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A QGIS Model for Detecting and Highlighting Magnetic Dipole Anomalies in Geomagnetic Data

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A QGIS Model for Detecting and Highlighting Magnetic Dipole Anomalies in Geomagnetic Data

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MSc Thesis Archaeological Science

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I would also like to thank my supervisor, Tuna Kalayci, who helped me through the process of writing a thesis.

1. Introduction

Through the study of magnetometry in Cyprus, along with a basic understanding of its functioning, its current applications and potential challenges of magnetic surveys in the Mediterranean could be determined and tackled. The geomagnetic prospection, including the utilisation of magnetometry in archaeology, provides and has much potential for the future of archaeology. To understand how it works better, the presentation of dipoles, from their fundamental physics to their relevance in archaeological studies. That is why the magnetic dipolar anomalies and their interpretation based on data obtained from magnetic survey are under investigation and they are explored further.

The challenges of using geomagnetic prospection in Cyprus are a part of the investigation of the area and its archaeology. The geology of the region, soil types and current activities are explained further to understand their connection with magnetic maps and data as well as their types such as magnetic dipole anomalies. That is why the difficulties of conducting magnetic surveys in certain geological formations, as well as the issues of taphonomy in specific soil types are highlighted. Additionally, the data is presented, and various sites are examined in terms of their landscape, history of research, and project aims. This helps to provide a more specific context for understanding the data used in this thesis. The data cannot be shared with the public as they are unpublished up to this date.

In the case of Cyprus, geophysical research is relatively new, giving much space for further geophysics applications. Moreover, Cyprus and many islands in the Mediterranean have a rapid increase in tourism every year. This leads to tourist accommodations and modern buildings expanding towards areas with significant archaeological interest. As a result of this expansion, rescue archaeological excavations are undertaken with demanding timeframes and poor handling of archaeological sites. Geophysical surveys can provide a faster and non-invasive solution to resolve such problems. However, geophysical surveys produce vast data that need much processing, something that is essential but at the same time could be time-consuming. Further analyses and processes, including visualising data and detecting anomalies, add to the general workload. Automation at a particular process level could positively contribute to such projects and that is the main goal of this thesis. For the creation of a model through an open-source software a detailed explanation of the methodology and workflow used in the project is provided. That is why a further break down of each feature and algorithm as well as how they work section is presented. The methodology used for model development is also included, along with thorough presentations of the selected algorithms and the customisations used to optimize their usability. Additionally, suggestions are given for secondary processes and how they can enhance the overall processing experience, even though they are not part of the model.

A discussion is made at the end about how to interpret the results in relation to the research questions and goals. Additionally, the challenges, limitations, and issues that were faced while creating and using the model and algorithms are covered.

1.1 Aims and Research Questions

If we consider the case of Cyprus, geophysical research is relatively new, giving much space for further geophysics applications. Moreover, Cyprus and many islands in the Mediterranean

have a rapid increase in tourism every year. This leads to the expanding accommodations and modern buildings towards areas with significant archaeological interest. As a result of this expansion, archaeological excavations are undertaken with demanding timeframes and, therefore, poor handling of archaeological sites. Geophysical surveys can provide a faster and non-invasive solution to face problems like that.

That said, as the number of geophysical surveys in Cyprus is increasing, the need to better understand geophysics use in archaeology is also expanding. More specific questions about each method arise. In this case, the magnetometry is under investigation and, more specifically, the magnetic dipole anomalies in Cyprus's environment, which is limited so far.

- How can the magnetic dipole anomalies be highlighted to determine the presence of archaeological features in the Cypriot landscape?
 - What do the dipole anomalies and the direction of their magnetism indicate for the area's archaeology?
 - How do the geology, chemical soil properties and modern activities in Cyprus affect these results, and how and to what extent can we salvage them through filtering in order to have viable data for archaeological purposes?

1.2 Thesis Structure

The first chapter of the thesis is the introduction, including its sub-chapters, where an overview of magnetometry in Cyprus as well as a basic understanding of how it works, is provided. The current applications and further challenges of magnetic surveys in the general area of the Mediterranean are mentioned. The challenges are extensively described in the third chapter.

In Chapter 2, the background of geomagnetic prospection is presented and how magnetometry is seen and used in archaeology. The dipoles as features are also explained in the second chapter, from their fundamental physics to their presence and importance in archaeology. The magnetic dipolar anomalies and their direction are seen through their interpretation in the data provided by the magnetic surveys.

The third chapter presents the challenges of Cyprus as a landscape for geomagnetic prospection. The geology of Cyprus, as well as the soil types and modern activities existing in Cyprus, are mentioned. This chapter describes the issues of taphonomy in certain soil types and the magnetic surveys in inconvenient geological formations. Further, it shows a suggestive answer to the sub-question of the leading research question on the above issues in the archaeological context. Throughout the third chapter, the data are presented and described. The sites are also shown and analysed, from their landscape and topography to their history of research, the project's aim and finds, to put the previous chapters into a more specific context and understand the data used to evaluate the package created through this thesis.

Chapter 4 provides the methodology and workflow step by step and shows how each feature and algorithm incorporated in the project works. It provides the methodology used for the model development as well as detailed explanations of the components included in the model. The selected algorithms are thoroughly presented with the customisations used to make them

optimal and usable. Furthermore, secondary processes are mentioned, that are not included in the model but are great additions and suggestions to such processing.

Chapter 5 is the follow-up of Chapter 4, as it provides the resulting decisions from the algorithm and features selection. It is the chapter where the outcomes of the model are presented, including example visualisations of how the detected and highlighted features of dipole nature are shown in different ways. Further, it provides some comparisons on the components of the model, related to their effectiveness.

The sixth chapter is providing a discussion on the interpretations of the results in the context of the research questions and goals. Moreover, it presents the challenges, limitations and issues encountered during the creation and use of the model and the algorithms.

The thesis concludes in Chapter 7s, where the research questions mentioned in the introductory chapters are answered. Also, the concluding chapter summarises the key takeaways of the thesis and stresses the importance of it. Finally, it provides future directions for such research and improvements for the model.

2. Geomagnetic Prospection

2.1 Background

2.1.1 Magnetometry in Archaeology

A variety of geophysical methods are used in archaeology. Each technique has its applications; different methods are used depending on each case's characteristics. Research is always taking place on a known or suspected archaeological site. Various archaeological remains can be detected on the sub-surface as they cause magnetic anomalies. Often, anomalies are presented in various ways based on magnetism and how is affected by different factors. In these magnetic surveys, anomalies could be caused by material that differs from the local area's magnetism and that ranges from anthropogenic features to geological and archaeological ones, because features have usually enhanced magnetic susceptibility. Anomalies are essentially the features found in the magnetic surveys. Through magnetometry, these features could be found in the subsurface and that is why magnetometers are an excellent archaeological technique but not the only method (Armstrong & Kalayci, 2015, pp. 4–5).

The magnetic survey aims to better understand the sub-surface by mapping changes in the material's magnetic properties in the subsoil, as described below (Armstrong & Kalayci, 2015, p. 1). Magnetometers can measure the effects that sub-surface magnetised material has on the Earth's magnetic field method of magnetic survey is the measurement of the magnetic susceptibility of materials. These measurements are taken with small units named nano Tesla because archaeology requires that even the more minor changes can be traced. These changes are caused by buried material that forms features that affect the local strength of the Earth's magnetic field (Fedi et al., 2017, pp. 203–204). Magnetic geophysics started in archaeology with metal detectors and evolved into platforms equipped with multiple sensors and differential GPS (Armstrong & Kalayci, 2015, p. 2). Concerning the instrumentation of magnetic surveys,

magnetometers are used. Among the magnetometers, the fluxgate gradiometer has increased in popularity as it offers a variety of features and a lower price than others (Armstrong & Kalayci, 2015, p. 3). The use of might not be the best at locating features that create empty spaces on the subsurface but contributes to a manifold approach. That shows that while other geophysical methods could be more effective in finding cavities underground, magnetometers have the advantage of being able to replace them when the rest are not as helpful (Moffat, 2015, pp. 49–51). The remains from buildings can still be detected because of the contrast that is created between the building material and the soil or shape, as it is visible in the structure in Petounta's magnetic map (Fedi et al., 2017, p. 206).

2.1.2 Magnetometers and the Mediterranean Environment

Some landscapes create more challenges for their study because of the different properties of the soil and geology of each area, as well as other factors. The Mediterranean has a fragmented landscape consisting of coastal zones, mountains, and different types of not inviting environments. This gets even clearer with mountainous terrain with steep and rocky surfaces, which leads to a more time-consuming survey. Another problem that archaeologists face with the Mediterranean environment is the continuity of the settlements, resulting in archaeological sites inside urban areas, making it challenging for a magnetometer survey (Armstrong & Kalayci, 2015, p. 5). Even though the complex landscape of the Mediterranean makes it difficult for this type of research, some traits of the area allow studies. One could be considered the region's climate, as it could be favourable for the magnetometers (Armstrong & Kalayci, 2015, p. 6).

2.2 Magnetic Dipoles

The magnetic dipoles are directly connected with the magnetic fields and forces and, by extension, follow their properties. The magnetic poles always are found in pairs, as seen by the permanent magnet's properties, where they always have a north and south side. The permanent magnet's formation depends on the magnetic field surrounding a magnetic substance (Serway & Jewett, 2004, pp. 895–896). A compass has a north and a south-seeking pole, and its needle seeks Earth's geographic north pole, considering that the Earth also consists of a north and south pole. The Earth's magnetic poles are located near the opposite geographic pole, meaning that the magnetic north is close to the geographic south pole and vice versa.

The magnetic dipoles are pairs of magnetic highs and lows and can be found on magnetic maps. They can provide depth and mass estimations of objects in the subsurface, and they cause anomalies in the data of magnetic maps. Further, and could be indicators of objects and provide a series of other information (Bevan, 2017, pp. 1–3). Through the analyses and interpretations of these dipoles, the location of the object could be determined in X and Y coordinates because of the anomaly that is created in a magnetic map, as well as an estimation of its depth represented by Z. Furthermore, the object's magnetic amount could be established with a bit of uncertainty. As a result of the objects' magnetic properties, the direction of their magnetic field could be determined, revealing more information on the object's properties, such as its material, distinguishing, for example, iron from steel (Bevan, 2017, pp. 4–5). Also, the inclination and declination of the magnetisation of the dipole could be shown through their interpretation. The magnetic declination depends on the fact that the magnetic poles are

approximately 1200 to 1300 miles away from the Earth's geographic poles creating an offset between the geographic north and the magnetic north. The compass indicates the true north, which is the geographic north pole, but it changes based on the location that one is on the Earth, meaning that in a case where an area will give a result of the true north, another could give an alignment of degrees off to east or west of the true north. (Serway & Jewett, 2004, pp. 953–954).

Their high magnetic value shows a high magnetic field in a more circular shape rather than the arc shape of the weaker low that is adjacent to the more potent high (Figure 1). However, not all circular anomalies show standard objects, as they could also create bipolar anomalies that are produced through features such as shallow-filled pits or basins and generally are described the same way as the dipolar anomalies, meaning as adjacent magnetic highs and lows (Bevan, 2017, pp. 1–3).

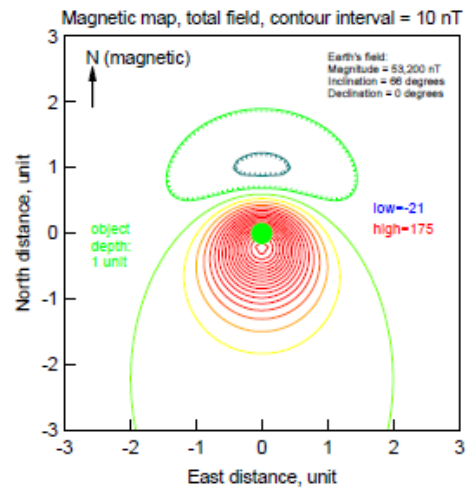


Figure 1 Dipolar anomalies, high positive (circular) and high negative (semi-circular) representation (Bevan, 2017, fig. 5)

Their identification, in the archaeological context, is not as straightforward as expected because “The magnetic low is often north of the high, but not always. The predominant anomaly is usually a magnetic high, but it can also be a low” (Bevan, 2017, p. 5).

3. Cyprus

Every landscape in the world differs in distinct aspects for different purposes. In the archaeological context and the prospection through geophysics, the geological features and geology, the chemical properties of the soil as well as current activities and infrastructure. The magnetic map resulting from the magnetic survey is directly affected by the topography, geology and properties of the surface and the subsurface (Bevan, 2017, p. 4).

3.1 Geology of Cyprus

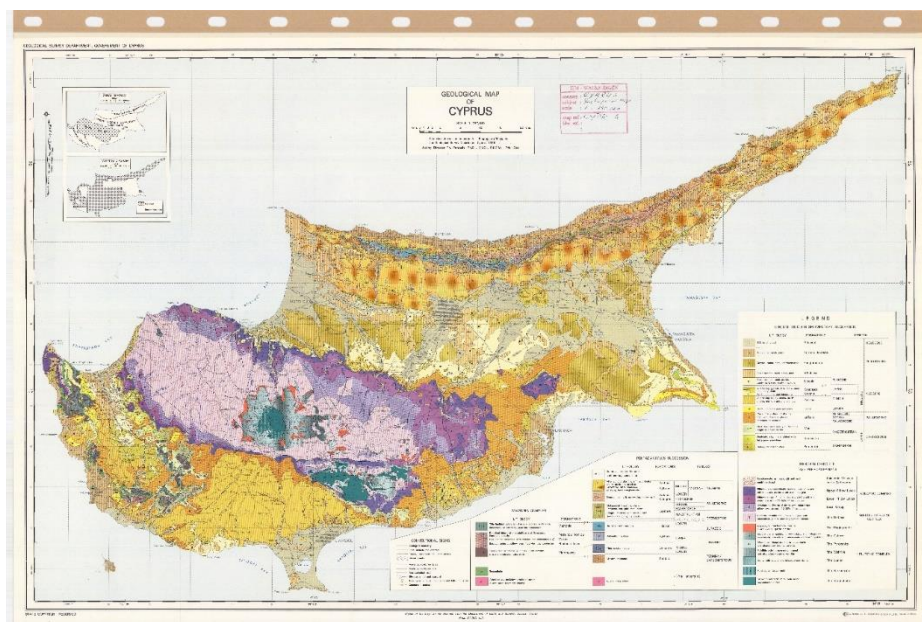


Figure 2 Geological Map of Cyprus (Geological Survey Department of Cyprus)

Even though the geology of Cyprus is complex, it still offers a considerably suitable landscape for magnetic prospection. However, in some instances, it creates too many anomalies obstructing a geomagnetic survey and its results, even after applying multiple filtering analyses.

The creation of Cyprus through the depths of the sea, combined with the magmatic processes that took place during that process, allowed the formation of various geological types and formations. The main types of sedimentary, volcanic, and plutonic rocks as well as other various rock types, create a diversity for each area's magnetic signature in Cyprus. The geology of Cyprus is divided into major formations. The site of Palaepaphos in the village of Kouklia in Paphos has a geology mainly consisting of the Pakhna and Moni formations and is surrounded by the Lefkara and an Alluvium formation. Pakhna and Lefkara formations are made of calcareous geology; the Moni one has predominantly clayey matrices, and the Alluvium with silt, sand and gravel, as shown in the map above. Paralimni as an area also has different formations with a lot of calcareous geology with the formations of terrace deposits, Lefkara, Nicosia and Kannaviou formations. The area around the Petounta, Alaminos and

Menogia sites have similar geology between them because of their proximity to each other and is Alluvium as a result of the river and its valley, as well as Lefkara, Paghna and Kalavassos (Geological Survey Department, 1977).

