Scuola di Scienze e Tecnologie
Università di Camerino

Forward Modelling of Magnetic Anomalies in Archaeological Geophysics: a New Software Tool

Antonio Schettino(1) & Annalisa Ghezzi(1)

[1]University of Camerino – School of Science and Technology, Camerino, Italy

E-mail: antonio.schettino@unicam.it

Forward Modelling of Magnetic Anomalies in Archaeological Geophysics

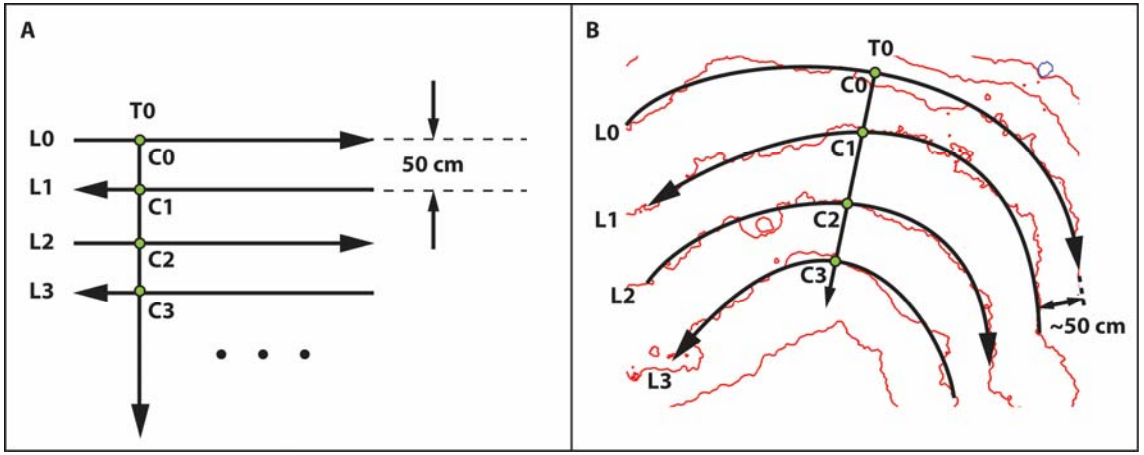
- **New approach** to the analysis of archaeological magnetic anomalies;
- **Geometry, physical properties, and location** of buried archaeological features;
- Occurrence of **fires**;
- No gradients. Acquisition of **total field data**, $T(x,y)$, and reduction to archaeological magnetic anomalies $\Delta T(x,y)$;
- **Forward modelling** and reconstruction of the 3D arrangement of buried features;
- In some cases, **historical reconstruction**

ArchaeoMag: A New Software Tool in Archaeological Geophysics

1. Reads magnetic anomaly and topographic grids;
2. Displays the grids at any scale through an advanced bicubic interpolation resampling algorithm;
3. Allows easy creation and editing of archaeological objects;
4. Interactive modelling by visual comparison of the observed data with the theoretical anomalies;
5. Modelling of both induced and remnant magnetization;
6. Automatic terrain correction;
7. Integration with GPR reconstructions

Acquisition of Magnetic Data

Typical mapped survey layout at sites with planar relief (A) and GPS–assisted survey in presence of complex topography (B). $\mathbf{L}i$ ($i = 0,1,\ldots$) and $\mathbf{T}i$ are respectively survey and tie lines (in black). Red lines are topographic contour lines. $\mathbf{C}i$ ($i = 0,1,\ldots$) are crossover points (green dots) for levelling.



Analysis of Magnetic Data

- Pre–processing;

- Calculation of magnetic anomalies:

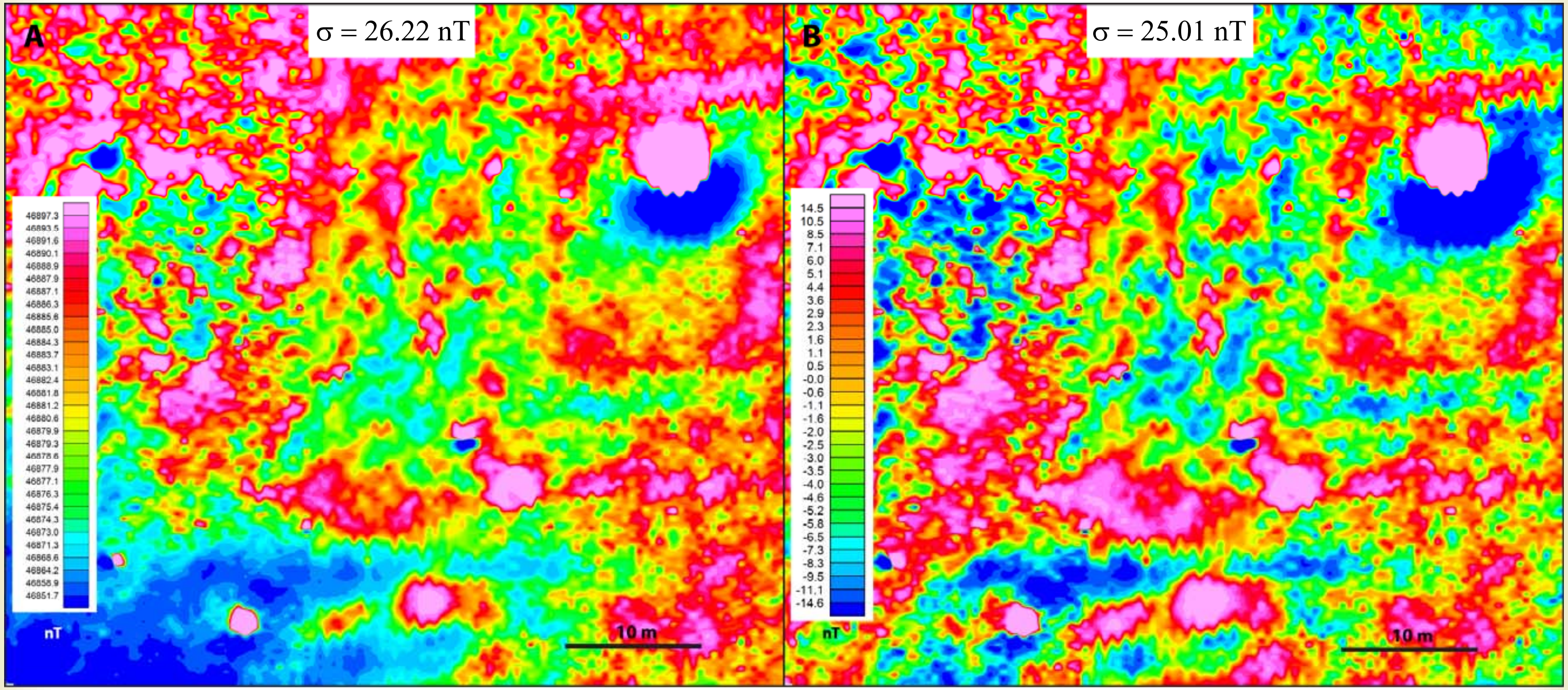
$$\Delta T(x, y) = T(x, y) - \sum_{n+m \le N} a_n b_m x^n y^m$$

