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GEORADAR INVESTIGATIONS IN THE CENTRAL NAVE OF HAGIA SOFIA, ISTANBUL (TURKEY)

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GEORADAR INVESTIGATIONS IN THE CENTRAL NAVE OF HAGIA SOFIA, ISTANBUL (TURKEY)

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Abstract

Within an interdisciplinary project to study Istanbul's Hagia Sofia, a georadar survey was carried out in the central nave to assess if the deformations of the structure previously observed could be related to a differential behavior of the subsoil caused by architectural remains underneath.

This study faces an unusual challenge since it was necessary to study the space beneath the scaffolding placed for the restoration works.

The survey of the central nave was successful and allowed the detection of remains of walls that probably formed the basement of a previous 18 by 22 m structure.

In addition, another interesting feature was discovered 2 m below the marble mosaic in the southeastern part of the nave. Although it is not possible to define its function, it seems that there could be a close relationship between this 2 by 3 m buried structure and the marble mosaic in the floor surface.

Although some structures were identified under the floor of Hagia Sofia, there are no major changes in the topography of the central nave floor.

Acknowledgments

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Introduction

Scientific investigations carried out at Hagia Sofia (Istanbul) have demonstrated the plastic deformation of the entire building (Avdelidis and Moropoulou 2004; Avdelidis et al. 2004; Erdik, Croci 2010; Mainstone 2009; Moropoulou et al. 1998, 2000; Van Nice 1965). To evaluate if underground structures could be related to the observed deformation, we planned to use georadar to detect the remnants of earlier structures built in the place. Those remains could be still present underneath the existing building, and the georadar might provide evidence to understand their characteristics, their depth and the kind of material present in the fillings beneath the modern marble pavement. This study was conducted as part of a broader project for the diagnostic of Hagia Sofia monument, carried out by an interdisciplinary team from the University of Calabria and the National University of Mexico, in which different techniques, such as 3D scan, thermography, mortar analysis and georadar, were utilized (Barba et al. in press; Cura *et al.* 2014).

As a building Hagia Sofia has a very long and complex history. It seems that the first church was built in an area near the current location (near the Topkapi Palace). Although it's still discussed, it probably owes its birth to Constantius II (Mainstone 2009: 152-153). This church was completely destroyed by fire in 404. The second church was built in 415 AD by Theodosius II. Again, a fire during the Nika revolt against the Emperor Justinian I, caused its destruction in 532 AD.

Immediately afterwards, the Emperor Justinian I began the construction of a new building, which was inaugurated in AD 537. It was built by the architect Isidore of Miletus and the physicist and mathematician Anthemius of Tralles. The earthquakes of 553 and 557 caused cracks that lead to the collapse of the dome in May 558 AD. Isidore the Younger was in charge of the reconstruction, using lighter materials and changing the profile of the dome (Mainstone 2009).

Our hypothesis was that remains of the second church destroyed in 532 AD, are still beneath the present floor and might be at least partly responsible for the deformation observed of the Hagia Sofia building. For this reason we conducted the georadar study of the ground floor of the building, which involved the survey of different areas of the central nave.

In order to better understand if the presence of remains shown by georadar reflections under the nave's floor could be related to the deformation of the building, we also compared the georadar data with the topographic map of the floor surface, obtained by taking into account the data of the 3D laser scanning of the building made in the framework of our project.

Georadar surveys inside historical buildings have shown to be useful for the conservation of the structures and the understanding of the features preserved underground (e.g. Barba et al. in press; Barilaroet al. 2007; Leckebusch 2000; Leucci 2006; Vega Pérez Gracia et al. 2000).

Prior georadar investigations mainly dealing with conservation problems and focusing on the study of walls and mosaics were carried out at Hagia Sofia (Cura 2010; Moropoulou et al. 2012a, 2012b, 2013). Hagia Sofia's ground floor was studied by Yilmaz and Eser (2005) and Yilmaz (2013). However, we decided to go deeper in a detailed study of the floor of the building's central nave in order to better comprehend the presence of underlying structures and the relationship with the stability of Hagia Sofia building. In particular, georadar survey was applied to study Hagia Sofia's main nave floor (Fig. 1), although facing serious problems arising from the presence of scaffolding in its northern half (Fig 2 and Fig. 3). This survey constitutes a novelty in georadar investigations, as usually no survey are carried out under the scaffolding, because of the risk of interference produced by the metallic structures. However, we succeeded in obtaining information on the remains preserved below that floor.

Methodology

The georadar study was carried out employing a SIR 3000 from GSSI with 400 MHz antenna with survey wheel. This antenna has been previously used successfully for the study of buried remains in urban contexts (Barba, Ortiz 2001; Barba 2003), mainly in streets. In this case it was applied to survey the main nave marble floor, penetrating over 4 meters.

The southern part of the central area inside Hagia Sofia was open and available for georadar study. In this part, the first georadar survey was carried out in parallel lines every 1 m (area E, Fig. 1, results in Fig. 4). After the analysis of the results we decided to intensify the resolution by performing another georadar survey with lines every 0.5 m from south to north for a more detailed study (area E, Fig. 1). Another two small grids were surveyed to better investigate an anomaly detected in the southeastern corner of the main grid. One small grid was surveyed inside the Islamic muezzin's gallery (area F of Fig. 1, Fig. 5) and to the East, in the southeast foil of the chevet of Hagia Sofia (area G of Fig. 1).

We undertook the work in the main nave on Monday because in these days the building is closed to the public and there are no tourists inside, which allowed for a better development of the work. As mentioned, the nave's northern half was covered by scaffolding set for the restoration works (Fig. 2 and Fig.3). Due to the long term of these works we decided to carry out the survey anyway. For this we draw lines S-N in the middle of the poles pulling the antenna and the georadar control unit all the way through from one end to the other of the scaffolding (Fig. 2).

This meant a difficult work, but in this way it was possible to obtain lines every 1 m in the area covered by the scaffolding (area B and C, Fig. 1). Due to the presence of the lift and other infrastructures in some points under the scaffolding, the survey had to be divided in several areas that are not continuous.