Examples that corroborate the difficulties that result in the complexity of the Cypriot environment are specific cases such as the ones of Evreti in the site of Palaepaphos and the village of Kokkinoxoria in the districts of Famagusta and Larnaka (Osmond & Stephen, 1957, p. 19). A magnetic survey was conducted in the area of Palaepaphos and, more specifically, around the area of Evreti. The magnetic map produced from the survey was unusable, even with the use of multiple filters and processing techniques, because of the geological features that were found in the subsurface. The area's geology was unexpectedly challenging as it has underground geological formations with intense magnetic properties. Ultimately, the magnetic map results were faulty and not used for archaeological research because of the high values around the map. The example of Kokkinoxoria differs from the former case as it is based on the chemical properties of the soil. This area of Cyprus consists of multiple agricultural villages. It is mainly known for its red soils because of its igneous geology and iron-rich composition, and this is where it gets its name as well, which directly translates to "red villages" (Osmond & Stephen, 1957, pp. 21–22). Because of the chemical properties of the soil, potato production is prevalent in these villages, leading to different problems for magnetic prospection. Farmers usually burn their fields after harvest to make the clearing of the fields, replantation, and other related processes easier. As a result, the iron oxides that are present in the soil go through a chemical interaction where the iron oxide turns into magnetite, creating a mirror-like surface for the magnetometers. The effectiveness of geomagnetic prospection does not degrade because of this diverse and rich subsurface. However, it is still dependable on many factors, such as the type of rock, magnetic anomalies and other challenges that are not directly related to geology.

The geology of Cyprus provides challenges in the magnetic survey processes, from the accumulation of data to their processing and visualisation. The visualised representations of the data produce a magnetic map that includes the magnetic measurements of the area. This area shows an admixture of noise and anomalies among the normal measurements. The anomalies could present in different ways including with dipole nature and extreme values. The anomalies produced should be interpreted through observation of the resulting images. However, even the interpretations are not exclusively archaeological as the anomalies are not only of archaeological interest. One of the major reasons for extreme values and anomalies is geological features. The anomalies of geological origin usually appear as extreme values because of the geology of the area that could consist of material that could be easily magnetised or have magnetic properties. These anomalies could appear in the visualised data as dipoles as well, making the process of interpretations more challenging. Soil properties have the same effects to the interpretations and also have a similar presentation in the magnetic maps as the geological features. The major soil types that occur in the Cypriot landscape are presented below.

3.2 Major Soil Types

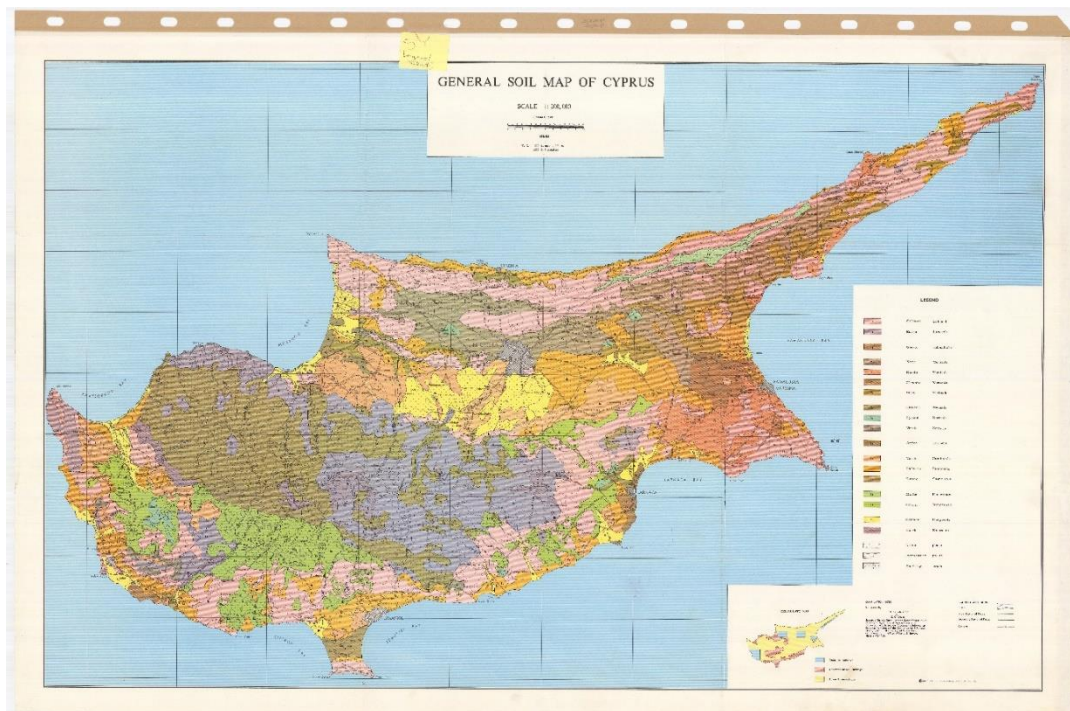


Figure 3 General Soil Map of Cyprus (Geological Survey Department of Cyprus)

The diversity extends to the soil types as well. The Troodos Mountains are the primary geological formation of Cyprus and the one with the most diversity in types. Soils from the plateau are considered calcareous with high content of calcium carbonate, which is the main component of limestone. Its effect on taphonomy is based on its alkaline nature and relatively dry consistency. It is more of a “landscape of production” where artefacts do not corrode as much and as fast, preserving them in a better state. In the same mountains, acidic soils, such as the Rendzinas and Ferralic soils, are also present. The Solonetz soils, mainly found in high salts areas, have a high pH, which is visible in Regosols too. Regosols are found in valleys and slopes around the lower parts of the Troodos Mountains.

Even though these significant soil types are considered mostly acidic, they are not the only soils present in Cyprus. Other types found in fertile plains are almost neutral in acidity and therefore do not affect the subsurface as many remains. As soil types affect the magnetic properties of surface soil and the subsurface and by extent, it could change the geomagnetic measurements and results. The different soil types could affect the magnetic field and direction as they carry other magnetic properties.

For example, the previously mentioned Ferralic soils contain high levels of iron minerals and, thus, higher magnetic susceptibility. The effect that leaves in the magnetic measurements is strong anomalies, skewing the results. Under different circumstances, such measurements could have indicated archaeological features. Most of the time, the chemical and magnetic soil properties are taken into account before proceeding with an archaeological magnetic survey to prevent false results or heavier processing routines.

The selected sites are no exceptions to the aforementioned chemical properties of the Cypriot soil. The site of Palaepaphos and its surrounding area have relatively the greatest variety in soils and, by extension, studies about them. The soils in Kouklia are mainly calcaric cambisols, pellic vertisols and calcaric rhegosols. Further from the main area, one encounters rhodic vertisols, ochric rendzinas, eutric rhegosols and calcaric lithosols. As for the areas around the Xeros Valley and the general area in the district of Larnaka, rhodic bertisols, ochric rendzinas, and the calcaric lithosols and calcaric cambisols which they share with the Paralimni region.

3.3 Surface Taphonomy

The taphonomy of archaeological sites in Cyprus presents a complex scenario influenced by various factors, including soil types, climate, erosion, and human activities. Applying dipole anomalies in magnetic maps can provide valuable insights when examining the connection between these factors and archaeological investigations.

One aspect to consider is the influence of soil types on taphonomy. Cyprus exhibits a range of acidic soils, which can destroy archaeological remains. However, it is essential to note that the acidity levels vary across different locations within the region. This variation in soil types highlights the need for precise site-specific analysis, where magnetic mapping can play a crucial role. Magnetic mapping utilises variations in the earth's magnetic field to create detailed maps of magnetic anomalies. Various factors, including soil composition and moisture content variations, can cause these anomalies. By employing magnetic mapping techniques, archaeologists can identify dipole anomalies in magnetic maps, which could indicate areas of interest for further exploration. These anomalies can result from underlying archaeological features such as structures, artefacts, or disturbances caused by human activities.

Moreover, the climatic conditions of Cyprus, characterised by warm and dry weather, contribute to taphonomic processes. Natural erosion resulting from weathering and other environmental factors, combined with bioturbation (soil disturbance by biological organisms), can lead to the degradation and loss of archaeological materials. Magnetic mapping can assist in identifying areas where these natural processes have caused disturbances, potentially guiding archaeologists to intact subsurface remains. While biological processes can affect taphonomy, human activities further contribute to the destructive impact on archaeological sites. Agricultural practices, constructions, and other human interventions can disrupt the integrity of archaeological remains, regardless of how well natural processes treat them. Magnetic mapping can help identify areas where anthropogenic activities have influenced the archaeological record, assisting in understanding the extent of their impact.

It is important to note that surface taphonomy tends to be generally destructive in most cases, irrespective of the region. However, in the case of Cyprus, the subsurface remains may only sometimes be concealed under substantial soil layers due to the interplay of natural processes. Magnetic mapping can aid in identifying areas where subsurface features may be relatively accessible, allowing archaeologists to focus their efforts on targeted excavation and preservation.

3.4 Modern Activities

3.4.1 The Impact of Modern Activities

Modern activities in Cyprus can impact magnetic prospection by altering the region's magnetic field. For example, human activities such as construction, mining, and heavy machinery can disturb the subsurface geology and generate magnetic anomalies that may interfere with the interpretation of magnetic prospection data.

Additionally, modern infrastructure such as roads, bridges, and power lines can generate strong artificial magnetic fields that can affect the accuracy of magnetic prospection results (Fedi et al., 2017, p. 205). It is essential to consider the presence of these artificial structures when conducting magnetic prospection in Cyprus and to take steps to minimise their impact on the results. Scattered metallic objects and material on the soil due to agriculture, modern buildings in the vicinity, metallic fences, power lines, wild animal barrows and many other reasons are responsible for several issues with the magnetic maps. Still, most of the time, they can be eliminated through processing (Fedi et al., 2017, p. 206). Surface material, though, can create spots that give too high values or immediately reflect the magnetometer's signals and create "blind spots". On the other hand, modern metallic objects provide great measurements if they do not intercept the signal. However, these measurements are unimportant for archaeology as they are contemporary and give "false hope" through the magnetic dipolar anomalies they create in the magnetic maps.

It is also worth noting that a magnetic prospection is a powerful tool that can still be effective in the presence of these types of modern activities. By carefully conducting magnetic prospection surveys and the proper filtering, it is possible to account for the impact of recent activities and still obtain accurate and reliable results.

3.4.2 Modern Activities and Archaeological Landscape

The intensity of modern activities within the archaeological landscape of Cyprus varies depending on the location and the type of activity. In general, areas with high levels of human activity, such as cities and towns, tend to have a higher intensity of modern activities compared to rural or remote areas. Archaeological sites and landscapes in Cyprus are often located in or near urban areas. Therefore, they are exposed to a range of modern activities that can negatively impact the preservation of cultural heritage. For example, construction, mining, and urban expansion can destroy archaeological sites and cause the loss of valuable information about the past.

Archaeological sites and landscapes are protected by law, and development projects must undergo an archaeological impact assessment to determine their potential impact on cultural heritage. In addition, many sites are considered archaeological parks or protected areas. There are also efforts to raise awareness of the importance of cultural heritage among the public and the private sector. However, efforts are being made by the government and various organisations in Cyprus to protect and preserve the country's rich cultural heritage.

Metallic fences, buildings, garbage, and other artificial structures can have a negative impact on the results of magnetic prospection. These features can generate artificial magnetic fields that can interfere with the natural magnetic field of the subsurface and cause anomalies in the

magnetic data. These anomalies make it challenging to interpret the results and accurately map the subsurface geology.

It is possible, though, to account for the impact of these structures in magnetic prospection by using advanced processing techniques, such as removing the contribution of artificial magnetic fields from the data. In addition, careful planning and design of the magnetic prospection survey can help minimise artificial structures' impact on the results. For example, it is possible to obtain accurate and reliable results by avoiding areas with high concentrations of these structures or by surveying at a time of day when the impact of the structures is minimised. As the magnetic surveys attempt to find features in the subsurface and as the features are basically anomalies, it means that there is no immediate distinction between anomalies of archaeological origin and modern ones. Especially modern activities could produce a variety of anomalies of different types, including the magnetic dipole anomalies. That is why it is wise to know what type of anomalies could be presented in order to interpret the results and distinguish what they represent and where do they come from.

3.5. Selected Sites

The datasets concern Palaepaphos, Paralimni, Petounta, Alaminos and Menogia sites (Figure 4). The sites were chosen by the availability of geomagnetic data. The available data are mainly meant to evaluate the final package and help evaluate various algorithms for processing, filtering, and visualising data. The names of the sites and the toponyms follow the sources and ways recording of geographical terms of the Permanent Cyprus Committee for the Standardisation of Geographical Names, which is responsible for the implementation and standardisation of geographical names and the transliteration system of the Greek alphabet in the Roman writing system of the Hellenic Organisation for Standardisation.

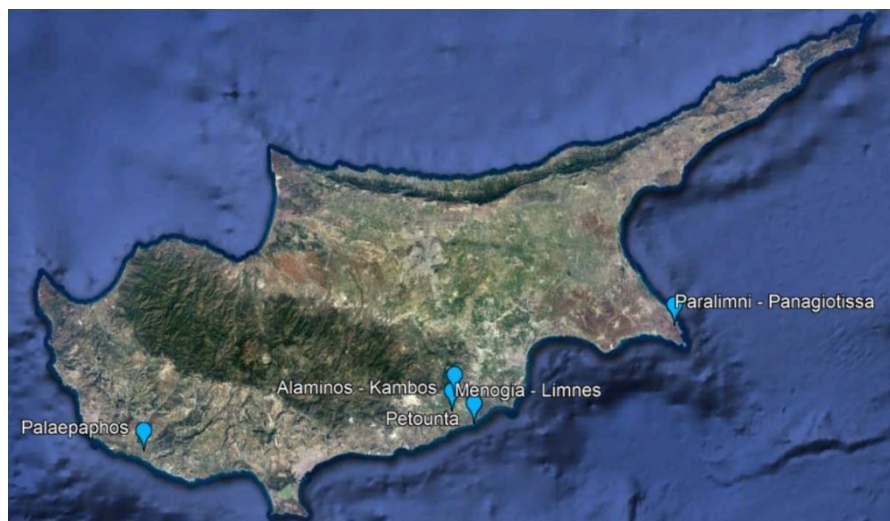


Figure 4 Map of the selected sites created in Google Earth Pro (by author)

3.5.1 Palaepaphos

Palaepaphos is located in approximately the same area as the modern village of Kouklia in the district of Paphos, which is in the southwestern part of Cyprus. Paphos as a district has mostly natural landscapes and meets the sea at the southern and southwestern sides of the island,

creating a variety of climates, landscapes, fauna, flora and natural resources throughout Paphos. Palaepaphos has a lot of archaeologically interesting sites because of its location and, by extension, its archaeological continuity from prehistory to medieval and later times (Sarris et al., 2014, p. 41).

Kouklia has several sites that appear in proximity to one another and add to the area's archaeological interest, which led people to it for centuries. The area of Palaepaphos has been investigated extensively through the centuries, starting with the first travellers and explorers of the 16th century. The first half of the 16th century found the Swiss and Venetian travellers Ludwig Tschudi and Francesco Attar, respectively, in Kouklia, searching for the sanctuary of Aphrodite, which was repeatedly mentioned in classical Greek literature. At the start of the 19th century, an Austrian traveller visited Kouklia, where he encountered and described the remains of the classical sanctuary of Aphrodite, as well as the temenos' walls, the cave of Regaina, and a rock-cut chamber tomb in the area of Arkallon. In the memoirs of these medieval travellers, the visible monuments and ruins were documented, which kept the area's interest alive for the upcoming centuries. One of these inspired people was Luigi Palma di Cesnola, who, as an Italian general and American consul in Cyprus, investigated and removed many antiquities from the island. The end of the archaeological investigation of Palaepaphos in the 19th century was marked by the first large-scale excavations in Cyprus, including Kouklia, from the Cyprus exploration fund, under the direction of the British School at Athens, which provided a publication with valuable information for the archaeology of Cyprus (Iacovou, 2023; Iacovou et al., 2010, pp. 20–22).