- Decorrugation and microlevelling

Analysis of Magnetic Data

A: Total field output grid

B: Raw anomalies

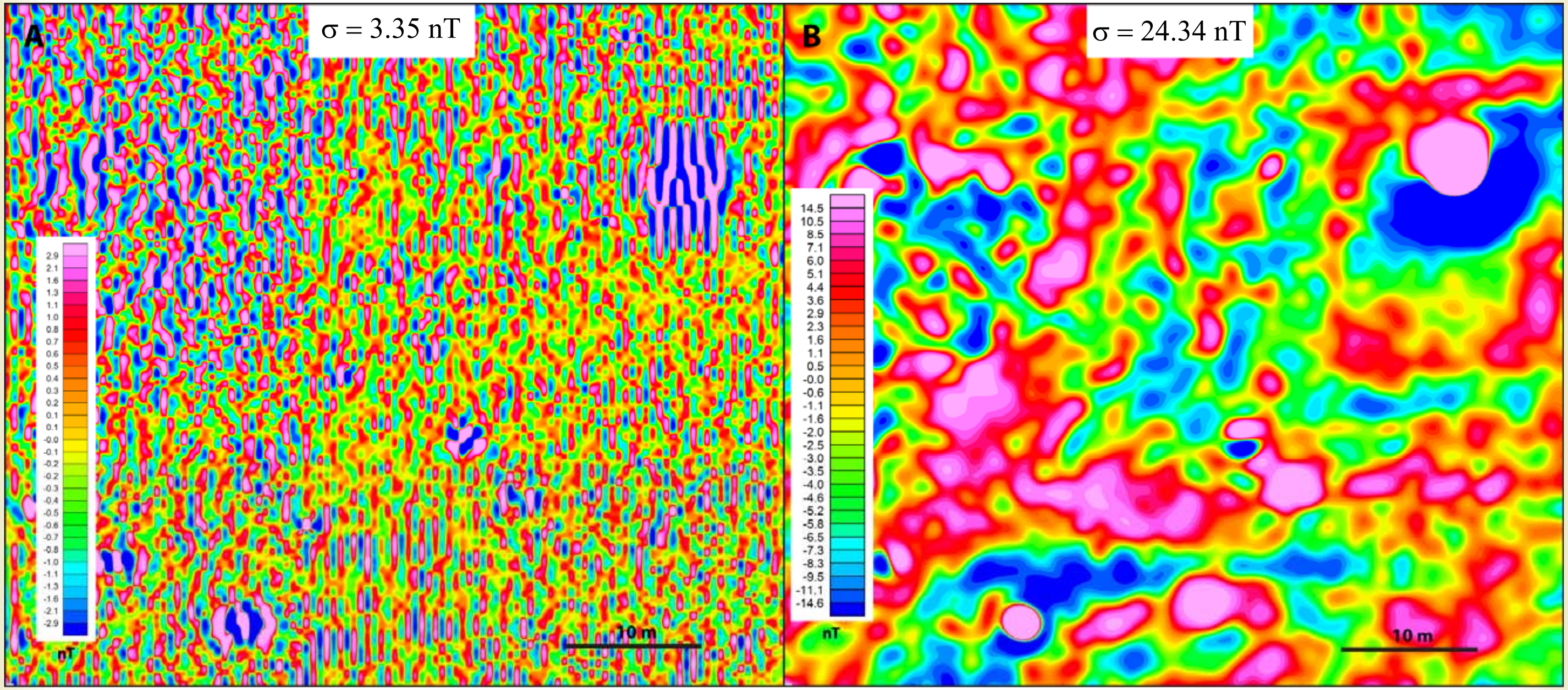


Data acquired at the Urbs Salvia Roman settlement, central Italy

Analysis of Magnetic Data

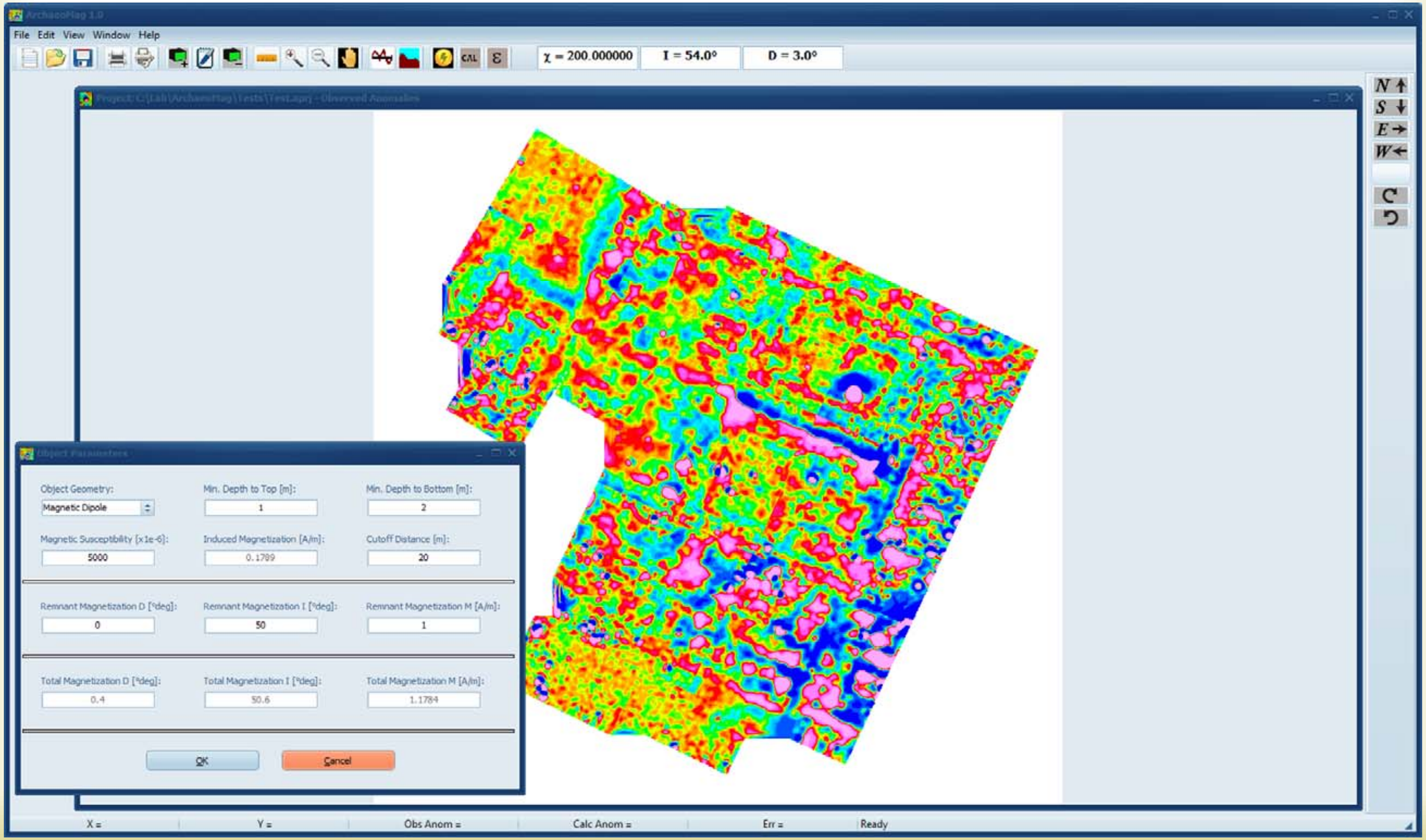
A: Residual grid after high–pass Butterworth and 2nd degree directional cosine

B: Final magnetic anomaly map, obtained subtracting grid (A) from the raw anomalies.



Modelling of Magnetic Data

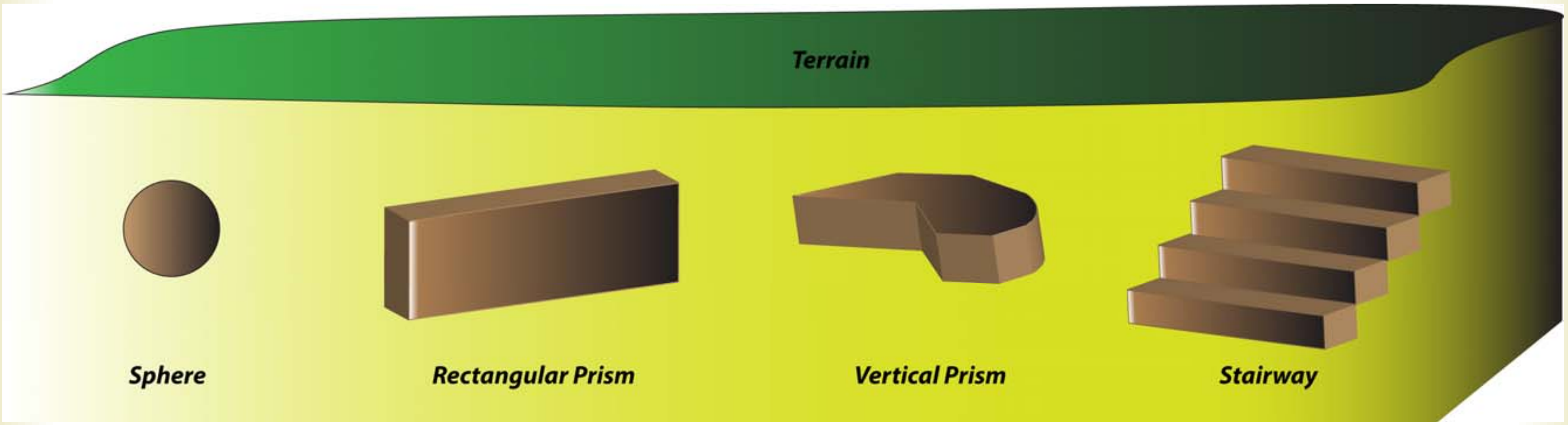
ArchaeoMag user interface:



Archaeological Features

ArchaeoMag allows to define three basic classes of shapes and a composite structure, corresponding to common archaeological features:

1. **Spheres** (magnetic dipoles), 2. **Rectangular prisms**, 3. **Generic vertical prisms**, and 4. **Stairways**



Magnetization

1. Minimum and maximum burial depths;
2. Magnetic susceptibility, χ;
3. Cutoff distance
4. Remnant magnetization vector (M_R, D_R, I_R)

The program calculates automatically the induced magnetization vector, $\boldsymbol{M}_I$, and the total magnetization vector, $\boldsymbol{M}$, by the following equations:

$$\boldsymbol{M}_I = \frac{\chi - \chi_0}{\mu_0}\boldsymbol{F} \equiv \frac{\Delta\chi}{\mu_0}\boldsymbol{F}$$

$$\boldsymbol{M} = \boldsymbol{M}_I + \boldsymbol{M}_R$$

Model Anomalies

Sphere:

$$\Delta T(\boldsymbol{r}) = \Delta \boldsymbol{F}(\boldsymbol{r}) \cdot \hat{\boldsymbol{F}} \cong \frac{\mu_0 a^3 M}{3r^3}\left[3\left(\hat{\boldsymbol{M}} \cdot \hat{\boldsymbol{r}}\right)\hat{\boldsymbol{r}} - \hat{\boldsymbol{M}}\right] \cdot \hat{\boldsymbol{F}}$$