Besides the practical challenge of carrying out the survey under the scaffolding, we also took into account that there was a risk of interference by the metallic structures, but georadar results did not show reflections produced by the scaffolding. Due to the fact that we were not able to obtain lines every 0.5 m under the scaffolding, but only every 1 m, for the northern part of the nave we have a lower resolution image than for the other half of the nave in which we could perform the georadar survey every 0.5 m (Fig.1).

The topographic map of the floor Hagia Sofia's ground level was obtained processing the data of the 3D scan of the building carried out with a Leica Geosystems' Scan Station2.

Results and discussion

The marble surface of the floor of the central nave of Hagia Sophia seems to be quite homogeneous and the georadar results have confirmed it. Nevertheless, there are some areas with different characteristics, which were evident since in the first survey undertaken with lines every 1m (Fig. 4).

In the middle of the 20th century, archaeological excavations carried out near the main entrance of the nave, discovered the presence of thick walls in some parts of the western area of the nave (Van Nice 1965, Fig. 6). Some reflections in the georadar survey (Fig. 4) can be related to the alteration produced by the archaeological excavations carried out in that time. These areas reflect properties contrast of the material used to refill and cover the excavated areas. In particular, the modern reinforced concrete that substituted the marble slabs acts in a different way to electromagnetic waves. These areas are evident in the georadar 1.5 m depth slice as the quasi-rectangular red spots that can be appreciated in the left side of Fig. 4.

In Fig. 4, it is also possible to observe other wide reflections, which are probably related to the presence of the architectural remains of previous buildings underneath the floor of Hagia Sofia. In fact, the high contrast in properties between the aligned stones which are marked in red, and the earthen matrix in green, produces clear reflections in radargram.

In order to go deeper in the understanding of the remains of previous buildings that could be present under the ground floor of Hagia Sofia, after the promising results of the first survey, we decided to improve the survey in two ways. On the one hand, we increased the resolution of the survey with lines every 0.5 m (Fig. 1 area E), and, on the other hand, we decided to go deeper with a wider window and obtain information under the scaffolding (Fig.1 areas B and C). Due to the higher resolution of the georadar survey in the southern area, here alignments are better defined; while in the northern area, where the density is lower, the image is blurred. In Fig. 7 the main reflections alignment are marked in dotted yellow line in order to trace the walls and the perimeter of this underlying building.

In the 2 m high-resolution depth slice (Fig. 1) it is possible to observe the walls, which are showed in the photograph of the old excavations (Fig. 6).

Other evidence of walls can be recognized to the right of the Fig. 7 with the red N-S straight line; in the red lines E-W in the lower and upper part of the figure. All these segments may represent the limits of an ancient building buried under Hagia Sophia. The western limit of this structure is not as clear as the previous ones.

The wall closing the structure on its eastern side is clearly visible at a depth of 1.2 and 1.6 m, while the wall in the southern side reaches almost 2 m in depth.

The above mentioned walls, are also visible in the radargrams. In Fig. 8, the radargram F1 shows wide metallic reflections at meter 4, and the thick wall that was excavated in the 50s below. In line F10 it is possible to observe the alteration caused by the refill of the excavated area from meter 3 to 7. In line F13, the multiple reflections between 8 and 12 m are probably produced by metal present in the refill of the excavated area. The radargrams also show a clear change in properties of the upper layers, suggesting the presence of a prior floor level that should be located 30-40 cm below the current marble floor (Fig. 8). In the first meter of the three lines (F1, F10 and F13) it is also possible to observe reflections suggesting the presence of another wall in the southern limit of the studied area.

Taking into consideration these data it is possible to propose a hypothetical reconstruction of the plan of an ancient building underlying the present floor. In Fig. 8 the main reflections alignment are marked in yellow in order to trace the walls and the perimeter of this underlying building. The georadar survey indicates that the remains of this building should be located between 1.2 and 2 m deep.

The reflections in radargrams (Fig. 9) can be interpreted as thick walls. Line F119 shows the wall that corresponds to the northern limit of the substructure, it seems to be more destroyed and closer to the surface, while line F58 shows the wall of the southern part of the substructure that seems to be better preserved.

The above mentioned evidence suggests that there is a building underneath the present Hagia Sofia, which was rather small: 22 m long (in E-W axis) and 18 m wide (N-S axis). Most remains of that building should be located less than 2 m under the current floor.

In the depth slice 1.5 m deep, (Fig 8) it is possible to observe reflections in the southeastern corner, where the Islamic muezzin's gallery and the southeastern foil of Hagia Sofia's chevet are located (areas F and G, Fig. 1). These reflections show an interesting alignment that has a NW-SE direction.

In Fig.10 it is possible to observe the previously mentioned walls, and slightly below, the presence of a structure remains. In fact, in the individual radargram of line F68, between meter 4 to 7 there are reflections suggesting walls close to 2 m deep. In F72 there are some disordered reflections in the first part (0-3 m). At meter 4 of the radargram, around 2 m deep, there is a slight reflection that is more clearly displayed in lines F75 and F77, where it shows up as a hyperbolic reflection. What is outstanding is that this structure is 1.5-2 m below the marble mosaic that is located in the SE part of the central nave pavement (Fig. 5).

Taking into consideration last six parallel radargrams they all show important reflections which could be related to a possible feature that is at least 3 m long and 2 m wide (Fig 10).