The archaeology of Palaepaphos continued with fieldwork excavations at Kouklia in the mid-20th century from the British mission directed by British organisations. The areas under investigation were mainly the plateaus of Marchello and Hadjiabdullah, where archaic to classical activity was uncovered in the form of ashlar masonry. Following the British missions, a Swiss-German mission under the auspices of the German Archaeological Institute and the Universities of Konstanz and Zurich undertook fieldwork research for a period of more than a decade, sparse into the decades from the 1960s to the 1990s (University of Zurich, 2007). The studies took place mainly at the plateau of Marchello but also focused on publishing the material and research of the British missions (Kopaniyas, 2022). The Department of Antiquities of Cyprus was also active throughout the years in the area with systematic and rescue excavations in mostly sites of mortuary context from the 1950s (Iacovou et al., 2010, pp. 20–22).

The Palaepaphos Urban Landscape Project (PULP) began in 2006 under the direction of Maria Iacovou and the University of Cyprus. The project's first phase ended in 2010, but the project continues until today (Iacovou, n.d.). The project aimed to define the extent of the city and landscape of Palaepaphos, inside and outside of its walls. During the geophysical surveys of 2007, the main goal of the project changed slightly as “the research strategy was based on false impressions” (Iacovou, 2019, p. 213), something that was soon after taken into consideration and redirected the project's aim.

The geophysical prospection was also an essential part of the investigation of the area, starting with surveys with magnetic prospection and electrical soil resistance in 2003 (Iacovou, 2017,

p. 190). Further geophysical surveys were undertaken after the beginning of the PULP in 2003, 2007, 2010 and 2012 and even more recent ones up to today (Iacovou, 2017, p. 204; Sarris et al., 2014, pp. 10–11). The 2003 and 2007 surveys had great coverage, with more than 44.000 sq.m. and more than 56.000 sq.m., respectively (Iacovou, 2019, p. 213). The geophysical surveys of 2007 and 2010 were broader, combining methods and multiple surveys in the large area that PULP investigates. The geophysical anomalies that appeared in the results of the fluxgate gradiometers had intense magnetic values in most of the investigated areas but also included really high measurements that showed no archaeological value since they were mostly of geological origin or were caused by modern disturbances, something that was confirmed by the excavations (Sarris et al., 2014, p. 41). The site of Arkalon had promising results and was surveyed twice in 2007 and 2010 surveys with a combination of techniques in order to pinpoint areas of archaeological interest. Marchello shows a broad range of values primarily because of the soil cultivation and erosion that created high noise measurements and because of some linear anomalies that were later named of archaeological interest because of the dipole nature and geometry of the anomalies. For the area of Mantissa, the measurements were problematic for archaeology as the values exceeded the dynamic range of the fluxgate magnetometers. The reason behind that result was most probably because of the volcanic rocks with ferrous-rich minerals that exist in the area. These anomalies of geological origin were also present in other sites in the area, including Evreti and Hadjiabdullah (Sarris et al., 2014, pp. 41–44).

3.5.2 Protaras-Panagiotissa

The site of Protaras-Panagia is situated in the district of Ammochostos, in the locality of Protaras region in south-eastern Cyprus, not far from the urban centre and about seven kilometres north-west of the cape Cavo Greco. The central part of the site is the chapel of Panagia-Panagiotissa, which is dedicated to the Virgin Mary and, more specifically, to the Theotokos' Dormition (Karlighioti et al., 2022, pp. 2-3).

The chapel sits at the top of the hill, on a rocky plateau, which overlooks a headland between two rivers. Beside the chapel is a natural spring called Mana tou Nerou, which has contributed to the continuity of the site and others around it (Christofi & Kantirea, 2020, pp. 219–20).

The excavations and research show that the site's history goes back to the Early Medieval times when it was destroyed during the Arabic raids of the 6th century AD. It is believed that the late basilica, and second church at the same spot, was erected in the 16th century AD. The present chapel results from restorations, with the latest one in 2021 (Christofi, 2021).

The site has been known since a 1973-4 survey conducted by Sophocles Hadjisavvas, who was the then director of the Department of Antiquities of Cyprus (DoAC), where he reported an early Christian site, a Venetian water system and a possible olive press in the area (Karlighioti et al., 2022, pp. 2-3).

In 2019, with the restoration plans of the chapel, an archaeological rescue excavation conducted by the DoAC under the direction of Polina Christofi (Christofi & Kantirea, 2020, p. 217) uncovered an early Christian Basilica of the late 6th-7th century AD and a later phase of a Medieval/Post-Medieval chapel. The rescue excavations extended into the Ayia Napa project and finished in 2021 (Karlighioti et al., 2022, pp. 2-3). During the excavations, DoAC and the

Municipality of Paralimni ordered a geophysical survey, which was done by Apostolos Sarris (University of Cyprus). The survey confirmed the archaeological interest in the area, and a geophysical map of the area was made. Further, with the contribution of Rafail Verengaris, 3D reconstructions and orthophotography of finds were made (Christofi, 2021).

The Ayia Napa Project aims to explore the living status of Cypriot people and monastic complexes during the decline of the Ottoman empire of the 16th-17th to early 19th centuries (Karligkioti et al., 2022, p. 7). The project includes the rescue excavations of the Ayia Napa monastery as well as the Panagia Panagiotissa chapel, which seems to work as pilgrimage centres for people travelling through to the Holy Lands and locals (Karligkioti et al., 2022, pp. 2-3).

Supplementary structures were found around the early basilica in a bad state of preservation (Christofi & Kantirea, 2020, pp. 219-20). Other finds included pottery of the two chronological phases and skeletal material and assemblages from the site Protaras-Panagia (Karligkioti et al., 2022, pp. 2-3).

3.5.3 Petounta

Petounta is a site in the Mazotos in the Larnaca district with an anchorage on its cape. The toponym Petounta means flying and is based on the myth that Panagia (Virgin Mary) passed through the area and sat on the edge of the cliff where the modern church of Panagia Petounta was built. The area is also one of the capes of the Larnaka district (Papakosta, 2020, p. 1).

Topographically, Petounta is a cape in the southwestern part of Cyprus. Modern Petounta is mainly an agricultural area and a popular spot amongst spearfishermen. The coast undergoes constant changes because of an average annual erosion of half a meter. This affects the sites' preservation but, at the same time, contributes to the uncovering of more archaeological material (Papakosta, 2020, pp. 2-3).

The site is split between its underwater part and its terrestrial part. At the latter part of the site, the Department of Antiquities permitted the collection of sample sherds. As for the former, a more thorough study was conducted through an underwater survey (Papakosta, 2020, pp. 2-3). The material collected from a survey in the area was sample sherds, which were dated in the Late Roman I and Late Roman IV periods. The cape of Petounta includes an anchorage as 47 anchors were found in the underwater landscape (Papakosta, 2020, pp. 4-5). Furthermore, remains of an early Christian baptistery were uncovered at the high promontory, confirming further the archaeological importance and activity in the area (Papakosta, 2020, p. 1). However, the site has been heavily damaged because of frequent erosion and modern activities with subsequent looting. For multiple reasons, including the latter, a magnetic survey was conducted to determine the existence of structures at the site.

3.5.4 Xeros River Valley

The project that studies the valley of the Xeros River is the University of Cyprus' research project, "Settled and Sacred Landscapes of Cyprus" (SeSaLaC), under the coordination of Dr Vionis. The project focuses on two main areas, including the Xeros River valley, with a size of 3900 hectares. SeSaLaC is a multiperiod intensive survey project, and its area is defined by a

natural buffer of hills (Papantoniou & Vionis, 2018, p. 1). The valley passes through multiple communities in the district of Larnaka. The survey's central area is Kophinou, and the general area of the survey includes the villages of Alaminos and Menogeia (Papantoniou & Vionis, 2018, pp. 2-3). The project's primary interest is the relationship between religious and other communal spaces and their natural environment and landscape.

In the mid-20th century, Porphyrios Dikaios, then Director of the DoAC, through the Cyprus Survey project, conducted a surface survey at Alaminos where he found chalcolithic material, indicating a site (Papantoniou & Vionis, 2018, p. 5). Later, the DoAC, under the direction of the Curator of Antiquities Giorgos Georgiou, proceeded to excavate trenches at the site of Alaminos-Kambos. Since 2014, the SeSaLaC project has studied the area of the Xeros Valley, where they systematically survey vital sites. In 2020 the field surveys ended, and in 2021 a geophysical survey was conducted to confirm and extend the archaeological structures and sites of the project area (Papantoniou & Vionis, 2018, p. 7).

In the Xeros River valley, there is evidence of human presence dating back to the Late Neolithic era, around 5200 to 4000 BC. The Chalcolithic site of Alaminos-Menoyiatika/Zorzakis is dated back to the Middle Chalcolithic period (ca 3500-2900/2800 BC) (Papantoniou & Vionis, 2018, p. 5). At Alaminos-Kambos, the DoAC excavations uncovered stratified pottery of Early and Middle Bronze Age (ca 2250/2200–2000/1950 BC and ca 2000/1950–1680/1650 BC), showing settlement activity at this part of the area (Papantoniou & Vionis, 2018, p. 7). The archaeological activity has been diachronic and continuous until the Byzantine and modern periods, with only a gap in the Late Bronze Age. The SeSaLaC systematic surveys have yet to identify Late Cypriot period material (Papantoniou & Vionis, 2018, pp. 9–10). The Iron Age is represented by Cypro-Geometric (ca 1050-750 BC) survey scattered material and Cypro-Archaic (ca 750-480 BC), and Cypro-Classical (ca 480-310 BC) finds that confirm the thriving and decentralised landscape of the period (Papantoniou & Vionis, 2018, p. 11).

The site of Alaminos-Kambos is in the locality of the village of Alaminos in the Larnaka district and not far away from the medieval tower of Alaminos. The Xeros River stems from the west of Stavrovouni Mountain and eventually empties into the sea at Alaminos. Alaminos-Kambos could be considered a central place and pertains to the system of hierarchically organised settling spaces (Papantoniou & Vionis, 2018, pp. 2-3). The settlement of Alaminos-Kambos seems to be abandoned during the early Late Bronze Age, following the trend of other Cypriot rural settlements (Papantoniou & Vionis, 2018, pp. 9–10).

The site of Menogeia-Limnes is located in the northeastern part of the SeSaLaC project's survey area. Relatively to other known project sites, there is inadequate published information about the site.

4. Methodology

In a geophysical survey, magnetometry is an essential part of modern archaeological research using a manifold approach (Sarris, 2020, p. 398). With the data acquisition, their format conversion must happen to prepare them for processing. Also, the metadata accompanying the magnetic data needs to be changed into a new format and archived. The usual process of data is done with specialised and proprietary geophysics software. These software are not easily accessible and need specialisation and knowledge. The processing includes ways of making the data easier for interpretation. Some of these ways are spike removal, de-staggering, and de-stripping. The general direction for these is the reduction of noises found in the data, which could be achieved with basic statistical methods or even raster image analyses (Armstrong & Kalayci, 2015, pp. 9–10). In the case of magnetic dipole anomalies, the process usually takes place manually. Through the visualised data, the researcher looks over the raster image in order to find which data and anomalies have archaeological interest, including the dipole anomalies.

For the case of this thesis project, open-source and open-access software QGIS was used as a primary tool, and a model was created through the feature Graphical Modeller. This process will be presented in the following sub-chapters step by step, from the preparation of files and data to the primary processing and visualisations of the data and dipoles.

4.1 QGIS

Quantum Geographical Information System (QGIS) is an open-source software developed and maintained mainly by a community of people volunteering and contributing actively to keep the software free for distribution, modification, and use.

One of the main reasons is that QGIS has open source, which means their scripts for everything behind the creation of the software and every single algorithm and option inside it are freely available. Because of that, exploration and experimentation took place by testing and modifying existing algorithms, adding and using local and third-party plugins to create a model that best serves the purpose and aim of this thesis through the Graphical Modeller and Processing Toolbox features of QGIS.

4.2 Python

Python is a well-established programming language, and even though using it was primarily based on personal preference, its popularity and widespread use are justified. Also, as the use of QGIS was a priority in this case, Python was used, which has an integrated module in the software and thus can work well with Python scripts and logic, regardless of where the script was created, inside or outside the software.

To write the scripts in the programming language of Python version 3.10.9, Spyder Python version 5.4.2 was used as it is a helpful and lightweight environment for coding, and it is also another software that is free and open source. For the steps of converting the files and preparing them for the next steps, only a few packages outside of the basic Python ones were needed. However, as one of them did not have a working version for the Python 3.10 series, a different new environment with the 3.9.16 version of Python was needed. To convert the files from .dat to .csv, the “os” and “pandas” packages were used to work through directories and read the files, respectively. Concerning the process of converting the .csv files to shapefiles, the “os”

and “pandas” were used for the reasons mentioned above and then “geopandas” and “Point” from “shapely.geometry”. “Geopandas” and “Point” contributed to the forming of a geometry column in the data, so QGIS recognises the data as geographically related data and not just numbers, without the need to specify in QGIS the possible names for X, Y and Z. As some data files seem to present delimitation with tab instead of commas, an extra part was added in the code to make sure that this would not be an obstacle in the later processes.

4.3 File and Data Preparation

As the magnetic data come in significant amounts, it is necessary to process them all together. This means that even data preparation was required through a script to make the process faster and more effective and, by extension, make further processing feasible. Even though the data used are raw, they should have a particular structure, as only some geophysical equipment, in this case, magnetometers, has the same output files. The data preparation is primarily statistical analyses, making the datasets easier to visualise with fewer disturbances and noise.

To make the data's availability and processing more manageable, the data were put in columns based on the concept of coordinates and measurements. More specifically, the raw data structure was three columns in a .dat file delimited by commas, “,”, each column representing X, Y and intensity of magnetism, which in this case are named Z for ease. Through a code in Python, the .dat files were converted into .csv files, separated in actual columns, in data frames, based on the comma delimitation and got X, Y and Z headers to make their use in QGIS easier. Because of the way that the data were exported, some values were marked as muted with the word “MUTE”, which made them strings instead of floats, meaning that they had text instead of numbers with decimals. As strings cannot exist in the data when importing them in QGIS, the “MUTE” values were converted to the numeric value zero, “0”. The latter steps were taken in order to make the files more readable for QGIS, as CSV files can be imported in QGIS as Vector Layers instead of Delimited Text Layer because the latter layer produces issues in the processing, filtering and interpolation of the files. However, in .csv files, when imported as vector layers, you need to specify the possible names of the columns that correspond to X, Y and Z. To avoid the extra step and make the importation of the files directly from the computer without the need of importing it first in QGIS before using it in the model, the files were converted to shapefiles.

4.4 Model Development

The model developed in this thesis aimed to serve the purpose of detecting and highlighting magnetic dipole anomalies from raw data. The model uses several algorithms in the QGIS environment, most specifically in the Graphical Modeller feature, allowing a certain level of automation for the processing part. In order to achieve the final raster image, the model goes through the steps of pre-processing, then visualisations and finally, refinement of these images with main processing.

In this subchapter, the model development is the QGIS Graphical Modeller, which is the main tool, is described as well as its environment with its interface and capabilities. Furthermore, the algorithms that are incorporated in the model are explained, including their selection and

any customisations that they went through. The algorithms below are mentioned in a similar order that is met in the model, giving a better understanding of each model component.