Rectangular Prism:

$$\Delta T(\boldsymbol{r}) = -\frac{\mu_0}{4\pi}\hat{F}_i \frac{\partial}{\partial x_i}\int_{\mathbf{R}} M_j(\boldsymbol{r}')\frac{\partial}{\partial x'_j}\frac{1}{\left\|\boldsymbol{r} - \boldsymbol{r}'\right\|}dV$$

General Vertical Prism:

$$\Delta \boldsymbol{F}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\oint_{S(\mathbf{R})}\hat{\boldsymbol{r}}\frac{\boldsymbol{M} \cdot d\boldsymbol{S}}{r^2}$$

Remnant Magnetization

Presence of a remnant magnetization component can be established by the detection of one or more among the following conditions:

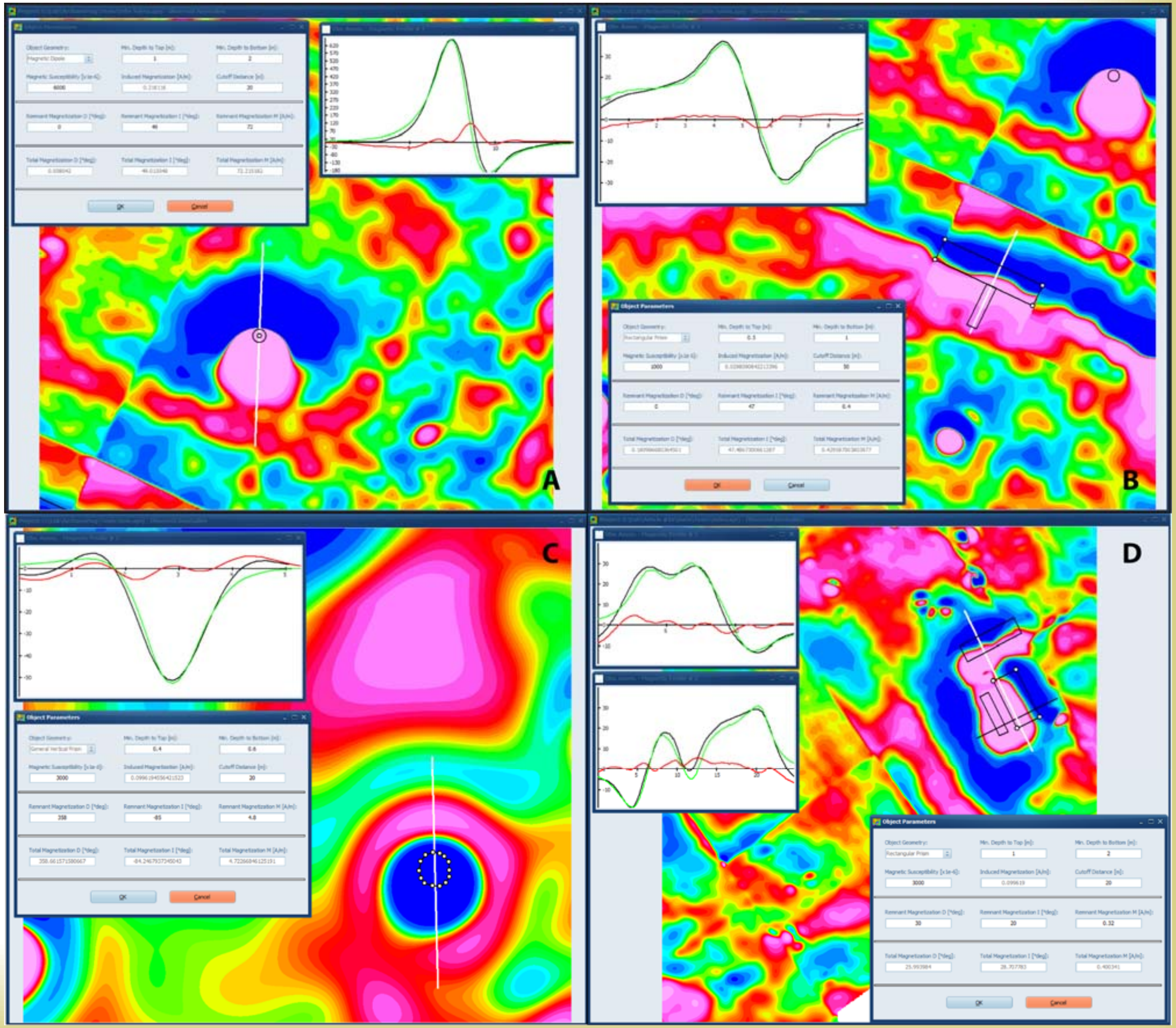
1. A magnetic anomaly amplitude exceeding a few nT;

2. A deviation of the strike of the simmetry axis of a dipolar anomaly from the present day reference field declination, D_0;