Moreover, in the radargram of line F72, there is a smooth zone between meters 4 and 5, under that zone (2 m deep), there is a reflection that suggests the edge of an element, which is more clearly visible in the radargram of line F75, 1.5 meter apart. In line F77, the smooth zone goes from 3 to 5 m, suggesting a conductive and homogeneous filling material on top of the feature. In the radargram of line F77, which is located 1 m away from line F75, it is possible to observe that there are two walls bordering the aforementioned hyperbolic reflection. In the same position, closer to the surface it is possible to observe in radargram F77, the presence of a horizontal reflexion at 30 cm depth, which could be related to the placing of mosaic marble pieces. The georadar data now shown suggest that probably before placing the present floor, an excavation of an area of 4 x 4 m, reaching at least 2.5 m depth was made here, and that walls were built at least in two sides of this area in order to built what seems to be a possible chamber. Then the hole was filled with very homogeneous material, and covered it with slabs placed 30 cm below the present mosaic floor like in other places of the nave. These data are remarkable as they point to the identification of features just under the mosaic visible in the present floor surface, which we could imagine that have been placed there to keep memory of the location of this feature.

Inside the Islamic muezzin's gallery, radargrams of lines F84 and F87 (Fig.11) show a horizontal reflection close to 2 m deep. Underneath that layer, in the first two meters of the radargrams, there is a slight reflection that suggests some kind of anthropic alteration.

It cannot be excluded that this channel could be part of the “wells, passage, tunnels and water systems” previously detected by Özkan-Aygün (2006) in other parts of the building. However, thus far we do not have enough data to suggest the function of the feature. Lines F78 and 80 are in the southeastern foil of Hagia Sofia’s chevet, show reflections between meter 1 and 2 and 1.5 m deep that follow a trend towards the southeast corner, visible in Fig 7.

Overall, we can say that the interpretation of the georadar results of the survey of Hagia Sofia’s central nave show that there are many architectural remains buried at different levels under the present floor.

Once the remains have been identified, in order to better understand if the remains located under the floor of Hagia Sofia’s central nave can be related to the deformation of the building, we compared the georadar data with the topographic map of the ground level floor surface, obtained processing the data of the 3D laser scan of the whole building (Fig. 12). Before commenting on the map, it is important to remember that the rectangular area in the apse of the central nave must not be taken into account, because it corresponds to the presence of a wooden structure placed in the area, which arises the level of the floor recorded by the 3D scan.

It is relevant to state that the topographic map of Hagia Sofia’s floor reveals that there are neither deformation, nor topographic changes in the central nave floor surface after more than 15 centuries of different uses of the building (Fig. 12). This reveals that the burial of the previous structures was made with great care using adequate materials and compacting them properly in such a way that, although there are remains of previous structures under the floor of Hagia Sofia, the central nave floor is stable, with almost no deformations.

On the contrary, in the lateral naves it is possible to observe slight changes in the level of the floor, indicating some sort of deformation of the ground surface. This is evident especially in the northeastern part of the building, where there is an augmentation of 40 cm in the height of the floor. This suggests that future studies should take into account the georadar survey of the lateral naves in order to understand if a relationship could be found between the presence of underlying structures, a different topography of the area and the deformation of the Hagia Sofia building.

Conclusions

The interpretation of the results of the georadar survey in the Hagia Sofia’s central nave makes it apparent that there are many architectural remains buried at different levels, suggesting the presence of several features which are preserved under the current floor of the building. In particular, it was possible to posit a hypothetical reconstruction of the plan of an ancient building, which looks rather small (22 x 18 m), and should be located at less than 2 m depth.

Below the marble mosaic, close to 2 meters deep, an interesting structure was identified with a hyperbolic reflection limited by two walls. It seems to run towards the southeastern corner of the central nave. The identification of the structure under the marble mosaic suggests an unexpected relationship between them and point out that the mosaic was placed there to mark the presence of an important feature below, although the presence of a linear track could also suggest that it could be related with the system of tunnels and channels detected by Özkan-Aygün (2006) in other parts of the building.

Although our hypothesis was that some of the structural deformations that can be observed in the Hagia Sofia building could be the consequence of differential sinking of previous architectural remains underground, the results obtained in this work showed that these deformations are not related to the presence of the buried structures in the central part of the building. In fact, the topographic map of the ground floor obtained after the laser scanning of the building reveals that there are no deformations or topographic changes in the central nave floor surface. Although, georadar revealed that there is at least one level of important architectural remains under the current floor of Hagia Sofia, the central part of the floor is stable, with almost no deformations, contrasting with lateral galleries.

Therefore, the hypothesis for the deformations of Hagia Sophia structure as being a consequence of the presence of previous architectural remains below the central part of the building has been rejected and these deformations must be caused by other factors.

Finally our study also shows that the burial of the previous structures was made with great care using adequate materials and compacting them properly, which allowed to avoid deformations of the floor although the building was used with different aims during more than fifteen centuries.

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Figure Captions

Figure 1 Areas investigated with the georadar. A: northwest area. B and C: north area. D: central area. E: south area. F: Islamic muezzin’s gallery. G: southeast area. The results presented here are on the depth slice 2m deep

Figure 2 The georadar equipment SIR3000 with 400 MHz antenna with survey wheel making parallel lines every 1 m, under the scaffolding

Figure 3 To the left, it is possible to observe the northern part of the nave, covered by the scaffolding for the restoration works. To the right observe the marble floor of Hagia Sofia

Figure 4 Depth slice at 1.5 m from the southern part (E) of the floor of Hagia Sofia. The first approach survey was carried out with lines every 1 m. The rectangles mark the reflections produced by the previously excavated areas

Figure 5 Acquisition of georadar lines on the central nave floor close to the marble mosaic. To the back the Islamic muezzin’s gallery can be seen

Figure 6 Picture from the 50’s showing some of the excavated areas. Marked with *d* letter are thick parallel walls under the marble surface (modified after Van Nice 1965)

Figure 7. Individual radargrams, F1, F10 and F13, showing multiple reflections in the western part of the central nave

Figure 8 Central nave plan of the ground floor of Hagia Sofia showing on the 1.5 m depth slice the most feasible interpretation of substructure walls marked in dotted lines. In full lines are georadar lines F58 and F119 crossing the walls

