

PRELIMINARY RESULTS OF INVESTIGATIONS OF POSSIBLE GROUND DEFORMATION STRUCTURES IN THE EARLY CHRISTIAN BASILICA, ANCIENT LECHAION HARBOUR, CORINTH, GREECE

**Minos-Minopoulos D.¹, Pavlopoulos K.¹, Apostolopoulos G.²,
Dominey-Howes D.^{3,4} and Lekkas E.⁴**

¹ Harokopio University, Department of Geography, 70 El. Venizelou Str., Kallithea, 176 71,
Athens, Greece, dminou@hua.gr, kpavlop@hua.gr

² National Technical University of Athens, School of Mining and Metallurgical Engineering,
Applied Geophysics Laboratory, 9 Iroon Polytechniou Str., Zografou, 157 80, Athens, Greece,
gapo@metal.ntua.gr

³ University of New South Wales, School of Biological, Earth and Environmental Sciences, Sydney
2052 NSW, Australia, dale.dh@unsw.edu.au

⁴ National and Kapodistrian University of Athens, Faculty of Geology and
Geoenvironment, Department of Dynamic, Tectonic and Applied Geology,
Panepistimioupolis Zografou, 157 84, Athens, Greece, elekkas@geol.uoa.gr

Abstract

The Early Christian Basilica of Lechaion, Corinth, located on the western jetty of the ancient Lechaion harbour, was constructed during the late 5th century AD and archaeological excavations suggest that it was destroyed by seismic activity during 551-552 AD. Numerous depressions and buckling structures observed on the Basilica floor are indicative of ground deformation structures, likely associated with liquefaction. In an attempt to investigate the subsurface soil structure, and stratigraphy, a GPR survey and horizontal distribution of ground conductivity along ten selected transects was carried out, supplemented by stratigraphic data as described by archaeological trenches. The results of the study revealed subsurface deformation features providing sufficient indications that allow us to suggest that the surface structures observed on the Basilica floor are the surface expression of earthquake-induced ground liquefaction.

Key words: ground liquefaction, GPR survey, ground conductivity.

Περίληψη

Η Παλαιοχριστιανική Βασιλική Λεχαιού, Κόρινθος, κατασκευάστηκε στα τέλη του 5^{ου} αι. μ.Χ. στον δυτικό βραχίονα του αρχαίου λιμανιού του Λεχαιού, και σύμφωνα με αρχαιολογικές ανασκαφές καταστράφηκε από την σεισμική δραστηριότητα του 551-552 μ.Χ.. Διάσπαρτα βυθίσματα και υβώματα που παρατηρήθηκαν στο δάπεδο της Βασιλικής αποτελούν ενδεικτικές δομές εδαφικής παραμόρφωσης η οποία πιθανόν να σχετίζεται με ρευστοποίηση εδάφους. Με στόχο την διερεύνηση της στρωματογραφίας και της δομής του υπεδάφους πραγματοποιήθηκαν γεωφυσικές διασκοπήσεις GPR και

μετρήσεις αγωγιμότητας του εδάφους κατά μήκος δέκα επιλεγμένων τομών και συσχέτιση τους με τη στρωματογραφία όπως αυτή περιγράφεται από αρχαιολογικά σκάμματα. Τα αποτελέσματα της μελέτης είναι ενδεικτικά δομών παραμόρφωσης των υποκείμενων εδαφικών σχηματισμών με χαρακτηριστικά που επιτρέπουν την συσχέτιση των επιφανειακών δομών που παρατηρήθηκαν στο δάπεδο της Βασιλικής με το φαινόμενο της ρευστοποίησης εδάφους.

Λέξεις κλειδιά: ρευστοποίηση εδάφους, διασκόπηση GPR, αγωγιμότητα εδάφους.

1. Introduction

The archaeological site of the ancient harbour of Lechaion is located on the southeastern coast of the Corinthian Gulf, 3km to the west of the modern city of Corinth, Greece. It is the western harbour of the ancient city of Corinth. Its construction dates to the 6th-7th century BC, and archaeological evidence suggest that its use continued throughout the Roman period (Pallas 1959, 1965, Rothaus 1995, Stiros et al., 1996). The harbour was located in a marshy area and is composed of an outer harbour edged by moles and an inner artificially excavated harbour (cothon) connected to the Corinthian Gulf by a stone-lined channel surrounded by two dredging mounds (Figure 1).