3. A deviation of the anomaly shape from the expected shape for the given reference field inclination, I_0.

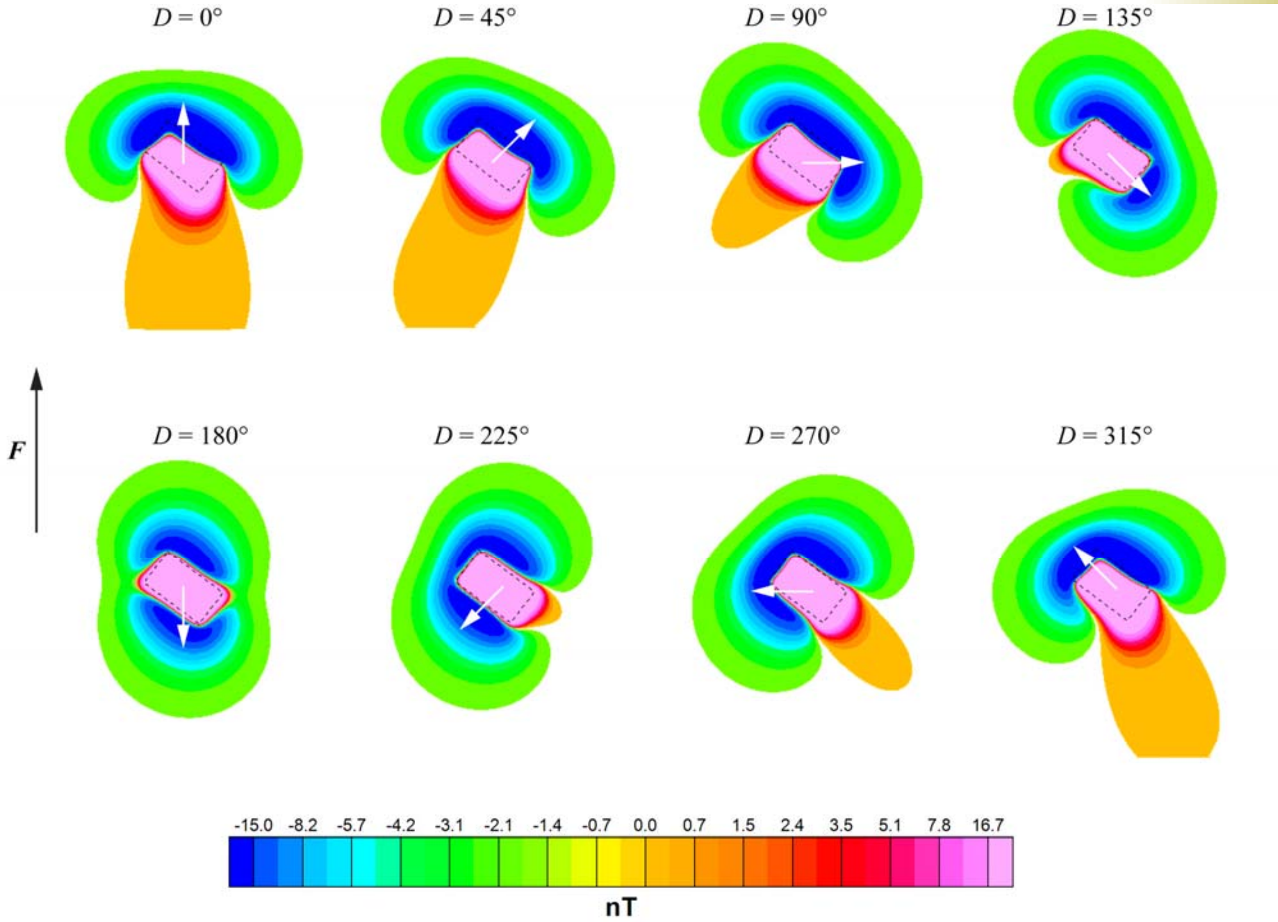
Forward Modelling: NRM

A: A strong dipole anomaly whose peak exceeds 620 nT, most probably a furnace. B: A T–structure, probably representing a combination of a segment of a long and 2m large WNW–ESE oriented wall and a transversal smaller wall. C: A small cylindrical structure, 70 cm diameter by 20 cm height, characterized by a very anomalous inclination (I = –85°) of remnant magnetization. D: A composite anomaly, resulting from the superposition and coalescence of the anomalies associated with three distinct buildings. The northernmost feature has D = 30°, I = 5°, M = 1.8 A/m, while the western prism has D = 30°, I = 60°, M = 0.3 A/m.



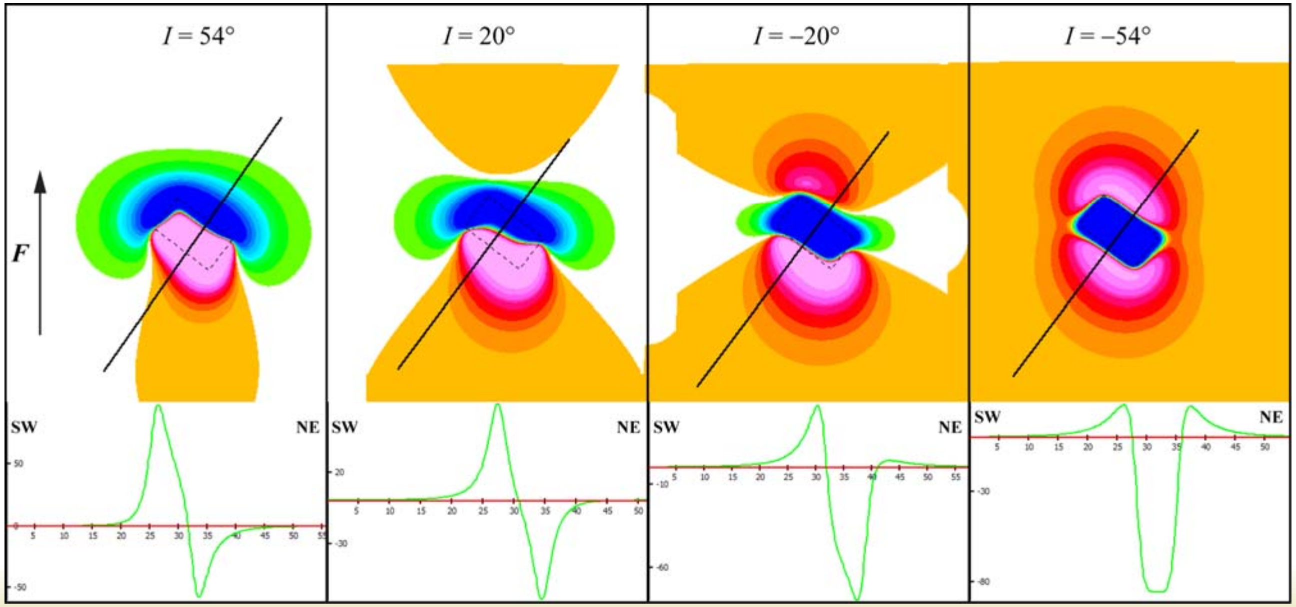
Forward Modelling: Declination of NRM

Effect of NRM declination. A NW–SE wall (dashed rectangle) has NRM inclination $I = 54^\circ$ and $M_R = 1$ A/m. It is assumed that the ambient field has intensity $F = 46824$ nT, declination $D_0 = 0^\circ$, inclination $I_0 = 54^\circ$ and that the sensor height is 0.5 m above a flat terrain. It is also assumed that the susceptibility contrast is zero. The white arrow shows the the horizontal projection of the RNM vector.