During the starting part of the model, an input layer parameter is added to allow the importation of shapefiles directly into the model. Alternatively, the datasets from .csv files are imported into the QGIS environment as vector layers with a few extra steps, as explained below (see section 4.4.2 Importing Files). Following the importation of data, the first part of processing is next. For this pre-processing step, a few algorithms are used to prepare the datasets for the parts of visualisation and main processing. When the data are imported into the model as vector layers, their geometry must be checked before proceeding. The output of the available valid layer is then used to determine the basic statistics of the layer. This step produces an HTML file that shows basic statistics of the fields X, Y and Z to analyse and interpret results, but in this case, it is to provide the information needed for the main processing steps. Next on the list is the alignment of the vector layer to the north in order to have north-oriented images.

Once the vector layers go through these processing steps, the main processing occurs in the model. The starting point of it is the first interpolation, which provides the user with the first visual representation of the data. The reason that an initial visualisation takes place is to show the first version of the geomagnetic map, indicating the intensity and the type of noise present. The model does not offer the denoising solutions concerning the issues of spikes, stripes and zigzags, which are some of the more usual noises that appear in geomagnetic data but are mentioned later in the methodology (see section 4.6 Secondary Processes). Then, a second and final interpolation takes place, providing a reasonably clear raster image with minimised noise. This step is considered the last one for processing the raster images but not for the total model and dipole anomalies detection. The model could have ended on that step and still provided a good way, with a little more automation, for preparing and processing data.

However, this thesis aims to detect and highlight magnetic dipole anomalies, which allows a more specific visual detection of possible archaeological features. A branch of the model continues towards the process of dipole anomalies with a cluster of algorithms that manipulate the vector layer to provide the detected dipole anomalies and highlight them. In order to do that, an anomaly isolation process occurs first, where the points of the vector layer that include high positive or high negative values are extracted from the rest of the points. As the high values are isolated, the model determines which ones out of the high positives appear next to high negatives and vice versa. That is the reason buffering is the next step. With buffering, the model is able to determine, with pre-defined buffers, which points fall into the “personal bubble” of other points. Once the buffers are defined, the algorithm of Extract by Location is used to gather these points in different layers, where they are later merged. As the magnetic dipole anomalies are now detected, one has to highlight them. To do so, the Z values of the points in the vector layer around the dipoles are replaced with zero. With all the processes done for the vector layers, the data are interpolated as the last step of the model. This way, the magnetic dipole anomalies are detected and highlighted automatically.

4.4.1 Graphical Modeller

Graphical Modeller is a valuable feature in QGIS that allows the user to add a certain level of automation in data processing. The interface of the Graphical Modeller includes mainly the inputs and algorithms windows (Figure 5). The Inputs are necessary to import your layers in different forms through the parameter options available in the window. The algorithms in the Graphical Modeller are categorised to make the interface more user-friendly and include the majority of the algorithms and tools available in the Processing Toolbox of QGIS, including the basic QGIS algorithms and algorithms from the geographical information systems GDAL, GRASS and SAGA. Most importantly, they are slightly tweaked to work best in an automated environment. Also, it allows the addition of algorithms that were created by the user in a processing Python script through the Processing Toolbox. As with every processing algorithm in QGIS, the Graphical Modeller allows the use of the complete model to be executed as a single and batch process. Through multiple executions of the model, the Graphical Modeller presented the message that the layers used are not spatially indexed. That is why the use of the algorithm “Create Spatial Index”, which indexes the layer to speed up the process through faster access to the features in a layer, was necessary.

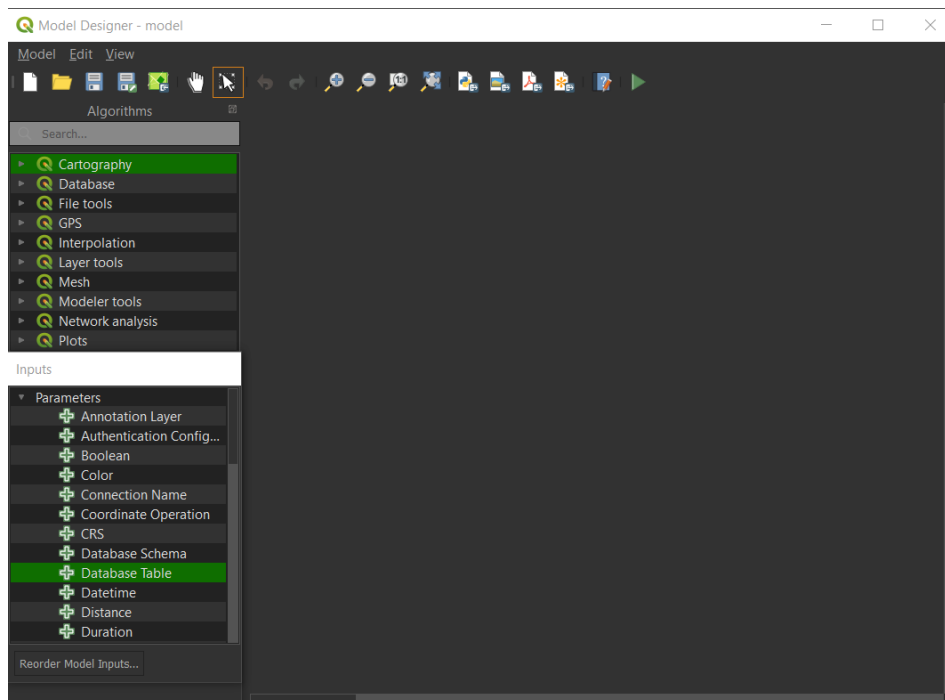


Figure 5 Graphical Modeller interface in QGIS

4.4.2 Importing Files

The data could be prepared in numerous ways, with different coding and mapping software and with even more methods and analyses. Importing the files in QGIS allows the further processing and filtering of data, but it depends heavily on how you import them, as the data type affects the analyses. In such cases, the files should be imported as vector layers to work smoothly with the algorithms used for filtering and manipulating the data. Importing the files as vector layers requires assigning the X, Y and Z values so the software knows which columns are the coordinates and which represent the measurements. Alternatively, the files could be in a vector layer type, such as shapefiles, in order to skip the manual assignment of columns for the coordinates. Furthermore, this also allows the direct importation of the files into the model. Although, we have to be mindful of the processing time extension of the direct importation into the model. If the files are imported as vector layers and added to the model, the model runs slightly faster. Notably, the importation of files as vector layers can happen with multiple files, meaning that the time lost from this process is insignificant. Considering the aforementioned statements and the time needed for the model to run with many files, the decision is up to the user.

4.4.3 Batch Process

The model is able to work as a single process but as a batch process as well, just like all the algorithms. The batch process allows multiple set of inputs to execute the model and algorithms several times. Through such process one could load the necessary information and run the algorithms without the need of loading them multiple times and that is why it is a helpful tool for large amounts of data. However, the time of a batch process is usually longer than multiple single processes, especially for models, and some of the reasons for that are the queue timers, algorithms running in different order in a model, and non-working algorithms because of the batch process. Even though one could encounter issues with batch processing, there are some easy solutions for the solvable ones. For example, when one runs the model explained below as a batch process, the model runs but do not produce the expected output layers. That is because the outputs are expected to have names with the right extension at the end. To make it more optimal for multiple layers is a good practice to give the names of the layers through the option of “Calculate by expression”, which fills the entire column with names based on an expression. In Table 1, the expression replaces the empty name with a combined name of the input layer, the output name for the layer and the right extension. If the input layer is imported from the computer directly, it will contain in its name the path as well, which could create issues to the process as the path contains extensions. That is why the expression shown in the Table 1 calls the input layer and then deletes everything before “.csvs” and after “.shp”, before adding the output name and the expression.

Table 1 Expression table for batch process output files

Layer example	Expression	Output example
Final vector layer with highlighted features	<code>regexp_replace(concat(@input_layer, '_'), '^.*.csvs/(.*?).shp.*\$', '\\1' + '_final_vector' + '.gpkg')</code>	'patched_g40_final_vector.gpkg'
Highlighted magnetic dipole anomalies	<code>regexp_replace(concat(@input_layer, '_'), '^.*.csvs/(.*?).shp.*\$', '\\1' + '_highlighted' + '.sdatt')</code>	'patched_g40_highlighted.sdatt'
First interpolated layer	<code>regexp_replace(concat(@input_layer, '_'), '^.*.csvs/(.*?).shp.*\$', '\\1' + '_first_interpolation' + '.sdatt')</code>	'patched_g40_first_interpolation.sdatt'

4.4.4 Pre-Processing

Pre-processing refers mainly to the preparation of data before the main processing. The pre-processing that happens in this model prepares the data before their visualisation. These steps occur before the visualised representations of the data, meaning that processes that occur on the vector layers mainly, but not exclusively, have to deal with the data as numbers and layers.

4.4.4.1 Geometry Check

The geometry of the features in the vector layers should be checked to ensure that the data will work well in the main processing. As the measurements are taken with a fluxgate gradiometer, a grid with points and a fixed distance from one another is also expected. That means that the geometry should and will be checked as points throughout the vector layers of each file. The QGIS standard algorithm of “Check Validity” (Figure 6) is available for the reason mentioned above, which also gives the option of producing a vector layer with only the valid geometries available (Figure 7). However, it should not affect the result directly.

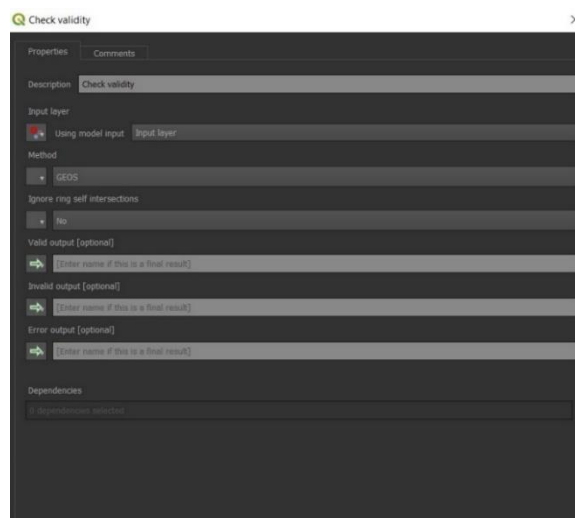


Figure 6 Check validity algorithm configuration

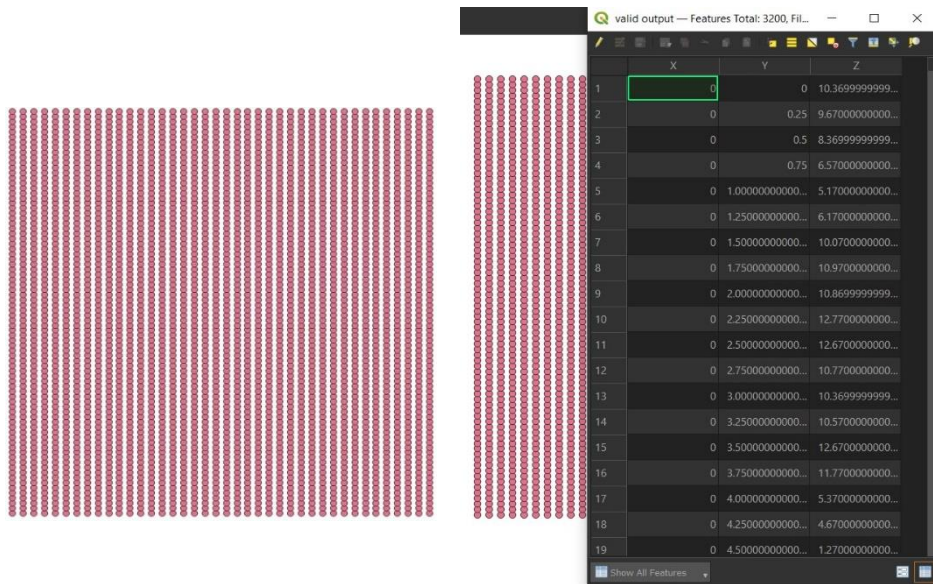


Figure 7 Vector layer with validated geometry (left) and its attribute table (right)

4.4.4.2 Basic Statistics

The maximum and minimum values of the X, Y and Z measurements could be determined through the algorithm “Basic statistics for fields”, as well as the mean, standard deviation, median, range and other basic statistical information. This step is used primarily for the main processing part as it provides general and more specific statistical details of the layers that can be utilised in different algorithms in the later stages. The results of this algorithm are generated into a list of all of these statistics for the fields X, Y and Z as an HTML file. Of course, the file can be saved into the computer, and even though the HTML file is a plain text document, it opens up in a browser. However, one might prefer to open them in different software, such as Notepad, which is possible by replacing the .html extension with a .txt extension.

4.4.4.3 Alignment of the North

Based on what direction a geophysical survey was conducted, the measurements will follow that trend. Sometimes, the direction of survey grids is oriented in a different way than the north because of the personal preference of the surveyor or because of the area’s geomorphology or even if the latitude and longitude were accidentally reversed. That is why realignment of the north through the X and Y coordinates could be necessary. To do that, the columns of X and Y could be reversed through the standard QGIS algorithm of “Swap X and Y coordinates” to align the layers towards the north.

4.4.5 Main Processing

Main Processing is the primary step of the methodology, where the prepared data are introduced to algorithms of QGIS to generate a visualised representation of the data and provide the right setting for interpretations. As the main processing focuses on the visualised data, the processes are image oriented, meaning they are about interpolating data and working with raster images to create better data representations. It is worth mentioning that the processes below, especially the ones that occur after the visualisation of the data, could come about in

different processing stages and different forms, such as statistical analyses of the datasets. In this case, processing following the data representations is performed on the raster images.

4.4.5.1 First Interpolation

As the data are prepared from the pre-processing steps, they can be visualised through interpolation. The QGIS offers multiple options for interpolating data from vector layers, but it does not have the great variety that someone would expect. That means that the choices available through QGIS tools are only a few but not limited, as the QGIS software allows the use of third-party plugins and user-introduced scripts. The software includes through its local package the interpolation options of Triangulated Irregular Network (TIN), Inverse Distance Weighted (IDW), Heatmap (Kernel Density Estimation) and Line density. Through the GRASS package, raster and vector interpolation are possible with spline, resampling and IDW options, and finally, with the SAGA package, raster-spline interpolations are likely. Having said that, the interpolation algorithms are not limited to the ones mentioned earlier, and not every algorithm is compatible with data such as the ones introduced above. Through experimentation, trial and error, the interpolations of TIN and IDW of the QGIS package and the Thin Plate Spline (TIN) one of SAGA are compatible and effective for visualising and processing these data.

Before choosing a singular interpolation algorithm, other processes affected the decision. Starting with the experimentation of different algorithms, I started first to explore the options of third-party plugins and “playing” with existing interpolating scripts as well as modifying them or trying to write one from scratch through the Python Processing Script Editor tool, because my previous experience with interpolation algorithms showed that Kriging was a reliable option. As this task seemed to be really time-consuming and challenging because of my limited experience and knowledge of coding QGIS scripts, I turned to the available QGIS algorithms. The IDW was the closest to Kriging and produced a good-quality image. However, the algorithm was running too slow compared to the TIN ones and had unexpected noise that, even with processing and editing of the image, did not reduce significantly in order to provide a usable raster image. The TIN algorithm of QGIS offered a faster and better-quality image than the SAGA Thin Plate Spline interpolation algorithm, which is why it was used for the rest of this thesis. Unfortunately, the QGIS TIN algorithm had several issues when using it in the Graphical Modeller, which made it unusable in that environment and beat the purpose of automation and multiple file processing. I tried to tweak the source code of the QGIS TIN algorithm as it was available online through the creator, which I managed to do to a certain degree until I stumbled upon an issue with the source code itself. The next best option was to use the Thin Plate Spline (TIN) algorithm of SAGA (Figure 8), which worked smoothly in the Graphical Modeller environment and provided a decent image.