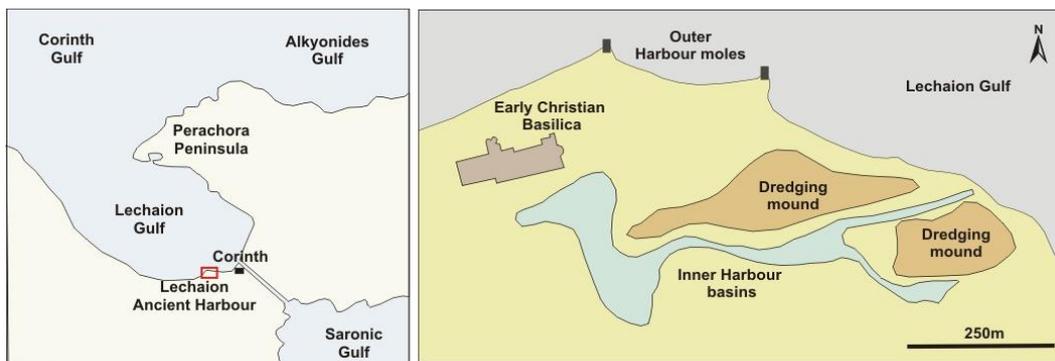


Figure 1 – Left: Location map of the study area, Right: The ancient harbour of Lechaion.

During the late 5th to early 6th century AD, an Early Christian Basilica was built in the western jetty of the harbour. The Basilica is thought to have only been in use for a short period of time since it is believed that it was destroyed by seismic activity in the mid 6th century (Pallas 1956, 1959, 1960, 1965, Rothaus 1995). This destruction is commensurate with the extensive damage sustained in ancient Corinth (Pallas 1956, Scranton 1957), and is thought to have been associated with the earthquake of 551 AD (Pallas 1956, 1959, 1960, 1961, 1965). The aim of this paper is to investigate the origin and triggering mechanism of deformation structures observed on the floor of the Early Christian Basilica. These surface structures are indicative of earthquake-induced liquefaction and an effort is made to examine their relationship with the subsurface soil stratigraphy and structure.

2. Background

2.1. Geodynamic Setting

The Corinth Gulf is an active continental rift system in a subduction zone setting, with extensional tectonics expressed through intense seismicity and marginal uplift. The Lechaion Gulf (Figure 1), the southeastern sub-basin of the Corinth Gulf is an asymmetric basin representing an inactive relict of early rifting (Sakellariou et al., 2004, Leeder et al., 2005, Turner et al., 2010). Spatial uplift rates of raised shorelines suggest a fault slip related uplift for the Perachora peninsula of the

order of 0.31 ± 0.04 mm/yr since Marine Isotope Stage MIS 7 (Leeder 2005, Turner et al., 2010) while the southern margin is considered to be exhumed independent of fault slip and uplift of basin sediments is attributed to non spatially uniform isostatic uplift with rates from 0.19 ± 0.05 mm/yr to 0.31 ± 0.05 mm/yr (Leeder et al., 2003, Turner et al., 2010).

2.2. Previous Work

For the Lechaion ancient harbour, geomorphological, and sedimentological studies suggest an episodic uplift of the order of ~ 1.1 m that according to radiometric dating of marine organisms (*Lithophaga*) bored in raised walls of the ancient port is dated to circa 340 BC, (Stiros et al., 1996). Supplementary radiometric data for this event comes from Morhange et al., (2012) from studies carried in the inner harbour basin, suggesting uplift of the order of ~ 1.2 m around 375 ± 120 cal. B.C. This uplift event is suggested to have been followed by coastal submergence of the outer harbour moles as recorded by Flemming (1978), (Turner et al., 2010). Koster et al., (2011), performed drill core sampling and GPR/ERT survey suggesting possible tsunamigenic layers and abrasion scours at the west part of the harbour at a depth of 2.00m. In addition, Hadler et al., (2011) based on geomorphological, sedimentological, geoarchaeological and geophysical data suggest a multiple tsunamigenic impact at the Lechaion harbour site and surrounding coastal area by at least three distinct event layers that according to radiocarbon dating occurred around 760 cal BC, 50 cal AD., with the youngest and obviously most destructive event dating to the 6th century AD triggered during the 521 or 551 AD earthquake series, related to the destruction of the Early Christian Basilica.