Forward Modelling: Inclination of NRM

Effect of NRM inclination. A NW–SE wall (dashed rectangle) has declination $D = 0^\circ$ and $M_R = 1$ A/m. It is assumed that the ambient field has intensity $F = 46824$ nT, declination $D_0 = 0^\circ$, inclination $I_0 = 54^\circ$ and that the sensor height is 0.5 m above a flat terrain. It is also assumed that the susceptibility contrast is zero. The profiles show model anomalies along the traces indicated in the upper panel (black lines). Vertical units are nT, horizontal units are meters.



Forward Modelling: Induced Magnetization

In general, the observation of anomalies associated with induced magnetization requires one or more among the following conditions:

1. A strong susceptibility contrast with the surrounding soil;
2. A random arrangement of natural remnant magnetization (NRM) components (e.g., a random orientation of magnetite grain spins in a paramagnetic matrix, a random build–up of bricks, etc.);
3. A low Koenigsberger ratio $Q = M_R/M_I$, and,
4. The absence of nearby objects with a significant NRM component

Forward Modelling: Induced Magnetization

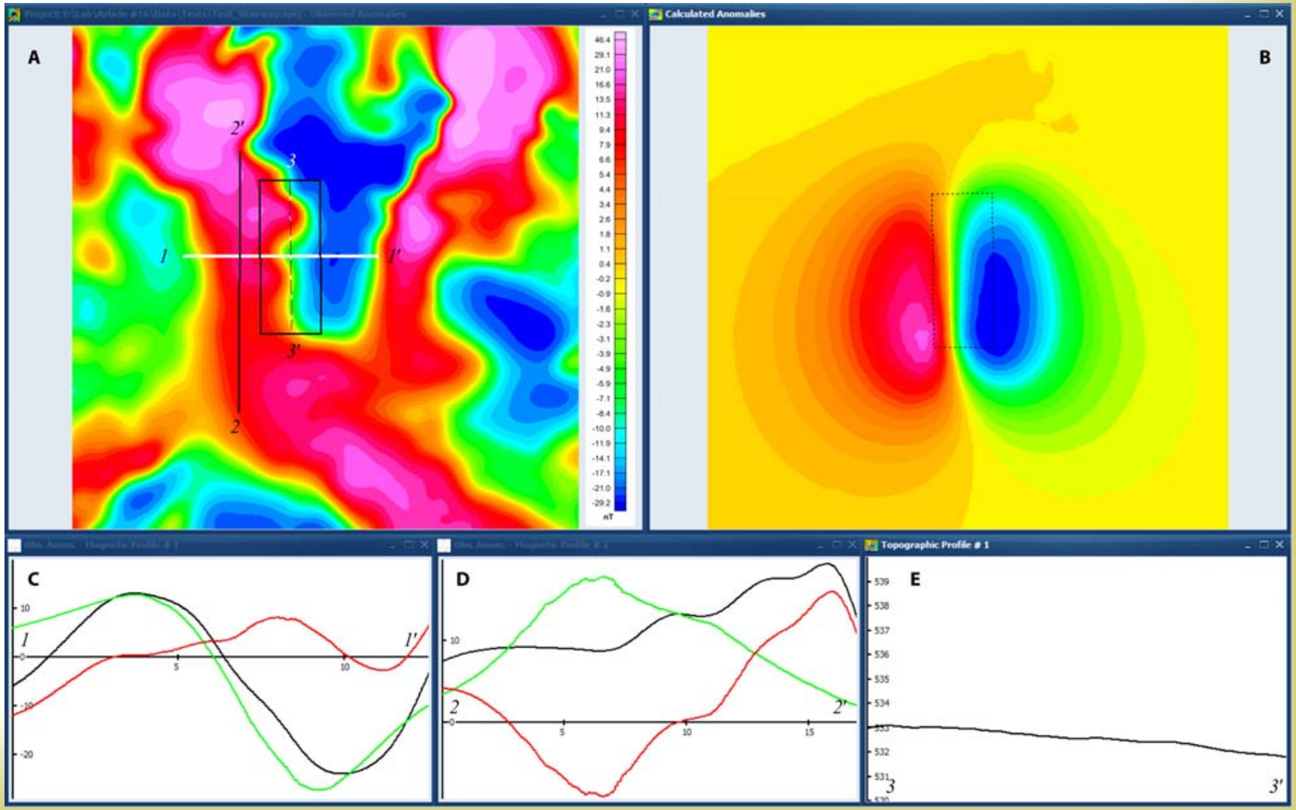
Examples of archaeological features dominated by induced magnetization contrasts: Graves, historical iron artifacts (Bevan, 2002), ditches and limestone walls.

Remnant magnetization produces strong anomalies in materials with:

- High Koenigsberger ratio (Q);
- Fired materials (e.g., bricks);
- Materials that have been fired at a later time during historical or natural events.