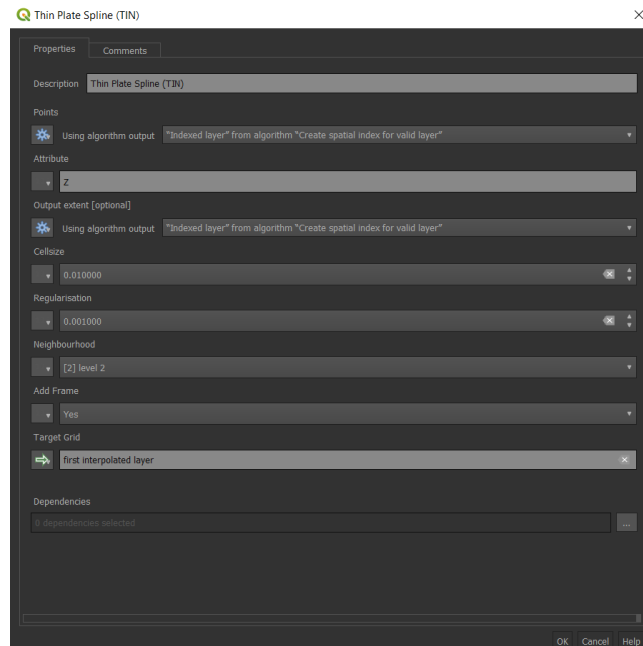


Figure 8 Thin Plate Spline (TIN) algorithm configuration

4.4.5.2 Anomaly Isolation

As mentioned above, after the first wave of algorithms and processes, the model ultimately aims to the detection and highlighting of the magnetic dipole anomalies through a few algorithms and an automated process. For that reason, the anomalies are isolated in the beginning of the process.

The anomaly isolation's goal is to take the Z measurements of each point in the vector layer that is considered high, based on the minimum and maximum values of the field. High values can have a positive and a negative sign. This leads to the extraction of two different datasets from each point vector layer, with high positive values in one and high negative values in the other. The dipole anomalies are determined by high positive and high negative values that appear next to each other.

For this process a single algorithm is used for each layer. The algorithm creates a layer with the matching features. Through the use of the "Extract by expression" algorithm, one could extract the high positive and high negative values. As there is not one way to determine the range of the high values, a percentage of 30% was used. The expressions used are " $Z \geq \text{minimum}(Z) \text{ AND } Z \leq \text{minimum}(Z) + (0.3 * \text{abs}(\text{minimum}(Z)))$ " and " $Z \leq \text{maximum}(Z) \text{ AND } Z \geq \text{maximum}(Z) - (0.3 * \text{abs}(\text{maximum}(Z)))$ ". The expressions take the high negative and high positive values respectively, that are determined by the 30% threshold. The "abs" part of the expressions is to ignore the sign of the values as negative and positive ones exist in the datasets (Figure 10). Therefore, the algorithm extracts the points based on these expressions and creates two new layers with only these values (Figure 9).

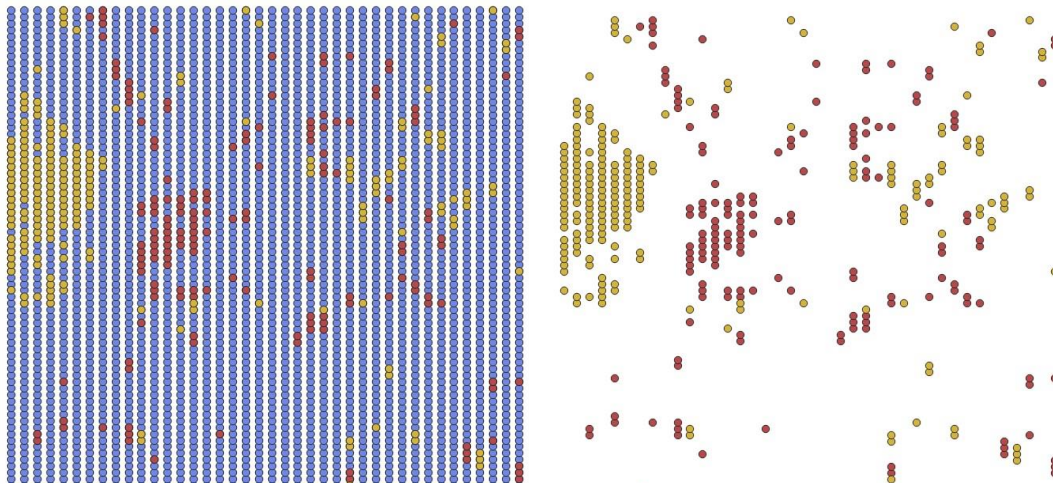


Figure 9 Extracted high positive and high negative values (right) and on top of the valid layer (left)

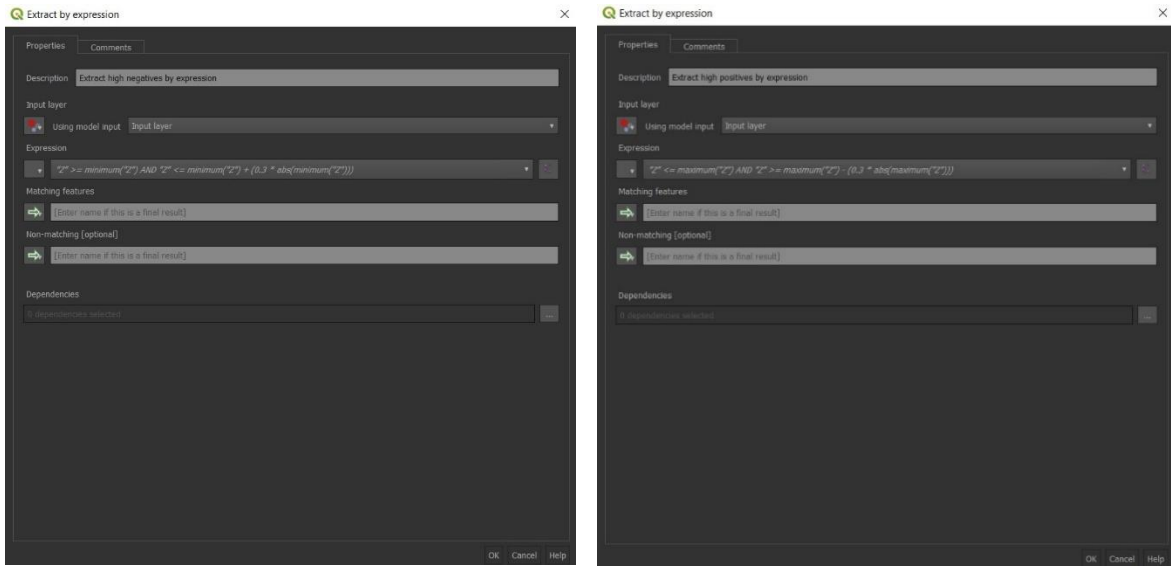


Figure 10 Extract by expression algorithm configuration

4.4.5.3 Buffering

To find the spatial relations between the two categories of values as mentioned above, buffers are incorporated. The buffers are relatively small and are applied into the two extracted dataset layers separately to create the “personal space” of each point. Then, the points that are left and have high positive values are extracted based on the buffers of the high negative points, meaning that the high positive points that are in the personal space of negative points are isolated. Once the buffers are defined, the algorithm of “Extract by location” is used to gather these points in different layers. Although as one is looking for the dipoles of the initial layer, there is a need to merge them before continuing.

To create buffers, the algorithm of “Buffer” is incorporated in the model. This algorithm computes buffer areas for all the features of a vector layer using the distance defined in the model (Figure 11). In this case the buffers were created to be round and relatively small with a single segmentation, in order to capture only the immediately related features (Figure 12).

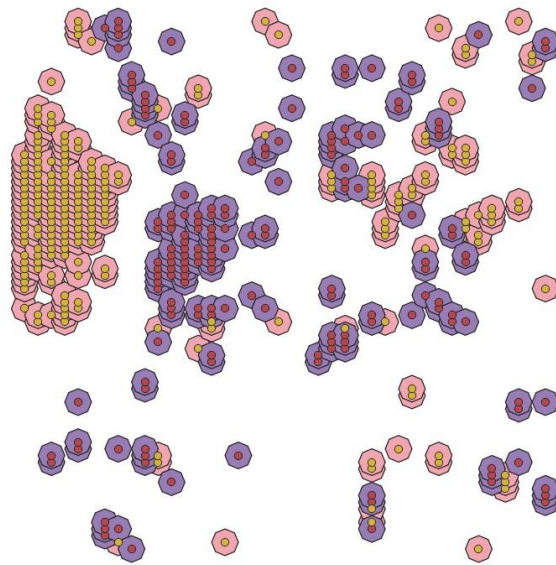


Figure 11 Extracted features and their buffers

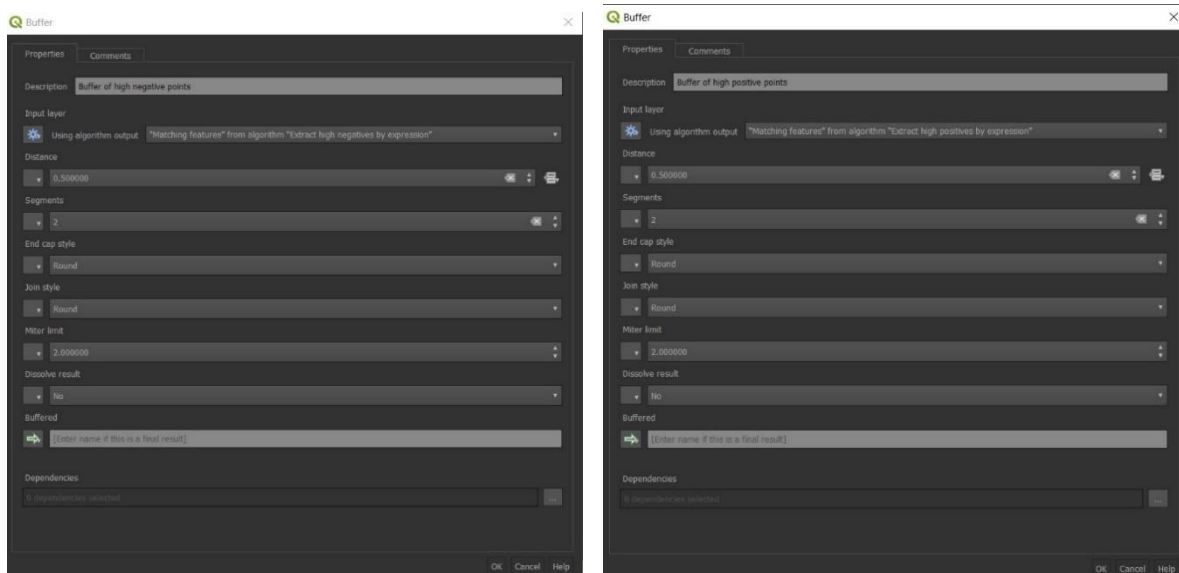


Figure 12 Buffer algorithm configuration

After the buffering the “Extract by location” is executed in the model for both existing layers. At the first execution, the algorithm extracts the high positive features from the layer created by the “Extract by expression” algorithm (Figure 14) in comparison with the Buffered layer with high negative points based on the spatial relation of intersection and for the second one the point layer has the high negative features, and the buffered layer has the high positives (Figure 13). The Intersect spatial relation, finds whether the geometries intersect, in this case if the points intersect with the buffer circles. To complete this section of the model, the two layers created by the “Extract by location” algorithm are merged with the help of the algorithm “Merge vector layers” (Figure 15), which combines multiple vector layers that has identical

geometry in one single layer (Figure 16). That means that their attribute tables are also merged, including their Z values.

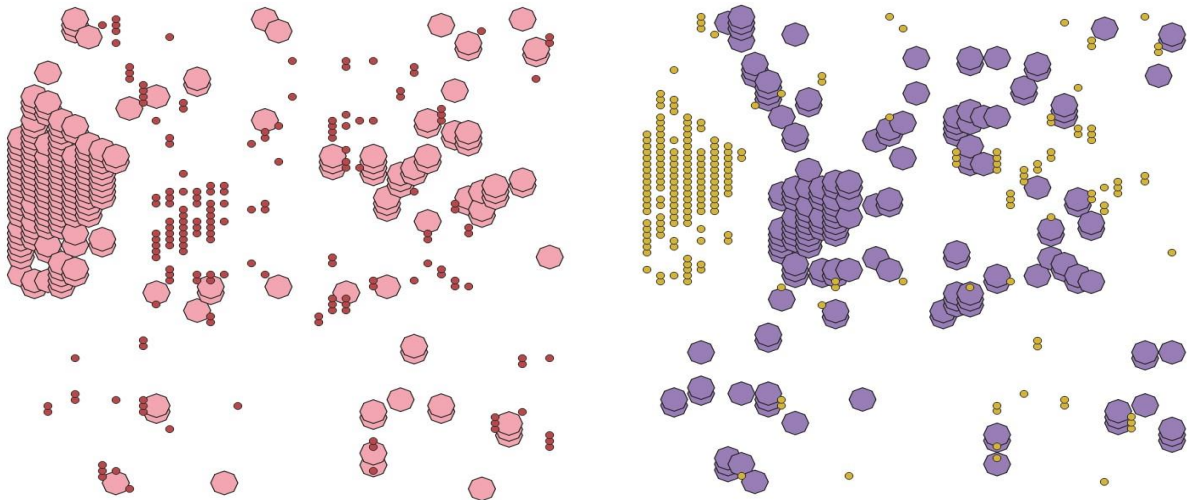


Figure 13 Vector layers showing how the features are chosen from the buffers.

