaction features will most likely be devoid of moisture, as potentially reflected in decreased plant growth
- interpreted wall, surface and area of compaction features could potentially signal an increase in calcium levels which can be related to plant health, but also a decrease of iron oxides which can be related to soil fertility
- brick drainage features can be mapped, or alternatively, the fill of cut drainage features
- identified ferrous disturbances are likely to be a result of modern intrusion, such as boundaries, construction/destruction episodes, service infrastructure or the dumping of material (e.g. compost contaminated with metal waste (Gerrard et al., 2015)); this also includes the potential to identify iron-encased, unexploded ordnance (UXO) at depth
- larger cut features identified in magnetic data such as former field boundaries where hedgerow has been removed could potentially point to surviving stocks of carbon, because of potential associations with vanished hedgerows (Black et al., 2014; Collier, 2021; *cf*. Van Den Berge et al., 2021)

Scope Note 2

Data in precision agriculture potentially relevant to interpretating magnetic datasets in archaeology

Soil analysis using XRF (gamma ray) instruments and ICP-OES sensors on core samples is established practice in precision agriculture. Mapping the physical, chemical and biological properties of soil provide information on relevant aspects such as mineralogy and nutrient balance.

Studies have demonstrated how topsoil phosphorus mapping can: (1) indicate areas of past human activity, as well as (2) refine their archaeological interpretation by complimenting the results of other non-invasive archaeological investigations including geophysics (Craddock et la 1985; Clark 1990, 107–9; Cummins *et al*., 2018: Chp. 19-1).

In some environments, such as soils with high iron content or very acidic soil, information on mineralogy might potentially be linked to magnetic soil properties, as one iron oxide (maghaemite), has been recently shown, under certain circumstance, to play a relevant role in linking phosphorus sorption and magnetic susceptibility in clays and tropical soils (Poggere et al., 2020).

Some approaches can even distinguish between naturally occurring phosphates and those resulting from past human activity (Eidt 1977; Holliday, 2017; Kolb, 2017). Recent studies emphasize the growing overlap between geochemical analysis of soils in agronomy and archaeology (Cummins *et al*., 2018: Chp. 19-5).

Other mineral elements detected might be indicators of deeper archaeological features brought to the topsoil by ploughing, worms or the action of roots. For example, an enhanced presence of:

- phosphorus, manganese and calcium might result from a burial, or set of burials
- phosphorus, potassium and lead might result from a buried midden
- calcium might result from a buried wall or structure constructed with limestone or lime mortar
- iron oxides (magnetite, maghaemite, haematite) might represent the topsoil survival of a cut features such as ditch(es) or pit(s) since destroyed by ploughing, or alternatively, zones of past human occupation or activity (especially increased levels of maghaemite)
- phosphorus might represent the traces of past agriculture practices relating to livestock and/or manure

Traces of these elements don't necessarily have to survive in situ and might be traceable in eroded and re-deposited soils onto lower lying ground. Clark (1990) points out such deposits can be indicators of vanished landscapes and inform on landscape evolution.

In archaeological prospection, magnetic gradiometers are often unsuccessful in detecting features of archaeological interest in alluviated soils and cannot be relied upon as the sole method of investigation of alluvial environments (Bonsall *et al*. 2014). In such instances, geochemical datasets could have the potential to complement archaeological gradiometer surveys of alluvial areas, as Craddock *et al* (1985) note an instance where a prehistoric site was discovered through phosphorus survey under half a metre of alluvium (see also Holliday and Gartner, 2007; Roos and Nolan, 2012).

Limitations
Possible limitations are the resolution of the soil sampling strategies in agriculture which vary and are considered course in archaeological terms.

Schema

(1) Related to – topography, geology, hydrology, complimentary soil mapping (moisture, texture, compaction), modern services, documented archaeological features (historic mapping, aerial photography, earthwork survey, geophysics, excavation)

(2) Recommended further processing / analysis

- translate vector data (magnetic anomalies / archaeological interpretation) into agricultural useful terms or soil management zones perhaps relating to erosion, disturbance, drainage, anthropic inclusions in soils, enriched soils, compacted soils, etc.

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