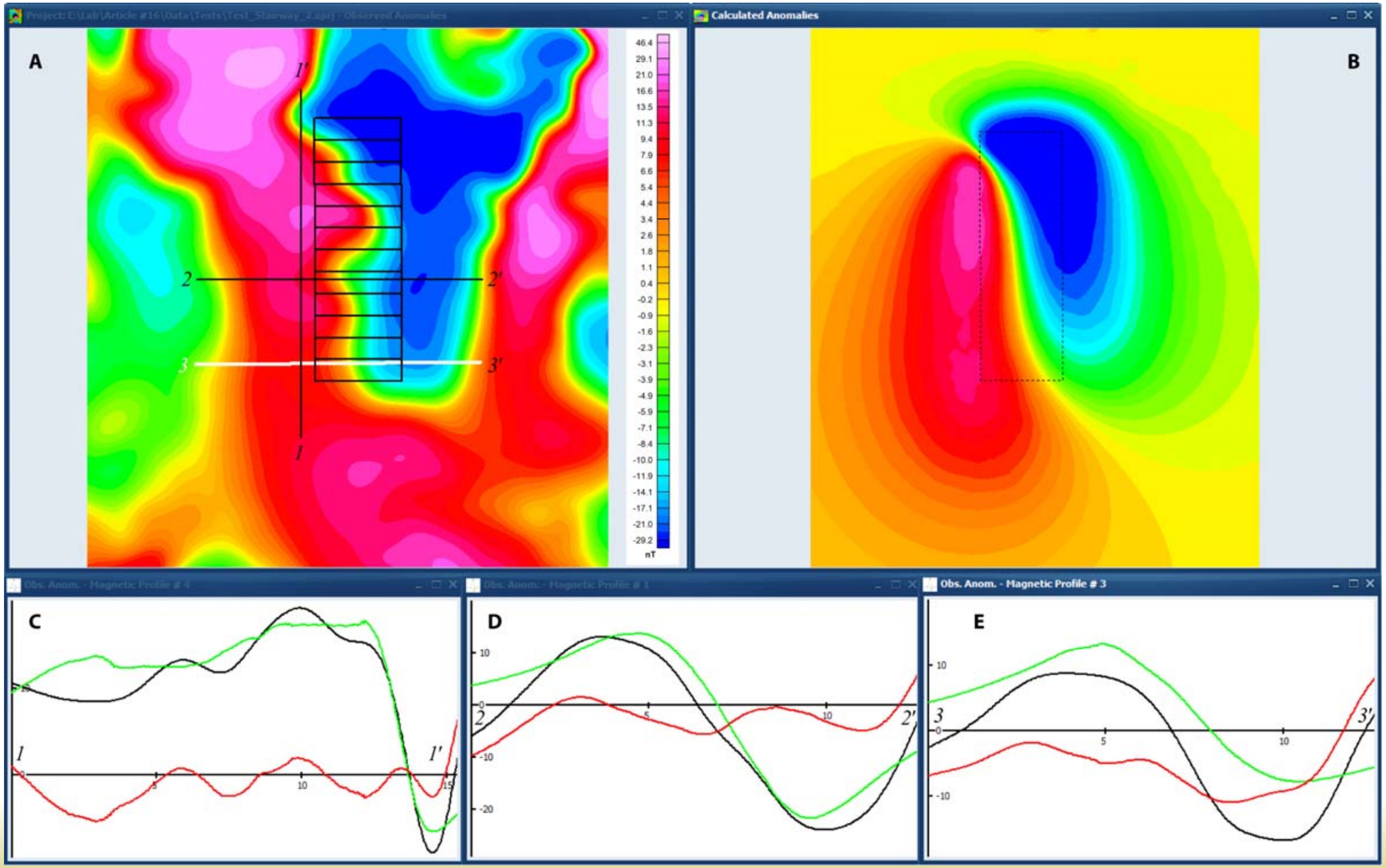
Forward Modelling: Rugged Topography

A rectangular prism model of observed anomalies (A) along a hill slope (Antigonea archaeological park, southern Albania, Schettino et al., 2017). These data were acquired 0.5 m above the terrain. The average soil susceptibility was $\chi_0 = 500\times10^{-6}$, while the ambient field parameters were: $D_0 = 3.95°$, $I_0 = 56.72°$, $F = 46336.00$ nT. Panel (B) shows the model anomalies, calculated assuming $\chi = 3000\times10^{-6}$, $z_1 = 2$ m, $z_2 = 3$ m, and a NRM vector with parameters $D = 90°$, $I = -20°$, $M_R = 0.9$ A/m. Panels (C) and (D) illustrate magnetic profiles with model and observed anomalies (green and black curves, respectively), and the error curve (in red). Finally, Panel (E) shows a N–S topographic profile through the prism.