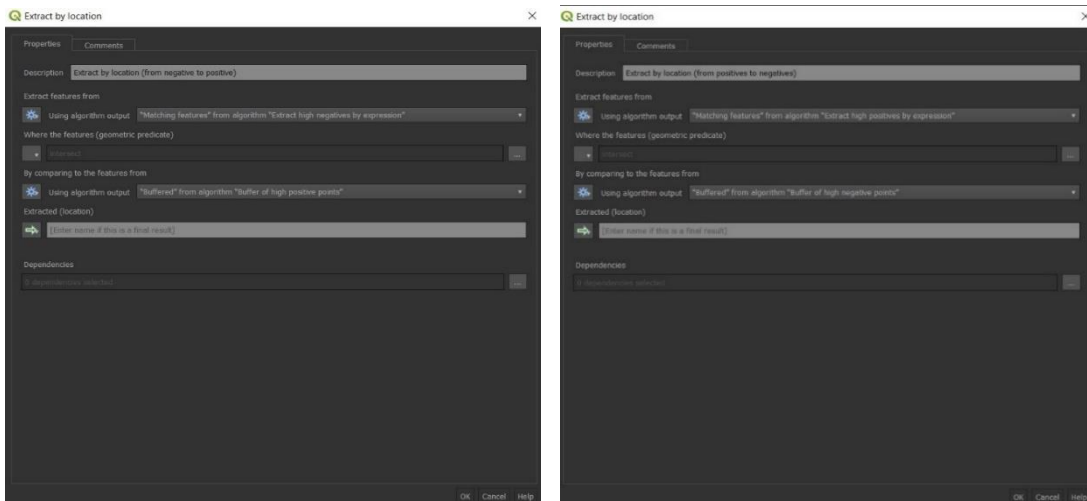


Figure 14 Extract by location algorithm configuration

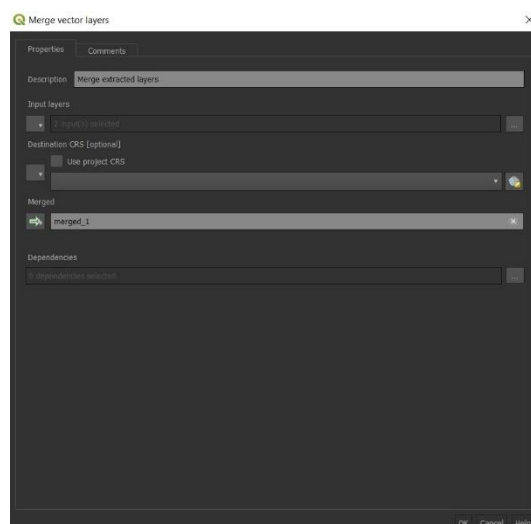


Figure 15 Merge vector layers algorithm configuration

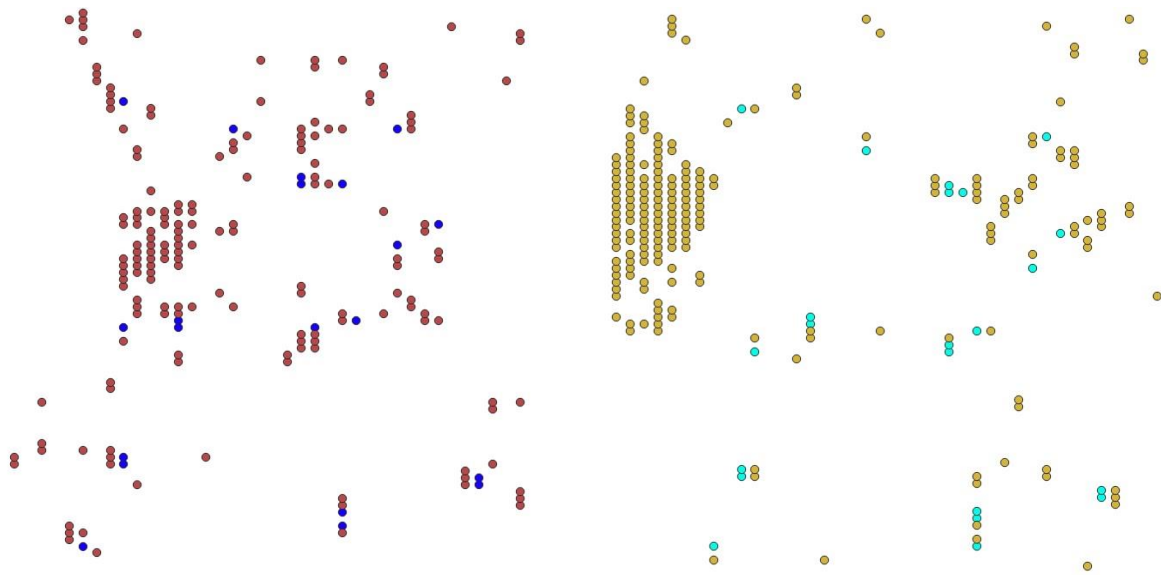


Figure 16 The extracted features by location (blue and light blue) merged with the extracted features (red and yellow)

4.4.5.4 Value Manipulation

At this point, the magnetic dipole anomalies are detected and exist in a single layer. However, there is a need to highlight them after including them in the initial dataset that was imported in the model. The highlighting is possible with several ways, but in this model the dipoles are highlighted by zeroing all the values surrounding them, meaning that the Z values of the points in the vector layer around the dipoles are replaced with zero.

To put the first merged layer that was produced in the step above in context, the algorithm of “Merge vector layers” is used again to combine the previously merged layer with the initial input layer of the model, producing a second merged layer. Furthermore, the “Select by location” algorithm is used to create a selection based on the spatial relations of the two merged layers (Figure 19). In this model the selection was from the second merged layer compared with the first merged layer based on the spatial relationship of Disjoint, which shows only the geometries that do not overlap or touch with each other. The model then, continues with the manipulation of the selected values with the algorithm of “Field Calculator”. This algorithm works with the attribute tables of vector tables and through expressions, creates a new layer with the calculated results (Figure 17). As the zeroing of values around the dipole anomalies is the goal, the field calculator should change all the selected values, from the previous algorithm, to zero. To do that, the algorithm uses as input layer the second merged layer and implements the expression “CASE WHEN is_selected() THEN 0 ELSE “Z” END” on the field of “Z”. The

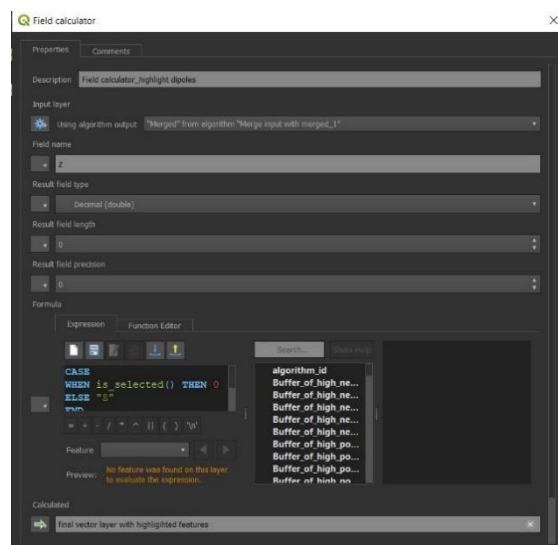


Figure 17 Field Calculator configuration

expression changes the selected values from the second merged layer to zero, “0”, and leaves undisturbed the rest values. The output of the algorithm produces a complete vector layer with all of the calculated values applied (Figure 18).

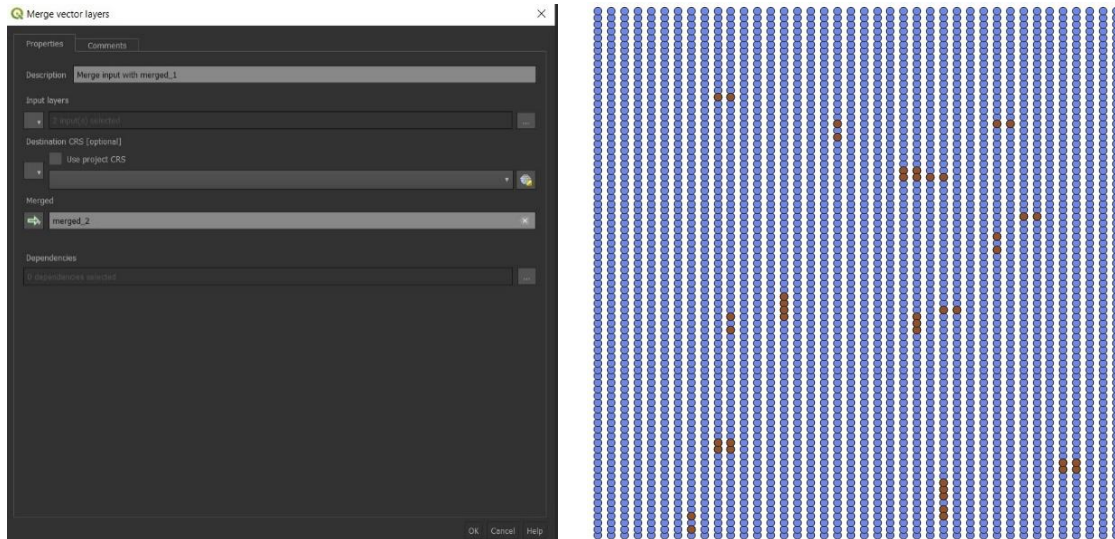


Figure 18 Merge vector layers configuration (left) and the result (right)

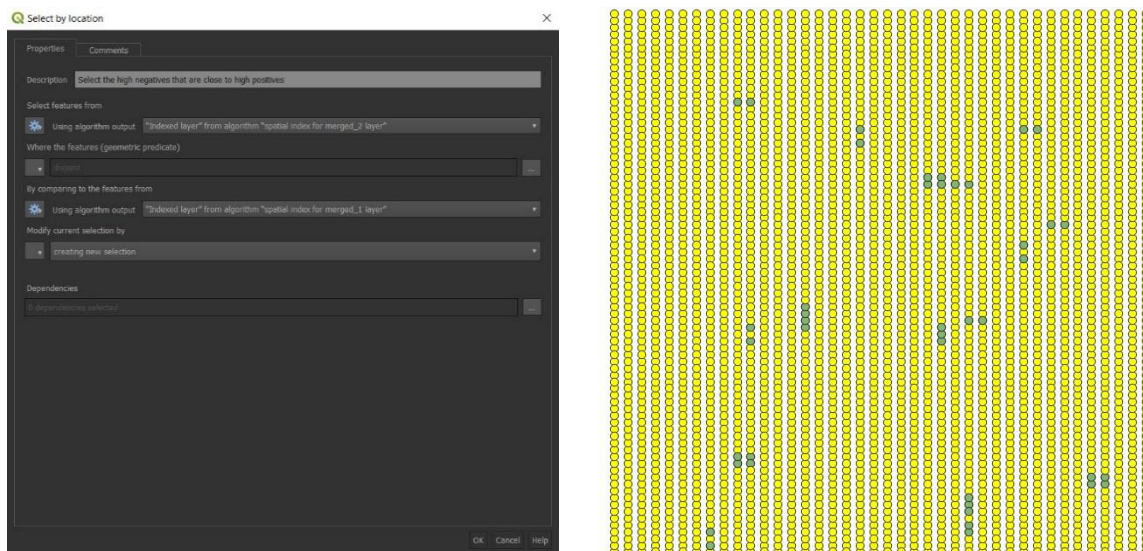


Figure 19 Select by location algorithm configuration (left) and the results (right)

4.4.5.5 Magnetic Dipoles Interpolation

With all the processes done for the vector layers, the data are interpolated as the last step of the model. This way, the magnetic dipole anomalies are detected and highlighted automatically. This interpolation visualises the calculated layer with the magnetic dipole anomalies and the surrounding zero values highlight the former.

The Thin Plate Spline (TIN) algorithm (Figure 20) was used to interpolate the calculated layer based on the attribute of “Z”. The output extent of the algorithm is determined as the input layer option to have a model that works with different files. To have a decent raster image the “Cellsize” as well as the “Regularisation” were set to “0.001000” and the process was executed in the second level of neighbourhood (level 2). The algorithm produced a raster image with the highlighted magnetic dipole anomalies only.

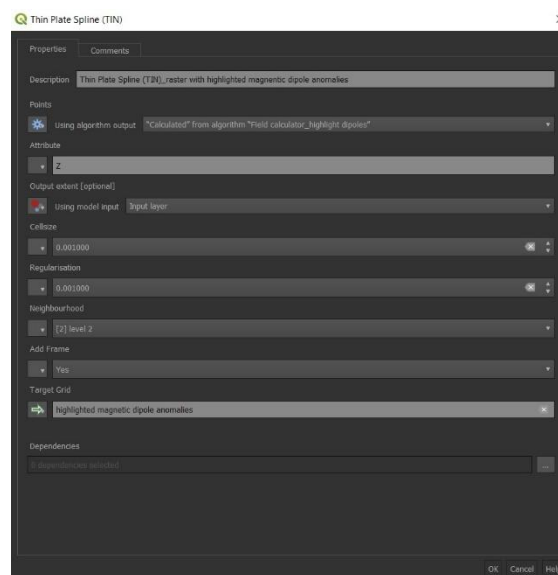


Figure 20 Thin Plate Spline (TIN) interpolation configuration

4.6 Secondary Processes

The model might not be ideal for the pre-processing and filtering of the data. One of the main reasons for that, is the type of evaluation data used. The data to evaluate the model went through a certain level of processing already. That means that initial processes for the data as well as image filtering and other procedures were possible but could not be evaluated through the available data as well as expected. It is noteworthy that most of the processes mentioned below were successfully executed in different environments and ways as well as their configuration and customisation but were working improperly in the model. Further, the QGIS available algorithms did not provide a way to use them in the model, creating the need of finding solutions outside of the QGIS environment. That does not mean that their use is impossible in the model and QGIS, but rather that the right configurations were not found through the experimentation and exploration stage of the thesis.

4.6.1 Dummy Values

The dummy values are mostly values that create anomalies in the data and produce abnormal results. These values could have been created by noise in the data, either natural or artificial, during obtaining the data. To counter the issue of problematic values, measures could be taken

before further processing, meaning that statistical analyses can be used directly on the data, but also after on the raster images, when the data are visualised. Facing the problem of Dummy Values is a pre-processing step which could affect the results. This type of value could also include outliers, meaning that their elimination could include manual removal of outliers and muting of dummy values for the data (Kalokerinos et al., 2004, p. 2). Furthermore, it could follow a different direction with the use of median filtering and generalised extreme studentised deviation for the visualised data as the following process of de-spiking suggests.

4.6.2 De-spiking

In the visual representations of the data, there are anomalies that are called spikes, which are extreme values that appear as high negative or high positive values or both. They could affect the interpretations as they appear similarly as archaeological features. They could occur because of instrumental error or failure of sensors during surveying (Ciminale & Loddo, 2001, p. 240; Fedi et al., 2017, p. 208). Their removal or smoothing is necessary to improve the quality of the data and their raster image visualisations. For the de-spiking process there are several methods, such as median filtering, Generalised Extreme Studentised Deviation (GESD) or even manual removal of the outliers. A way to use these methods is to work according to the noise level, where the noisy and less noisy data could be smoothed based on the relation of the de-spiking factor and the standard deviation (Kalokerinos et al., 2004, pp. 2–3). In the GESD method, the spikes are treated as outliers, where they are detected and then removed or replaced.

As they were not included in the model, different techniques were incorporated in QGIS and through a Python script. The GESD was first written as a script in Python, where test statistics were used before the determination of outliers. Then the outliers were removed and a .csv file was exported. After that step, the .csv file was imported into QGIS, in order to be visualised.

The smoothing of data through the relation of the de-spiking factor and the standard deviation was incorporated inside QGIS through the use of the algorithm “Field Calculator”, as an expression. According to Kalokerinos et al, the de-spiking factor needs to be lower than the standard deviation if the data are less noisy and higher with more noisy data (Kalokerinos et al., 2004, pp. 2–3). The expression that was used “*CASE WHEN "Z" >= mean("Z")-(2*stdev("Z")) AND "Z" <= mean("Z")+(2*stdev("Z")) THEN "Z" ELSE NULL END*”, was applied on less noisy data and the de-spiking factor was put to “2”, as it is close to the common range of a de-spiking factor for less noisy data. The expression defined the de-spiking range based on the mean and the relation of the de-spiking factor and the standard deviation of the field “Z”, by creating a lower and upper de-spiking limit. Then after the “Field Calculator” applied the expression on the vector layer, the layer was interpolated to visualise the results.

4.6.3 Striping and Zigzag Effects

The raster image of a geomagnetic map could sometimes present noise that appear in certain shapes. The striping or heading error presents as vertical lines in the magnetic data and is typical noise that occurs because of the bi-directional gathering of data, meaning that the operator was travelling in opposite directions (Ciminale & Loddo, 2001, p. 241; Fedi et al., 2017, p. 209; Schmidt, 2007, p. 6). As for the Zigzag effect, which is also known as displacement error, it occurs because of a systematic error in a bi-directional acquisition of

data, which is caused from an offset between the operator and the sensors (Ciminale & Loddo, 2001, p. 242; Fedi et al., 2017, p. 209).

To solve this problem in the field, one has to acquire the data in a single direction something that would slowdown the survey significantly. To fix that through statistical analyses, one could equalise the same mean value of the obtained data for each line of data (Ciminale & Loddo, 2001, pp. 241–242; Fedi et al., 2017, pp. 209, 211; Schmidt, 2007, p. 6). To face the error of displacement, one could work with directional filtering for the removal of elongated anomalies or with a Fourier directional cosine filtering. The statistical analysis of directional filtering is referring to the Discrete Wavelet Transform (DWT), which in simple words, breaks down the data in different levels in order to analyse it through the wavelets and represent the features at different scales. The DWT filtering extracts the lower values for smoothing and the high values for sharpening of the visualised data before downsizing the sampling to reduce the data and retain their essential information. Finally, it reconstructs the original signal to show a noise reduced product (Ciminale & Loddo, 2001, p. 242; Fedi et al., 2017, pp. 209, 211). According to Fedi et al., the statistical analyses used for the zigzag effect, could be effective for de-stripping as well (Fedi et al., 2017, p. 211). Those are techniques that were not implemented in this model but are useful in solving problematic features, such as stripes and zigzags, from the magnetic maps.