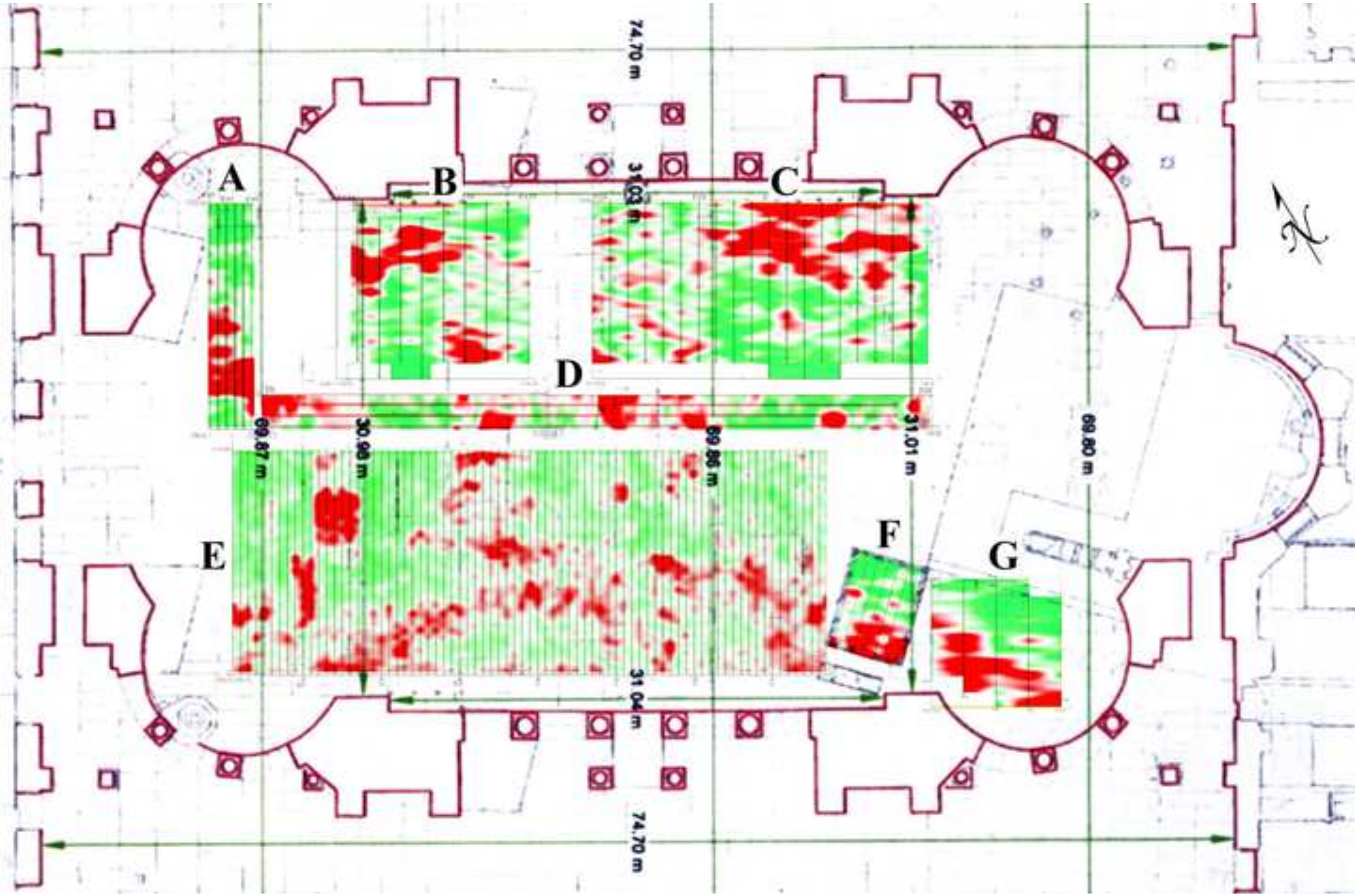
Figure 9 Radargrams of lines F58 and F119 showing the reflections caused by the presence of wall remains

Figure 10 Radargrams of lines F68, F72, F75 and F77, showing important hyperbolic reflection bellow 1.5 m deep

Figure 11 Radar lines F84 and F87 inside the Islamic muezzin’s gallery. Lines F78 and 80 are in the southeastern foil of the chevet of Hagia Sofia

Figure 12 Topographic map of the floor of the ground level of Hagia Sofia obtained by Leica Geosystems' Scan Station 2. In the central nave a flat area can be observed