2.2.1. Stratigraphy

The subsurface lithostratigraphy of the Basilica presented in Figure 2, represents a synthesis of the stratigraphic data described by Pallas during original site excavations (1956 to 1965). Trial trenching (Pallas 1959, 1960, 1965) was carried out at various sites in the Basilica floor (trenches 1 and 2) and surrounding locations (3, 4, 5 and 6). The ground on which the temple was founded can be observed at ~ 1 m below the floor of the Basilica (trenches 1, 2, 3, 4). It is composed of sand that at locations (trench 2) contains clay intercalations and fragments of calcareous sandstone (trench 1), representing the preparation ground for the Basilica construction works (Pallas 1960, 1965). This foundation horizon, having a minimum thickness of ~ 0.5 m is dated to the 3rd century BC according to coins found on trial trench 3. The stratigraphy that overlies the foundation horizon represents the artificial fill used during the works of levelling the floor of the Basilica (Pallas 1960, 1965). This levelling horizon is composed of sand and pebbles as observed in trial trenches 1, 2 and 3. In trench 1 the upper parts include lithic fragments, while in trench 2 it contains fragments of ceramics and mortar. Contrasting dates from coins dating from 408-450 AD (trench 1) to 518-527 AD (trench 2) and 425-475 AD (trench 3) are also indicative of the artificial nature of this levelling horizon. Finally, a layer of angular calcareous sandstone boulders mixed with sand was recorded in trenches 5 and 6 located to the SW of the Basilica extending from 1.45m below the ground surface. It represents an artificial layer possibly related to early harbour installations (Pallas 1959). Although the continuation of this layer under the Basilica is unknown, its existence is indicative of artificial fills extending to a depth of 3m.

Summarising, the subsurface stratigraphy of the Basilica could be characterised as an artificial fill composed mainly of sand and pebbles with occasional intercalations of clay, lithic and ceramic fragments and mortar. This fill extends to a depth of at least 1.50m below the Basilica floor. As suggested by the existence of a layer of boulders at 3m depth located to the SW of the Basilica, the artificial nature of the subsurface stratigraphy possibly extends to a depth of 3m.