4.6.4 Resampling of the Data

Resampling is a process used to reposition the pixel values in a different location to correct a raster image. As the images produced through this model are already checked for their geometries and alignment, this procedure contributes to the improvement of the quality of the visualised data. This procedure can take place in different steps of the processing as long as one has a raster image to work with (Argote et al., 2009, p. 1667; Kalokerinos et al., 2004, pp. 2–3). The resampling can take place inside the QGIS environment through the raster layer's properties. The available options of resampling in QGIS are nearest neighbour, bilinear interpolation and cubic convolution. The nearest neighbour resampling process uses the pixel's values from the original image in order to correct the image through repositioning of pixels. Even though the nearest neighbour choice could result to missing pixels and duplications, it does not alter the original data. The bilinear interpolation option for resampling uses the weighted average of four pixels to create the new location of the pixel. The third option of cubic convolution follows a similar approach as the second resampling option where it calculates the weighted average of sixteen pixels, creating a new pixel value (CCRS, 1999, pp. 152–153).

4.6.5 Mosaic of Grids

When one is working with several datasets that exist in different files, there is a need to connect and merge them. This process could take place in different parts of the process. It is possible to connect them manually before processing and work on them as a uniform dataset. Of course, this requires the datasets to have coordinates that are not artificial or at least continuous, meaning that the coordinates continue through different files and do not repeat. In the datasets that are used to evaluate the present model, the coordinates are artificial and have the same range throughout all the files for each area and they start from zero (0,0 – 0,0.25 etc.). With

such datasets, if the files are merged, the data will be mixed and not useable. The option that is left with these data is to give them new coordinates that extent through the files. The QGIS offers choices to change values in the data and extend them through different layers with the help of the algorithm “Field Calculator”, something that it was not achieved in this thesis.

If the datasets are merged and create a unified layer before their importation in QGIS, one could work on a single file to process and interpolate the data, creating by default a complete picture of the data. On the other hand, if the data are in a different form and get new coordinates in QGIS, the interpolated images should be merged into one. To do so, the SAGA and GRASS providers in QGIS offer raster processing algorithms. Through GRASS the algorithm “i.image.mosaic” is able to create mosaics from several images and extend their colourmap, where one just chooses which raster images will be included. A similar process follows with the use of the SAGA algorithm “Mosaicking”. This algorithm allows further customisation of the mosaic product as it provides options on resampling interpolations, how to treat overlapping areas, choosing blending distance and boundaries and the output choices of output extent and cell size.

5. Results and Analysis

The model managed to detect and highlight magnetic dipole anomalies from raw data to a raster image. As a result of a successful run of the model, the pre-processing and main processing steps are completed, providing clear visual representations of the data for the better detection of archaeological features and even more specific dipole features.

The first evaluation of the model occurred with the use of a single shapefile in order to see the compatibility of the file type with the model and by extension the Graphical Modeller and QGIS. Furthermore, the model was evaluated if it could run and execute all the algorithms included in it, as well as if it could provide clear images for further interpretation and use of the data. The first file that was used for the evaluation was named “patched_g40.shp”. After the successful completion of a run, multiple files went through the same process to make sure that it was not based on luck or randomness that the model was working properly. The test of the model took place on two more devices to ensure its interoperability.

Based on that first evaluation of the model with the file “patched_g40.shp”, two raster images were produced, one with the first visualisation of the interpolated data (Figure 22) and the second one with the visual representation of the highlighted magnetic anomalies (Figure 21).

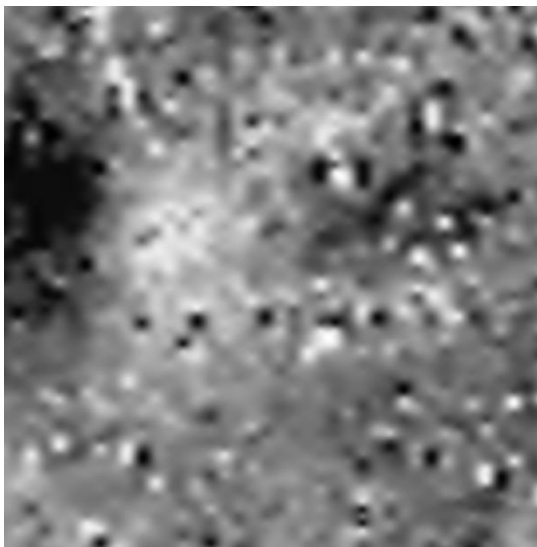


Figure 22 Interpolated data through Thin Plate Spline (TIN)



Figure 21 Highlighted magnetic dipole anomalies

The first interpolation provides a complete magnetic image of the subsurface of the specific area. It includes all of the anomalies that are distinct from the rest of the magnetic map because they contrast the normal magnetic values in the locality. The magnetic anomalies as values are high values, either positive or negative, and during their visualisation get darker or lighter colours from the values closer to zero, respectively. The second raster image produced through the visual representation of the data, provides only the magnetic dipole anomalies. As the other features were given zero values, the magnetic dipole anomalies are highlighted.



Figure 24 Highlighted magnetic dipole anomalies (40%)

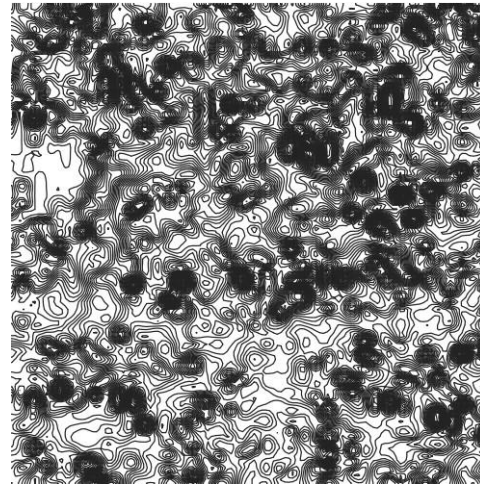


Figure 23 Contour map of the interpolated data

In the model, the produced highlighted magnetic dipole anomalies image was based on a 30% of high values around the features which limits the shown anomalies of dipole nature. That is why a second image was produced in order to examine the difference of an image with features up to 40% of the high negative and high positive values. Figure 24 shows more dipole anomalies which could mean more features of dipole nature. To check these results, the first interpolated image that was produced through the model, was also checked as contours as well. This process allows the dipole anomalies to be shown with their directions more clearly but at the same time not as highlighted as Figure 21, where all the other measurements are hidden.

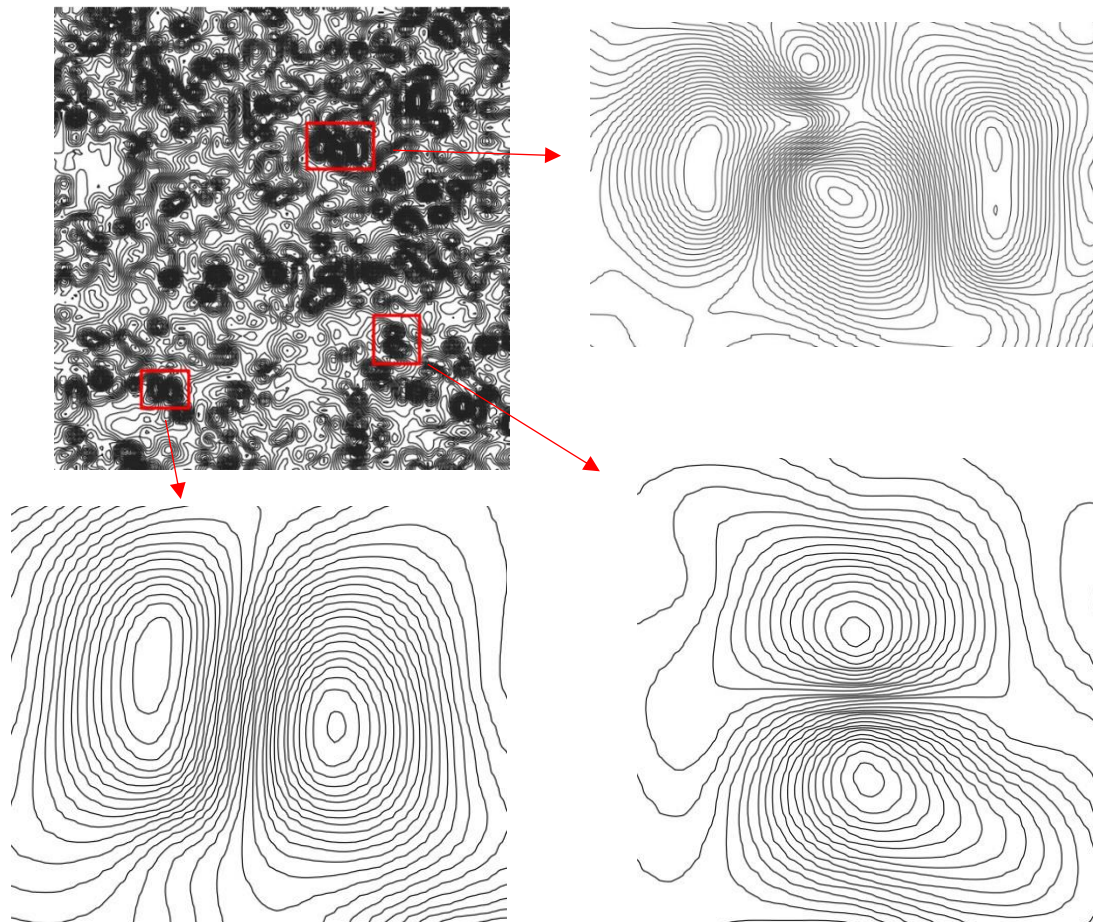


Figure 25 Magnetic dipole anomalies (magnified)

In Figure 25, there are multiple examples of dipole anomalies that are presented just like Bevan describes them in Figure 1. Thus, these dipole anomalies seem to follow the norm in presentation. The anomalies that are zoomed in, present a circular part of the anomaly and a semicircular one. As the high positive value are expected to be presented through circular shape contouring and the high negative ones as semi-circular, one could observe in the southwestern corner, the zoomed in anomaly following this pattern with a circular one on the right and a semi-circular contouring on the left. Through these anomalies the direction of them could be also determined (Bevan, 2017, pp. 1–3).

The images below, are the interpolated images from the complete data from all the sites. They were made with the processed data provided from the beginning, meaning that they have differences in resolution and size compared to the rest of the visual representations of data. The reason for that is that the data were preprepared in a single file for each site's full data and being mindful of the gaps as their complete coordinates were given to each dataset. In all of the figures below, features are visible of archaeological, modern and/or geological origin. Furthermore, the visual representations of the sites' data have clear dipolar anomalies, on top of all of the other anomalies that are shown differently in each picture.

In Figure 26, the data present anomalies of extreme values in the middle to east part of the image and a sparse spread of anomalies in the most east part. In the middle to west side of the magnetic map, there are promising linear anomalies that allow further interpretations.

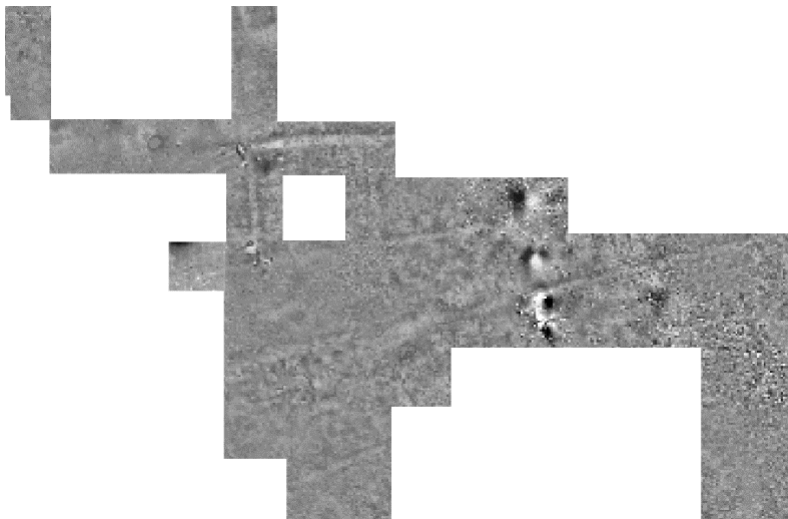


Figure 26 Palaepaphos magnetic map

Figure 27, has a really disturbed total image, making interpretations more difficult. There are extreme values, as well as anomalies of dipole nature in the whole magnetic map but mostly in the southern part. Especially in the southwestern edge of the picture, the anomalies seem to follow geometrical shapes. In the opposite side of the map, in the most northern part, the values exceed the measurements, resulting in a blank area on the image.

The next image (Figure 28), manages to showcase best a magnetic map but not as much about the magnetic dipole anomalies. Throughout the map there are visible anomalies of high magnetism but not as extreme as the previous case. The higher values are presented with dipole anomalies, and certain geometries. Other linear features are presented in the middle of the image as well.

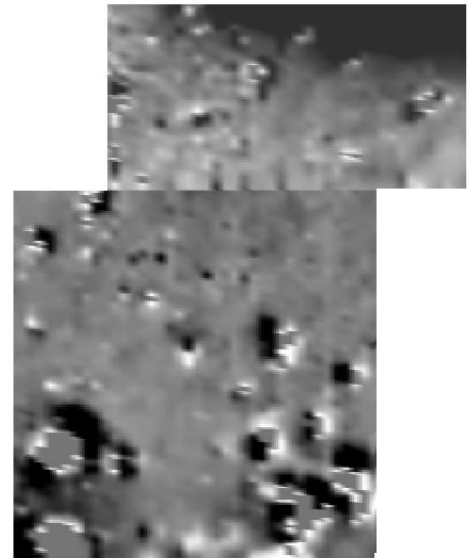


Figure 27 Paralimni-Panagiotissa magnetic map

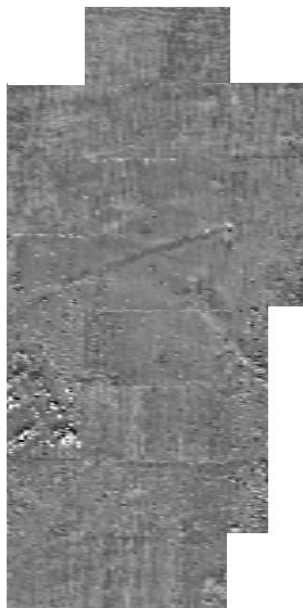


Figure 28 Petounta magnetic map

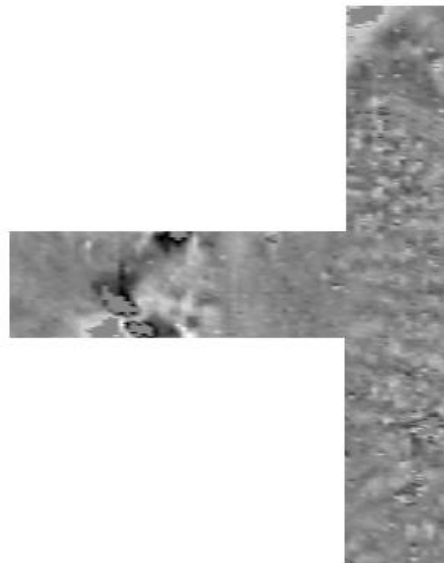


Figure 29 Alaminos-Kambos magnetic map

The Figure 29, is mostly removed from the processing of the data as they were a lot of extreme values around the anomalies in the western part of the magnetic map. These extreme values are forming in a certain spot which allows further interpretations. The entire eastern side presents several anomalies that do not follow any specific trend.