Figure
Click here to download Figure: Figure 1.jpg



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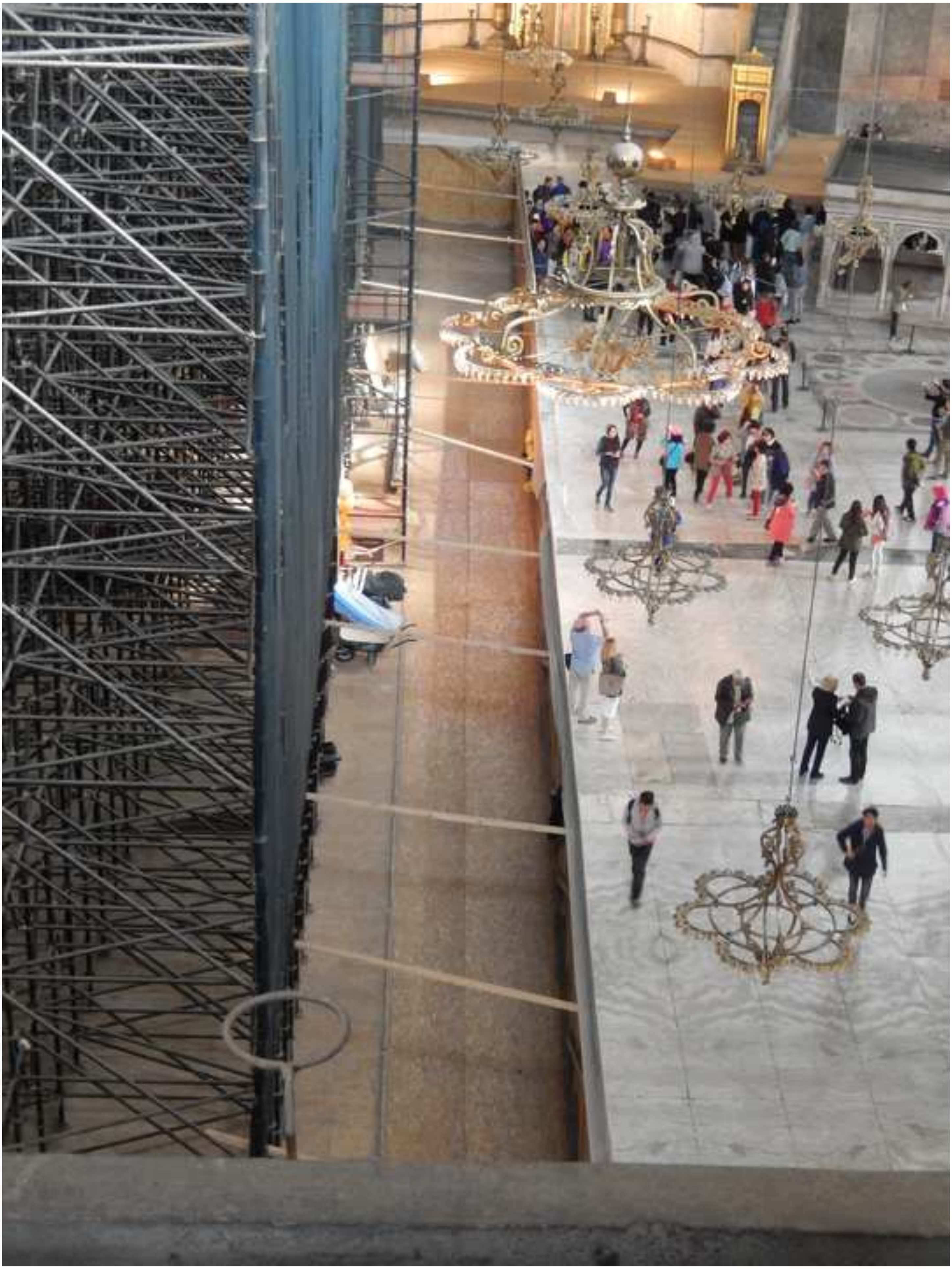

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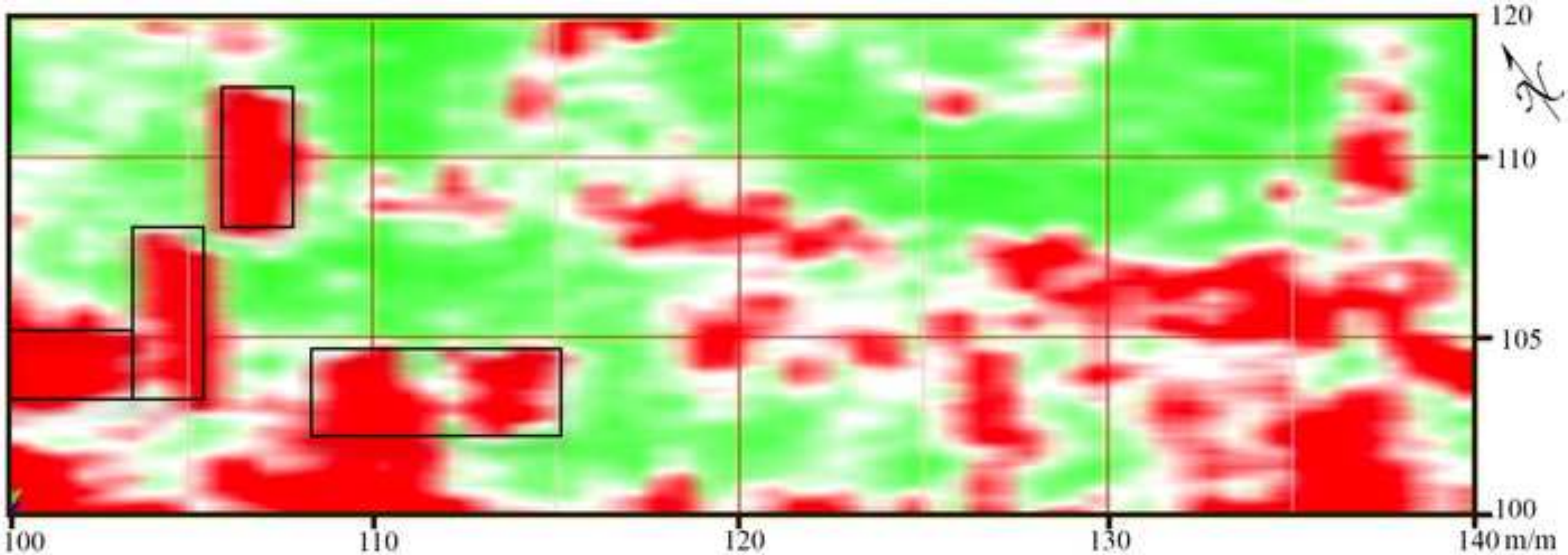