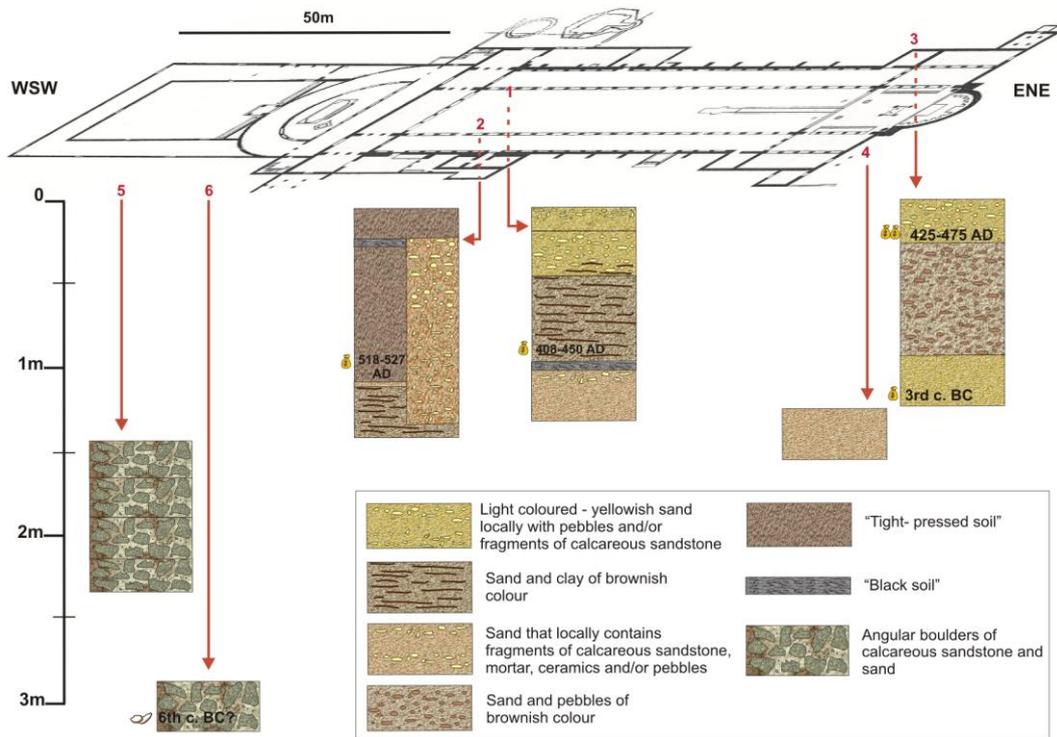


Figure 2 – Trial trenches stratigraphy within the Basilica (1, 2) and in surrounding locations (3, 4, 5 and 6) according to Pallas (1959, 1960 and 1965).

2.3. Ground Deformation Structures

Recent restoration works carried out on the Early Christian Basilica brought to the surface the decorated floor of the temple. Numerous depressions were recorded in the southern aisle, of circular and linear geometry, concentrated mainly at the northern end of the aisle striking in a general E-W direction (Figure 3a), with dimensions varying from 0.45x0.33m and 0.12m depth to 1.80x1.33m and 0.4m depth for the circular depressions (Figure 3b) while the linear depressions (Figure 3d) have a variable depth ranging from 0.05 to 0.12m. It has to be noted that some of these linear structures are in contact with the depressions (Figure 3c). In the central aisle, where the floor is not preserved in a good condition, scattered linear and circular depressions were recorded along with linear and circular buckling structures. Their distribution does not suggest any general trend besides clustering recorded in the central part and near the limit with the southern aisle. The northern aisle remained covered with gravel and soil and was not possible to identify surface ground deformation structures.

Liquefaction is the transformation of cohesionless loosely packed sediments from a solid to a liquid state as a result of increased pore pressure and reduced shear stress leading to ground failures due to hydraulic fracturing (Obermeier & Pond 1999). During earthquake shaking, liquefaction occurs in sediments such as silt, sand and gravel, originating at a depth ranging from a few meters to about 10m below the ground surface (Obermeier 1996). The phenomenon leads to surface failures such as cracking and formation of localised depressions due to densification and settlement of liquefied sediment that can reach 0.25 - 0.5m where thick sands liquefy severely (Obermeier 1996). In addition, circular depressions (craters) form along the length of cracks induced by seismic shaking in a clay rich cap (Obermeier 1996). Such depressions according to Takahama et al., (2000), represent the final “draw-in” process in liquefaction that occurs just after an earthquake.



Figure 3 – Depressions recorded on the southern aisle of the Early Christian Basilica.

3. Methodology

Since the study area is an archaeological site and special laws apply for its protection, a non-invasive approach with respect to the monument was applied (Wolf et al., 2006). After authorisation by the 25th Ephorate of Byzantine Antiquities in Corinth, a geophysical survey was carried out in the Basilica. GPR profiling along with electromagnetic measurements giving the apparent conductivity of the ground in two depths was performed in an attempt to examine the subsurface structure, its possible relation to the surface structures observed and to identify the triggering mechanism (Wolf et al., 2006, Maurya et al., 2006). All geophysical measurements were positioned with Differential GPS system (LEICA GPS 1200). The survey included 10 profiles of GPR using MALA system with shielded antenna 250MHz, and electromagnetic measurements using GF Instruments “CMD2” conductivity meter (compatible with Geonics EM-31) with two setups, “low” for 1.5m depth and “high” for 3.0m depth of detection, positioned by differential global positioning system (Figure 4). Both geophysical methods are affected by the conductivity of underground formations that is dependent upon the compaction, grain size, permeability and saline water intrusion of the sediments and have been used successfully in the past for imaging liquefaction features (Liu and Li., 2001, Al-Shukri et al., 2006, Maurya et al., 2006, Wolf et al., 2006).



Figure 4 – Location of profiles (lines) and major deformation structures (dots) based on Google Earth Imagery.

4. Results

4.1. Ground Conductivity Survey

The cumulative apparent conductivity distribution to the two depth levels (1.5m and 3.0m) is presented in Figure 5. Generally the apparent conductivity is increasing gradually from east to west suggesting at the western part higher permeability and/or higher percentages of fine-grained deposits in comparison to the eastern part where lower permeability and/or higher percentages of coarse-grained deposits are expected.