Figure 30, is the visualised representation of the last dataset that seem almost empty compared to the previously shown images. The southwestern corner showcases clustered extreme values. The rest of the anomalies are fairly subtle but are still present in various forms including of dipole nature.

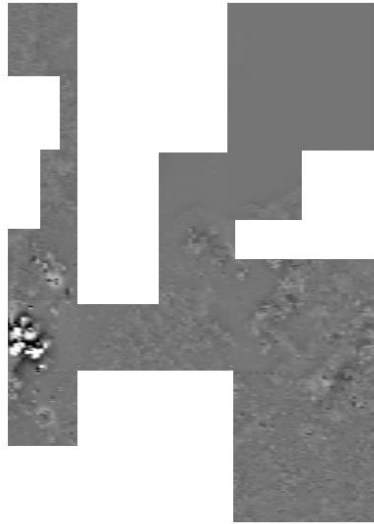


Figure 30 Menogeia-Limnes magnetic map

6. Discussion

The discussion chapter gives some interpretations of the complete results in the context of this thesis. Also, there is a good portion of the chapter, where the challenges and limitations found during this thesis, are explained in detail.

6.1 Results in Context

In the upper part of Figure 25, the anomaly is shown as a dipole but also is connected with more anomalies. Taking into consideration how they are presenting in a magnetic map, one could distinguish in the zoomed in part of this dipole anomaly, that the central part is the high positive one that shows a more circular shape and the side one on its right has a more semi-circular shape as it is the high negative anomaly. This also indicates that the direction of this anomaly follows a west to east direction. Concerning the dipole anomaly that appears in the southwestern corner of the contour map, one could observe that the shape is more squeezed together but still showcasing a normal dipole anomaly presentation, with a semi-circular anomaly on the left and a circular one on the right. Considering these shapes, one could determine their east to west direction.

As the results above are considerably objective, this subchapter allows a certain level of interpretations to be presented in the evaluation side of things. As seen in in Figure 26 above, of the Palaepaphos visualised data, the high values are visible around possible archaeological features and clustered in probably disturbed areas. As there is a lot of disturbance in the eastern part of the magnetic map, there is a lot of uncertainty. There is a good possibility that these anomalies are of geological origin or there are modern disturbances. In the middle to northwestern part of the map, there are some anomalies that could be interpreted of archaeological interest as they create geometrical shapes, with straight lines and right angles.

The survey in at Protaras-Panagiotissa took place in between a built suburban area. that is why a lot of modern disturbances are expected. Observing the visual representation, the high positive and negative values are creating a lot of dipole anomalies. Also, at the northern part of the image, there are extreme high values that blank out the image, creating a gap in the data. There are no obvious anomalies of archaeological interest, but the dipolar anomalies could be indicators of activity, modern or older.

Petounta's data are presented the cleanest ones. That allows more space for archaeological features without being a rule. There are a lot of visible lines in the middle of the raster image but because of their geometry, one could probably suggest that are occurred because of modern activities such as ploughing. In the southwestern part of the image, some high values appear and because of their arrangement they could be produced by archaeological features. They are arranged in a linear way, and it also seems that two of the lines are going through one opposite vertex.

In the Alaminos_Kambos visualised data, there is a lot of activity going on. The eastern part of the picture is full of noise and anomalies that are unclear which pushes the interpretation of the anomalies to geological origin. On the edge of the western layers of the magnetic map, there are really high values in an almost circular shape. This could be interpreted as of archaeological interest with burnt material that produces these almost extreme high negative

and positive values. This is the only clear part of the image that has magnetic dipole anomalies mixed with other anomalies.

Concerning the last image, that belongs to the Menogeia-Limnes survey, the high positive and negative values are appearing mostly on the western and eastern parts of it. The western part has a lot of variety of anomalies and noise. The brighter coloured anomalies in the southwestern part of the picture, presents anomalies of dipole nature. Of course, in this case it seems that are extreme values, something that also makes the rest of the anomalies to look faded. Most often, such anomalies are of geological origin without though excluding completely the chances of them being archaeological features. Right under this anomaly, there is a circular anomaly that could potentially be of archaeological interest. On the middle eastern part of the image, there are some linear anomalies that could lead to archaeology but there are not as clear as the previous cases of linear features.

6.2 Challenges and limitations

In the model development process, there were a several challenges and limitations that made the process difficult. Such problems range from QGIS customisation and configuration issues, compatibility of algorithms with QGIS, Graphical Modeller and batch processing to computer performance and time limitations. Through the exploratory and experimental part of the research, multiple algorithms were used that are not included in the model or the processes in general and there included in this chapter.

There were also issues with the algorithm providers themselves and even though GDAL, GRASS and SAGA algorithms are integrated into QGIS, they are partially incompatible with the Graphical Modeller, especially for the SAGA ones, which appear with a warning for possible compatibility issues.

As already mentioned, compatibility problems appear in greater volume in the Graphical Modeller, as the Toolbox algorithms are altered to work better in an automation environment supposedly. Even though algorithms with input layers and the subsequent editing of values exist in Graphical Modeller, such as Buffer, it does not work as well with all of them with the example of interpolation algorithms like TIN interpolation. The alleged issue appears in multiple community threads throughout the internet without a suggested solution. The interpolation algorithm is immutable after the initial addition to the modeller. It seems that it “locks up” the initial information, as they affect each other inside the algorithm, making it unable to connect with any input parameter. Thus, creating a package for more than just the specific data the model was developed for seems impossible with the algorithms provided by the QGIS. An examination of its algorithm’s source code shows that an Interpolation data value in the script contains more than just one feature, including the input data and interpolation attribute options. As in the script, the value is defined only at the input data level; the rest of the information and code exists in the input of the interpolation data value in the processing script. That makes this specific part of the code inaccessible, and thus one cannot tailor this algorithm for graphical modeller use.

As the batch process goes through more data and processes, in some cases at the same time, it sometimes requires a more elaborate and neater model. Quite a number of QGIS algorithms

are single-thread processes, which means that they might stress a modern computer slightly to none. However, the batch process pushes the limits of a computer's CPU more because it is a multi-thread process by default. That means that it attempts to use all of the threads available by the CPU without paralysing the rest processes of the computer. Even with an ASUS gaming laptop with 6 cores and 12 threads with a clock speed of 2.2 GHz and overclocking up to 4.1 GHz, the process freezes for a couple of minutes because it maxes out to a 100% the CPU's utilisation and up to 180% the maximum frequency while it fluctuates the clocking from normal to medium high levels. This makes the process of a single run of the model longer, while taking up to 10 minutes. Considering that, a multi-file process of about 10 files will take approximately up to 2 hours.

Furthermore, the batch process does not work well with all of the algorithms. For example, the algorithm "Create Spatial Index", even though was mentioned as necessary from the software itself, it does run in the batch execution of the model. While using the batch processing, the aforementioned algorithm becomes unavailable, producing the message that without spatial index the quality of the model as well as the speed will be degraded. Through a quick search in community forums, it was immediately obvious that is a bug that exists for a couple of years, and it remains unresolved.

Another issue was found in the data, where the files were already processed in a certain degree, making difficult the evaluation of filtering processes that were left in the secondary processes part of the methodology. Also, because of the way that the files were created and processed through the GPP algorithm (Kalokerinos et al., 2004) and Surfer of Golden Software, they had specific structure that needed further changes in the data. As the data went under some pre-processing and filtering steps already, the creation of a total grid with organised layers like a 9x9 was really difficult or even impossible. The reason for that is the missing layers to complete the grid. Through filtering and processing a lot of layers were excluded from the datasets, leaving gaps in between the layers. Finally, as the majority of the data are unpublished up to this date, archaeological interpretations of them are not supposed to be made by my part. Thus, these data are only used for evaluating the model created during this thesis and interpretations were made only at an evaluation level.

6.3 Exploratory Algorithms

During the creation of the model, a lot of algorithms were tested but did not make the cut. Some of them were even working decently but were not as efficient or produced flawed results. The main reason that these algorithms were not included is because I was unable to configure them in the right way so they can be part of the model or because there was no way to do so.

The initial idea for the detection and highlighting of the magnetic dipole anomalies was executed successfully through the "Aggregate" algorithm. This algorithm takes the data from the vector layer and aggregates the features based on a grouping expression that is user defined. That grouping was attempted with the mean of the field "Z" in order to create a categorised version of its values. The process had satisfying results for detecting and highlighting dipole anomalies; however, it created a lot of false positives, which could be considered problematic. That is why at the end process it was not included and was unsuited for the model.

The TIN interpolation algorithm is a great tool as it works really fast compared to other interpolation algorithms and it provides images of good resolution. Especially compared to the algorithm incorporated in the model, the TIN interpolation has a better overall performance. The major issue with this algorithm is that it is unable to be used in a model as it is unmodifiable after it is added to the workflow. Its configuration is only possible through the source code editing which is also problematic because “hidden” parts in the script.

An alternative algorithm that was used to organise the layers into a grid was the algorithm “Translate”. This algorithm can be used with an expression as well to manage multiple layers together or even with a batch process. “Translate” algorithm is able to move geometries with layers, as it offsets them to a new location. As mentioned above, the total grid had gaps in between the layers, which means that the right arrangement was unknown, making this algorithm obsolete.

7. Conclusion

The magnetic dipole anomalies have been really useful to determine the presence of anomalies in the subsurface, especially for archaeological purposes. Anomalies in the magnetic maps are not exclusively of dipole nature, thus the magnetic anomalies are not following a single trend.

In order to detect and highlight the magnetic dipolar anomalies, the use of open-source software is possible for the purpose of processing, visualising, and filtering data. The methods followed for that purpose are not exclusive to the QGIS software. Even though it does not provide the best results compared to proprietary software such as Surfer of GoldenSoftware, as of the user interface, possibilities, algorithms of interpolation and such, the QGIS provide easy and free access and automation. Further, the graphical modeller feature is also not exclusive to QGIS, but again, the open-source and open-access aspect of the software provides fair reasoning for its use. Throughout the project, various methods were used for interpolation purposes and filtering. The one that stood out for its fast and convenient processing of the data was the TIN. Also, compared to IDW, the other option of interpolation algorithm in QGIS, TIN showed a clearer image, even though it could be considered fuzzier, and the IDW interpolation suffered heavy stripping even after the main processing.

The dipole anomalies were able to be seen throughout the visualised data as well. In many cases, their direction was able to be determined. Even though the dipole anomalies were found manually, the primary indication that they provided was the presence of archaeological features. The detection and highlighting of dipole anomalies could contribute to a better understanding and interpretation of the magnetic maps and magnetic anomalies. The magnetic anomalies of dipole nature are good indicators of features of possible archaeology and the direction of them seem to help with the determination of what material are made of or what is expected to be found in the subsurface.

A magnetic survey is evidently affected by several reasons including the modern activities in and around the areas of archaeological interest. The geology of Cyprus is complex, making magnetic prospection challenging in some areas due to anomalies. The island's formation through magmatic processes created various geological types and formations, leading to a

diverse magnetic signature. Examples include the area of Evreti in Palaepaphos and the red soil villages of Kokkinoxoria. Although the subsurface is rich and diverse, factors such as magnetic anomalies still affect geomagnetic prospection. The Troodos Mountains in Cyprus have a diverse range of soil types, including calcareous soils with high calcium carbonate content, which preserve artefacts well. Other soil types, such as acidic Rendzinas and Ferralic soils, can affect magnetic measurements during archaeological surveys. The site of Palaepaphos has the greatest variety of soils, including calcaric cambisols and vertisols. The Xeros Valley and Larnaka district also have a range of soil types, such as rhodic bertisols and lithosols.

Modern activities like construction, mining, and infrastructure can impact magnetic prospection in Cyprus by generating magnetic anomalies that interfere with accurate data interpretation. High levels of human activity in urban areas of Cyprus can negatively impact the preservation of cultural heritage, as archaeological sites and landscapes are often located nearby. Also, development projects must undergo an archaeological impact assessment, and many sites are protected by law. Magnetic prospection can be challenging due to interference from artificial structures, but advanced processing techniques and careful planning can minimise their impact on results. Steps should be taken to minimise their impact and filtering can still provide reliable results.

Concluding, the model is proving that there are several ways to process and present magnetic features and data and how it contributes to the detection of magnetic dipole anomalies through highlighting them. It is not the only way but through the use of not proprietary software and common tools, the process of feature detection could be automated or at least assisted by automation processes. The model provides a good point of ways to automate the process and the entire thesis showcases multiple types of pre-processing and main processing for the better visualisations of data. Of course, there is room for improvement, as the model do not include or incorporate any algorithms to pre-process and improve the datasets directly. That means that the processes that could not be included in the model but are described in this thesis, they could be incorporated through the better configuration of the algorithms or creating custom ones or even with tweaking the source codes of the existing algorithms. Furthermore, the case of the TIN algorithm and the modification of its source code, shows that is possible to work with source codes as they are widely available online. However, such cases could be obstructed by “hidden” parts of the code, something that could be improved in a software that is open source.

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Appendix

```
1 # -*- coding: utf-8 -*-
2 """
3 Created on Sat Aug 12 15:55:14 2023
4
5 @author: andre
6 """
7
8 import os
9 import pandas as pd
10
11 # List of directory names
12 directories = ["_alaminos_csvs", "_menogia_csvs", "_palaepaphos_csvs", "_paralimni_csvs", "_petounta_csvs"]
13
14 # Loop through directories
15 for dir_name in directories:
16     folder_path = f"D:/Data/{dir_name}"
17     files = os.listdir(folder_path)
18
19     # Loop through files in the directory
20     for idx, file_name in enumerate(files, start=1):
21         file_path = os.path.join(folder_path, file_name)
22
23         if os.path.isfile(file_path) and file_name.lower().endswith(".dat"): # Check if it's a .dat file
24             df = pd.read_csv(file_path, delimiter=";", names=["X", "Y", "Z"])
25             df = df.replace('MUTE', 0.00)
26             output_file = os.path.splitext(file_path)[0] + ".csv" # Change extension to .csv
27             df.to_csv(output_file, index=False)
28
29
```

Figure 31 Python script for file conversion (.dat to .csv)

```
# -*- coding: utf-8 -*-
"""
Created on Thu Mar 30 16:32:06 2023

@author: andre
environment called geodude - only geopandas
"""
import os
import geopandas as gpd
import pandas as pd
from shapely.geometry import Point

# List of directory paths containing CSV files
csv_directories = [
    "D:/Data/_alaminos_csvs",
    "D:/Data/_palaepaphos_csvs",
    "D:/Data/_menogia_csvs",
    "D:/Data/_paralimni_csvs",
    "D:/Data/_petounta_csvs"
]

# Loop through each directory
for csv_directory in csv_directories:
    for csv_file in os.listdir(csv_directory):
        if csv_file.lower().endswith(".csv"):
            csv_file_path = os.path.join(csv_directory, csv_file)
            csv_data = pd.read_csv(csv_file_path)

            # Convert 'X', 'Y', and 'Z' columns to numeric (replace non-numeric values with NaN)
            csv_data['X'] = pd.to_numeric(csv_data['X'], errors='coerce')
            csv_data['Y'] = pd.to_numeric(csv_data['Y'], errors='coerce')
            csv_data['Z'] = pd.to_numeric(csv_data['Z'], errors='coerce')

            # Fill NaN values with zeros
            csv_data = csv_data.fillna(0.00)

            # Create the geometry column
            geometry = [Point(xy) for xy in zip(csv_data['X'], csv_data['Y'], csv_data['Z'])]
            geo_df = gpd.GeoDataFrame(csv_data, geometry=geometry)

            # Output shapefile path
            output_shapefile_path = os.path.splitext(csv_file_path)[0] + ".shp"

            # Save GeoDataFrame as a shapefile
            geo_df.to_file(output_shapefile_path, driver='ESRI Shapefile')
```

Figure 32 Python script for file conversion (.csv to .shp)