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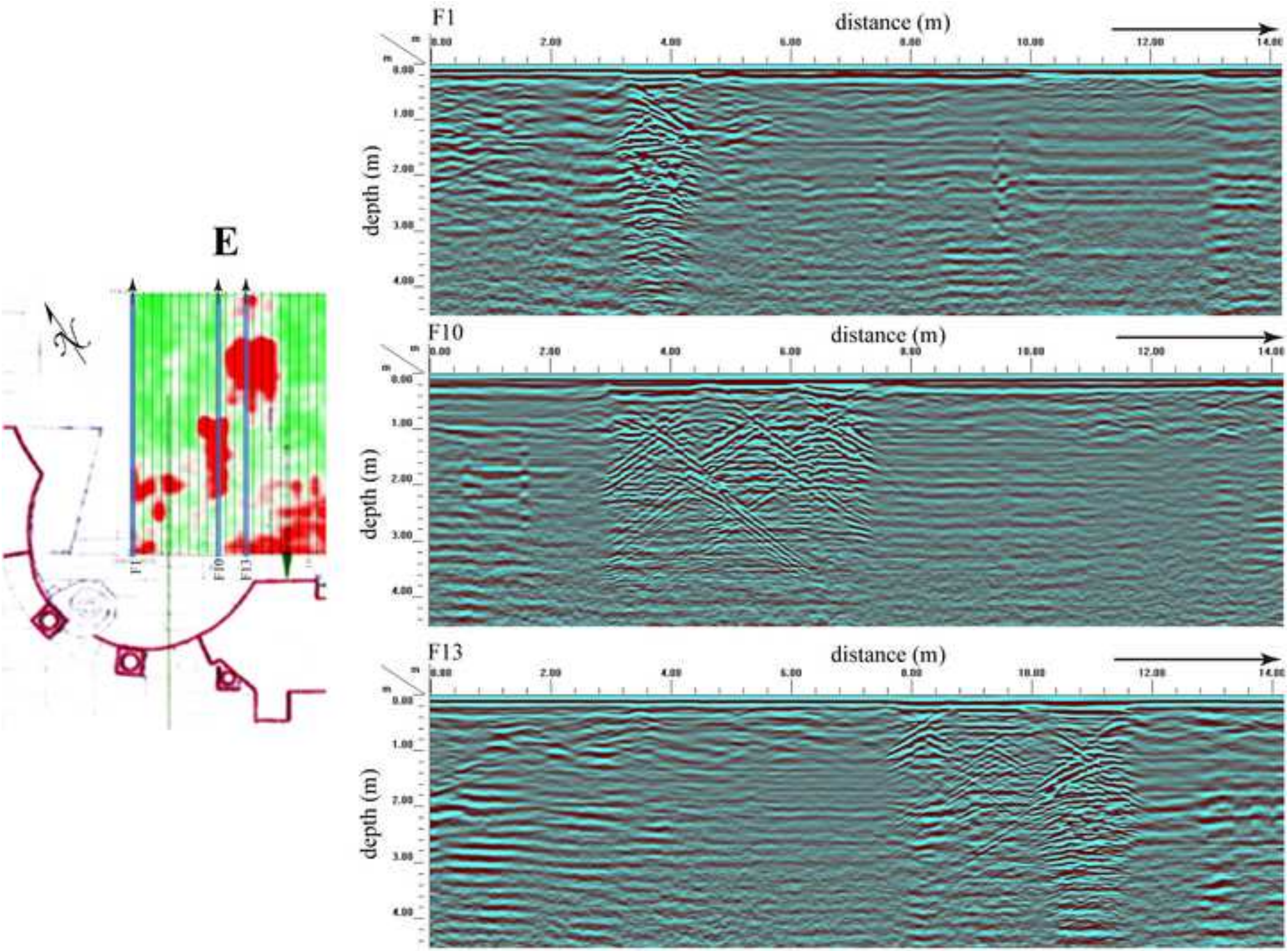

Figure

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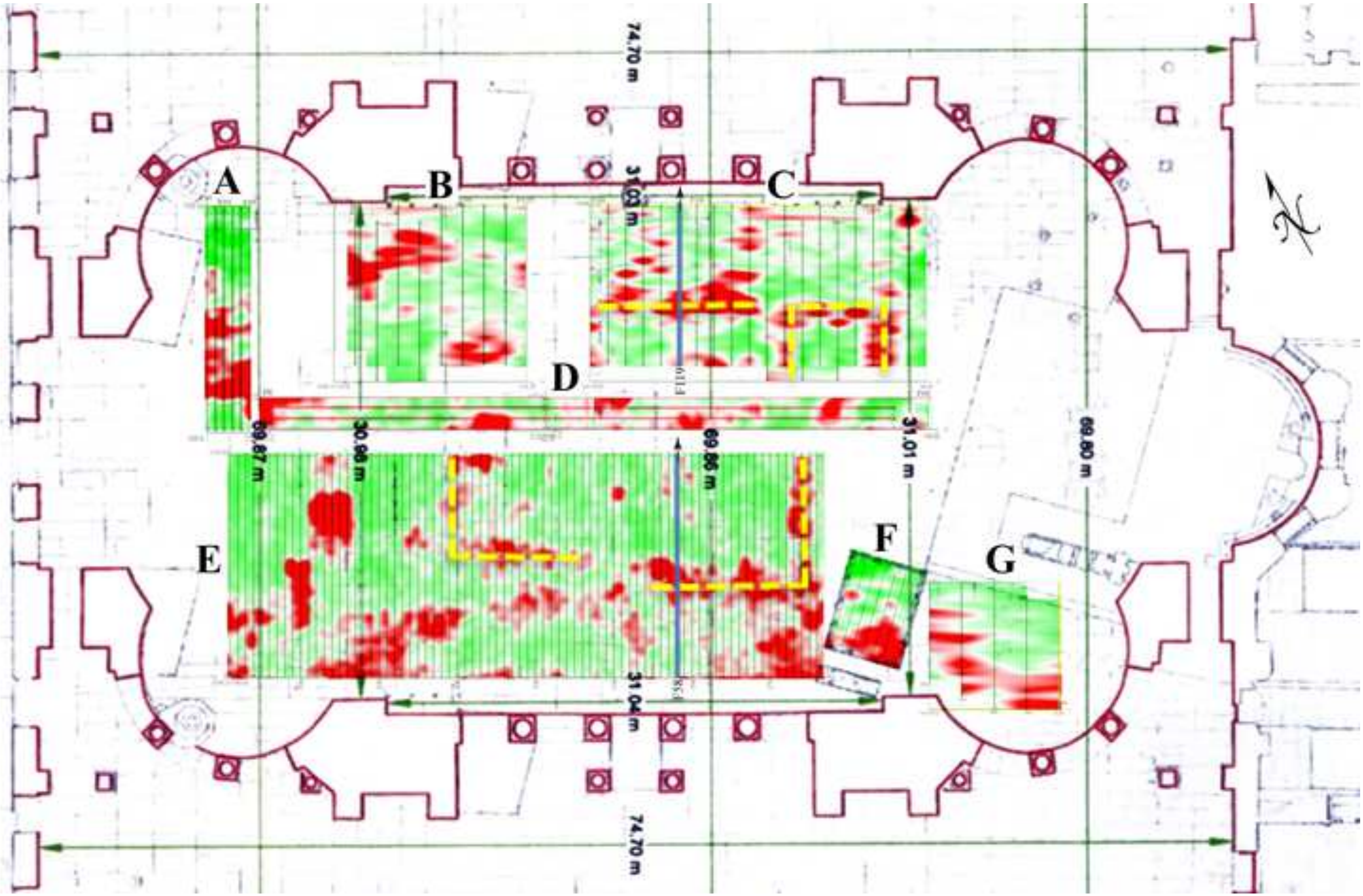