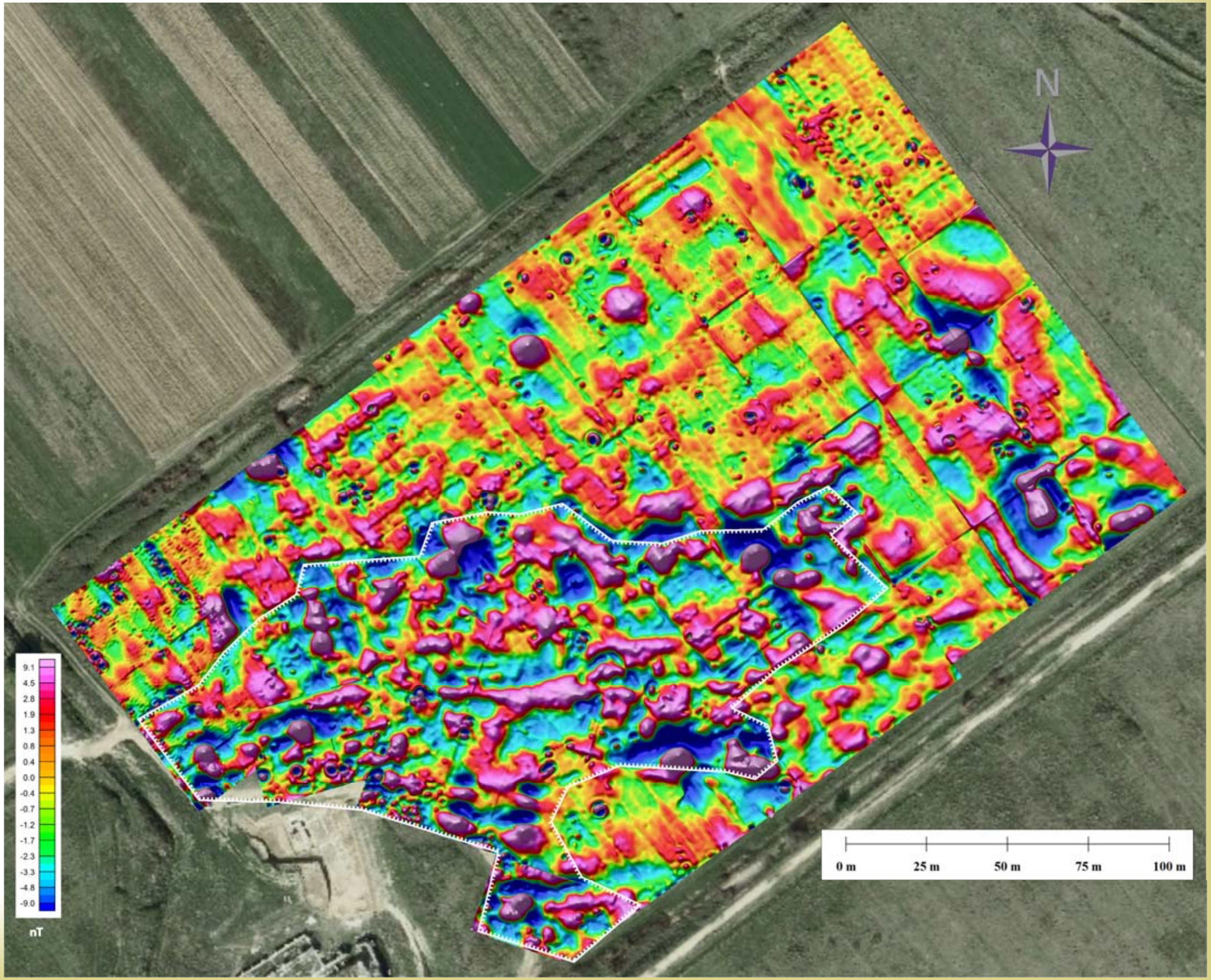
Forward Modelling: Rugged Topography

An alternative stairway model:



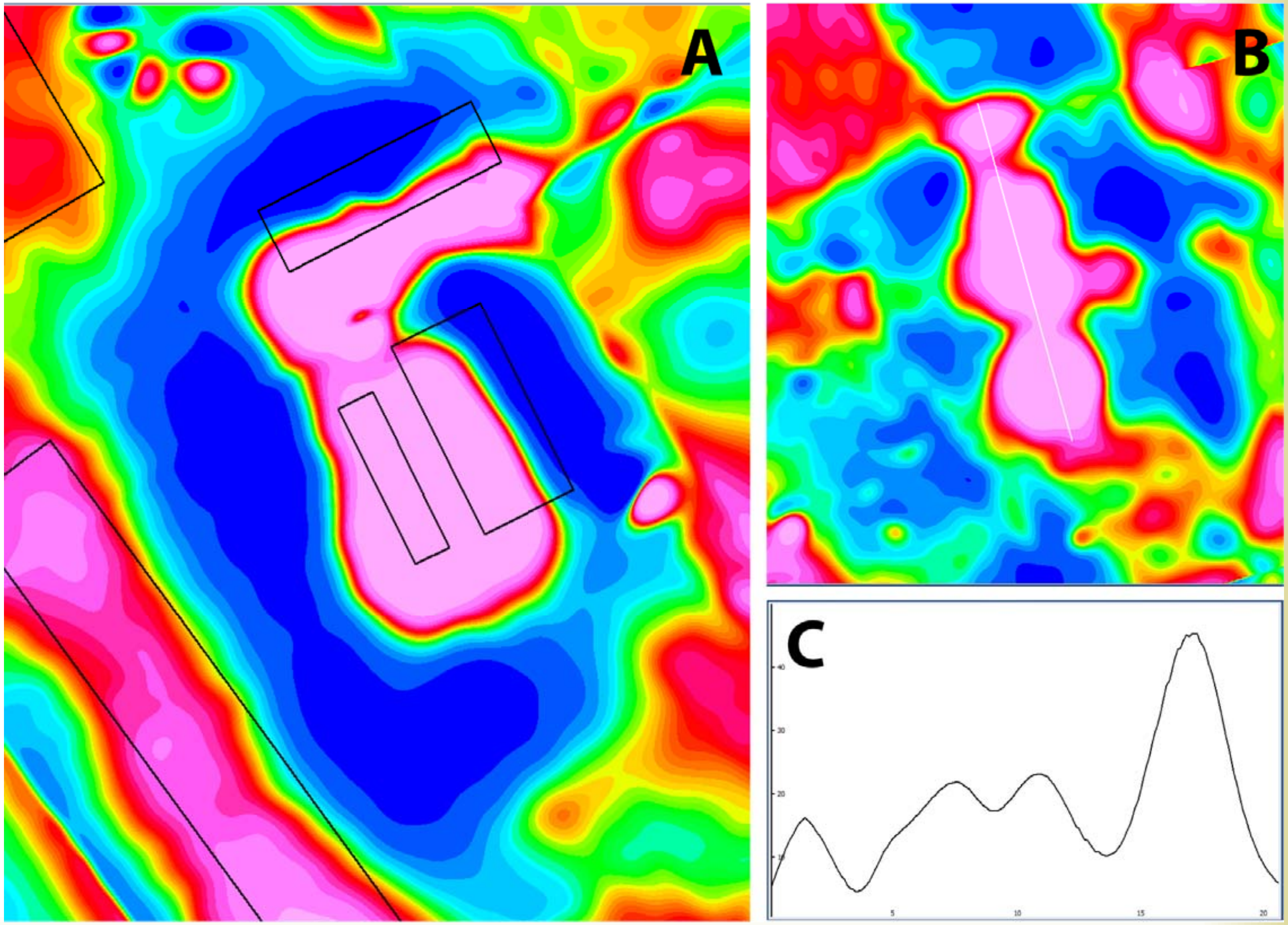
Forward Modelling: Coalescence of Anomalies

Hadrianopolis, southern Albania:



Forward Modelling: Coalescence of Anomalies

Hadrianopolis,
southern Albania:



Conclusion

- In this approach, total field data are acquired, filtered, and reduced to archaeological anomalies according to standard procedures;
- An interactive forward modelling software, *ArchaeoMag*, is then used to create and edit magnetization models of buried settlements. It can be freely downloaded at: http://www.serg.unicam.it/Downloads.htm;

Some advantages:

- *ArchaeoMag* allows to distinguish between induced and NRM components of magnetization, allowing a fine calibration of the model and dating of firing events;
- Export the magnetized blocks as a file that can be subsequently loaded in a GIS and integrated with other data sets for the study area. For example, it is possible to combine or compare magnetization maps with resistivity or GPR data to build an integrated archaeological model

Thank You