Figure

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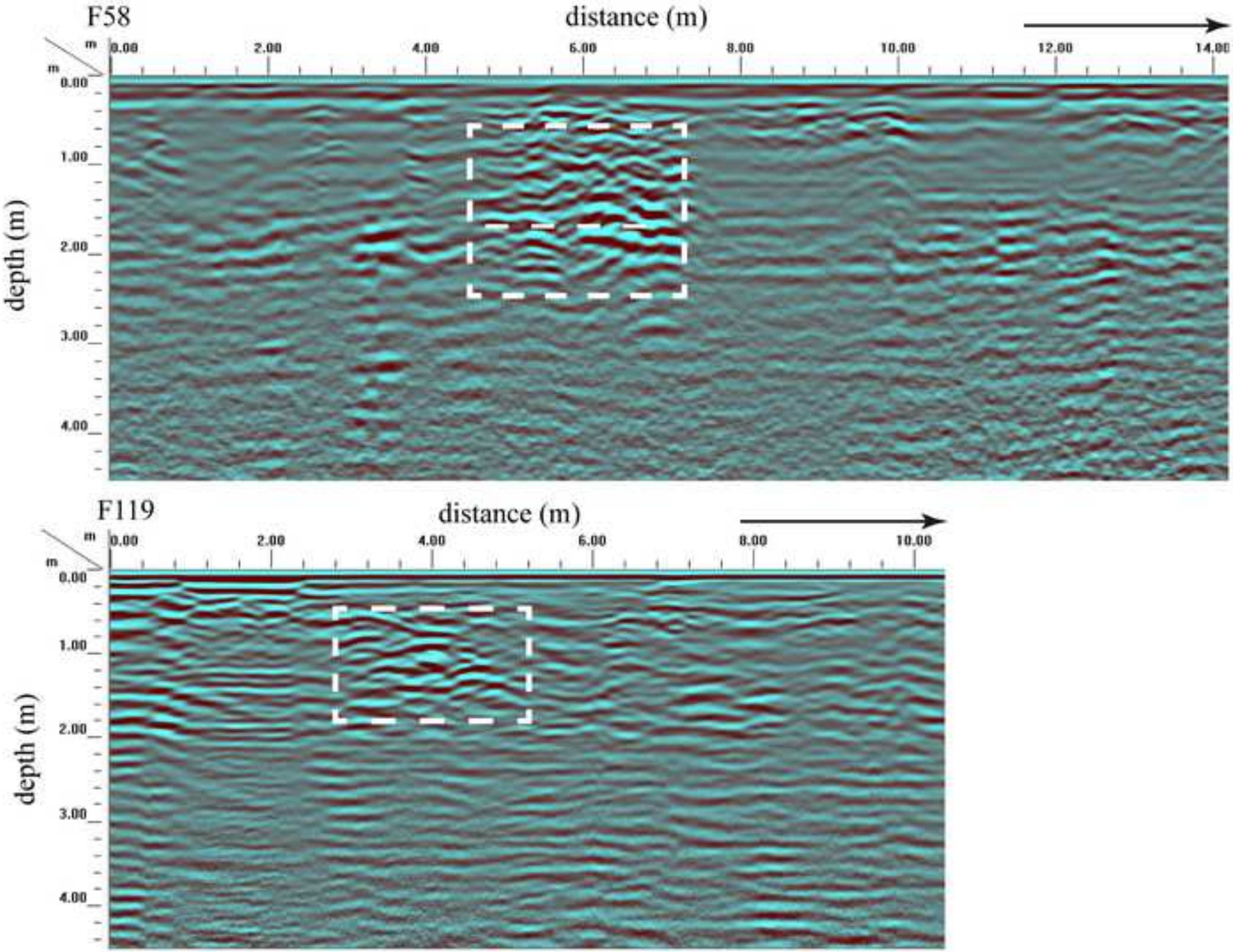

Figure
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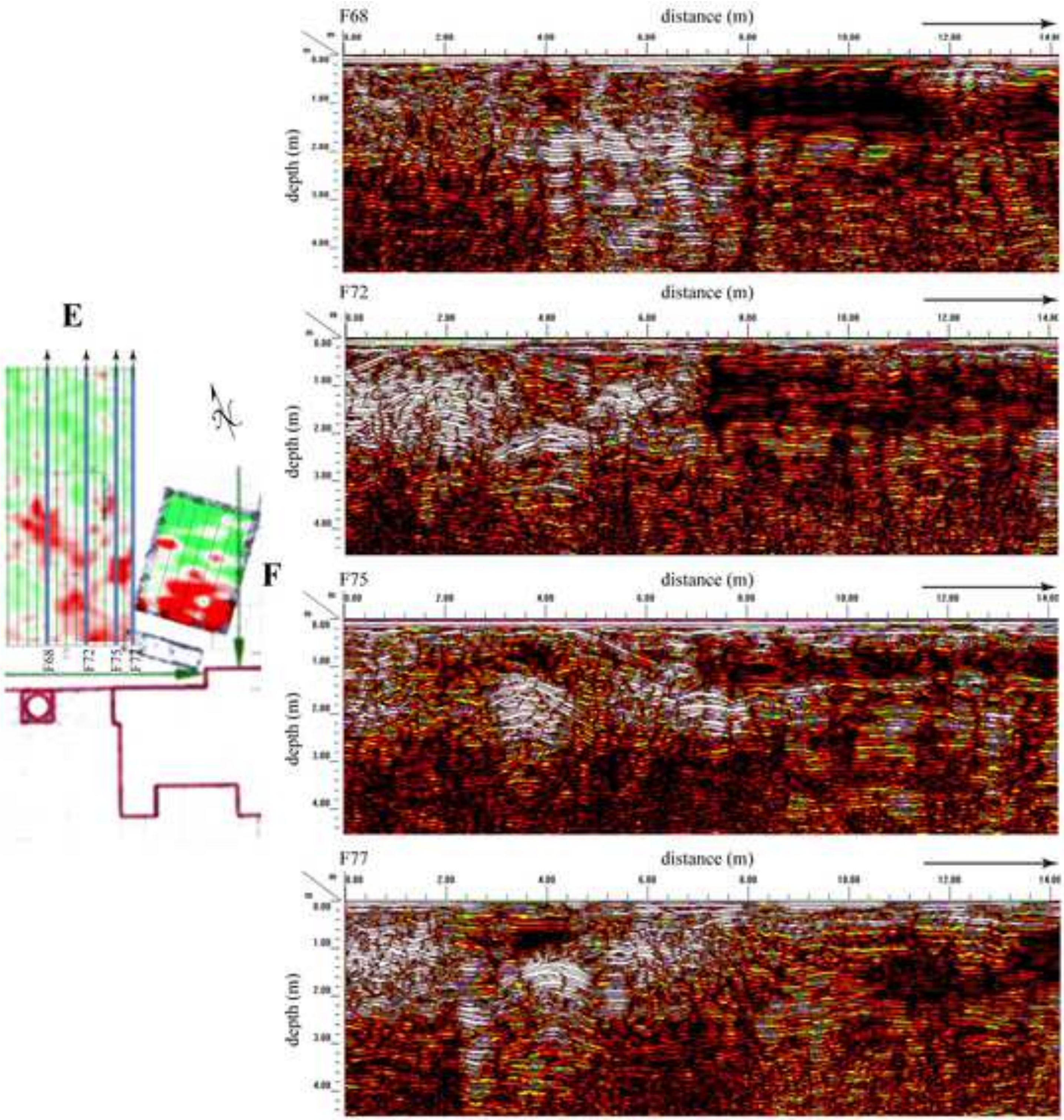

Figure
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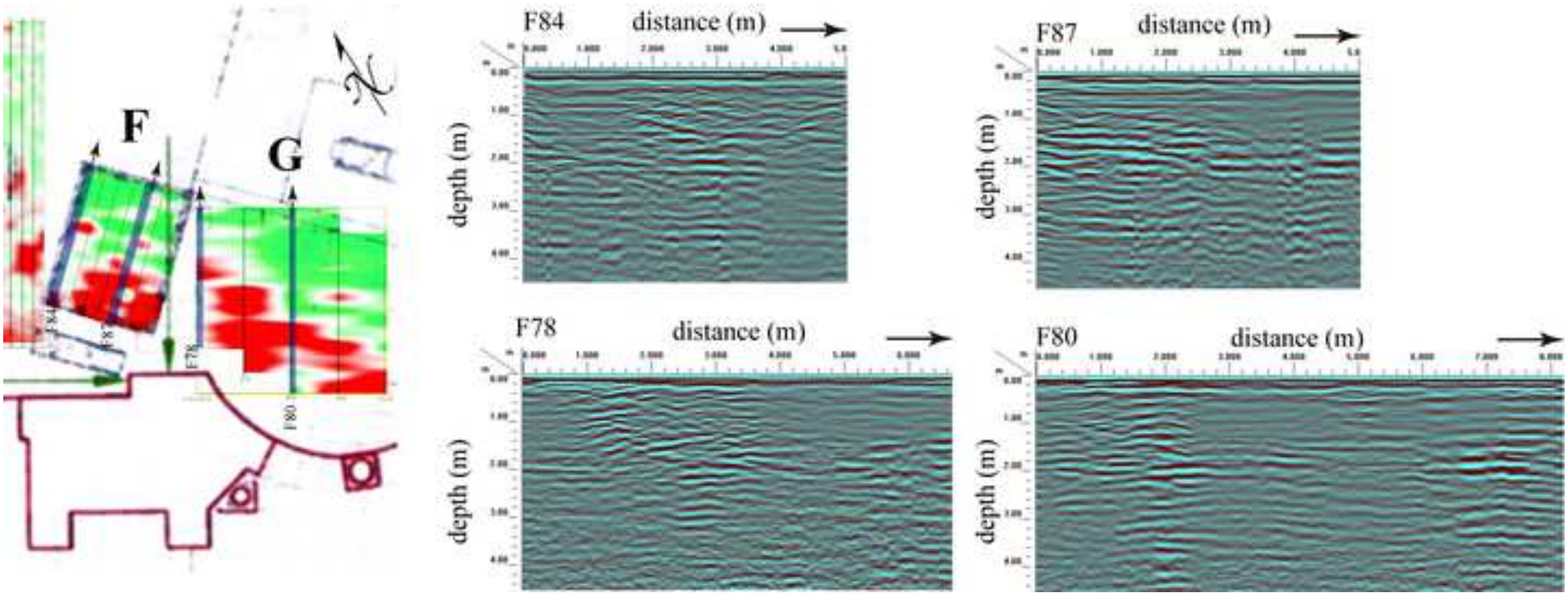

Figure
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