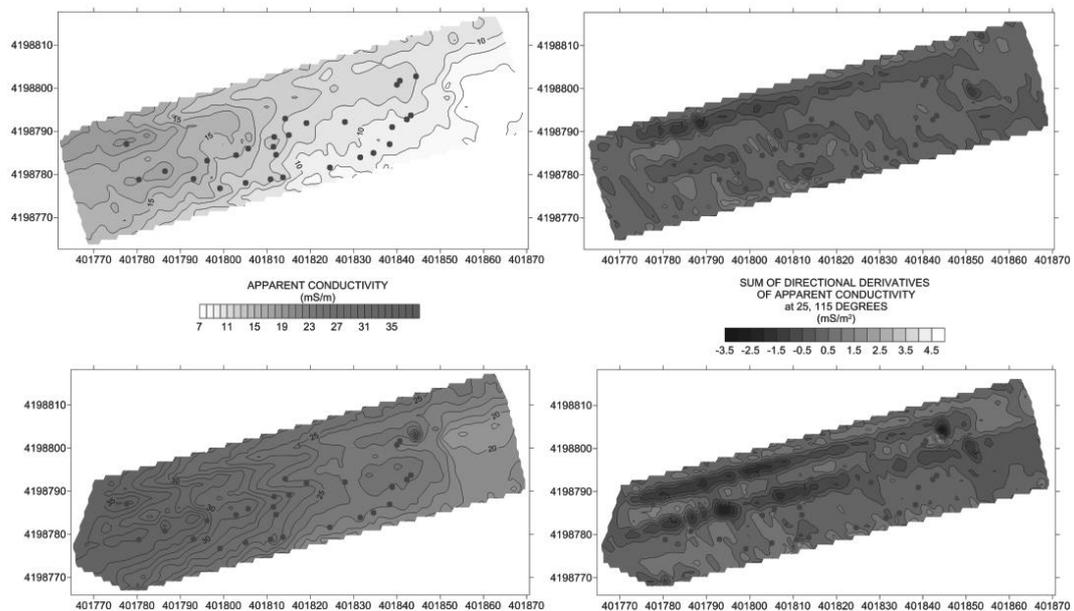


Figure 5 – Left: Apparent conductivity distribution, Right: Sum of directional derivatives of apparent conductivity distribution, in two depth levels, (1.5m top maps and 3.0m bottom maps). Blue dots indicate major ground deformation structures.

Tight circular contours indicate areas of possible liquefaction vent locations (Wolf et al., 2006). These are better discernible on the 3m depth level but only a few correlate well with the surface deformation structures. The contours at the eastern part of the temple and more specifically under the sanctuary of the Basilica are indicative of a potential anthropogenic structure. In addition to the general apparent conductivity distribution, “linear” like and continuous disturbances of the contours are observed under the northern aisle and the northern part of the central aisle of the temple, striking in a direction parallel to the Basilica. In order to enhance the effect of this latter observation the directional derivatives of the apparent conductivity in two directions, 25° and 115°, parallel/vertical to the walls of Basilica was calculated, and the sum for the two depth levels was produced (Figure 5). It seems that two linear structures-zones exist under the northern aisle and the northern part of the central aisle of the temple, striking in a direction parallel to the Basilica. Both resistive structures are clearly documented on the 3m depth map and although the structure-zone under the northern aisle also appears in all of its length in the 1.5m depth map, the structure-zone under the central aisle appears fragmented in two parts. Since the northern aisle structure has been detected by both setups it is suggested that it is located near the surface, while the central aisle structure is possibly located at a depth under but near 1.5m.

4.2. GPR Survey

The GPR profiles provided the opportunity to investigate the lithology/stratigraphy, geometry and deformation of the Basilica sandy substratum to a depth of 6m (suggested velocity 0.12m/ns). The GPR processing steps were a) subtract mean, b) move start time (statics), c) manual gain, d) band-pass frequency filtering, e) background removal and f) deconvolution. In Figure 6, two indicative GPR profiles are presented with interpretation depicting interfaces between different formations (solid and dashed lines) or local features being related either to coarse material (dashed line circles) or fine material (solid line circles). Distinct surface depressions observed along the GPR profiles are indicated by arrows.

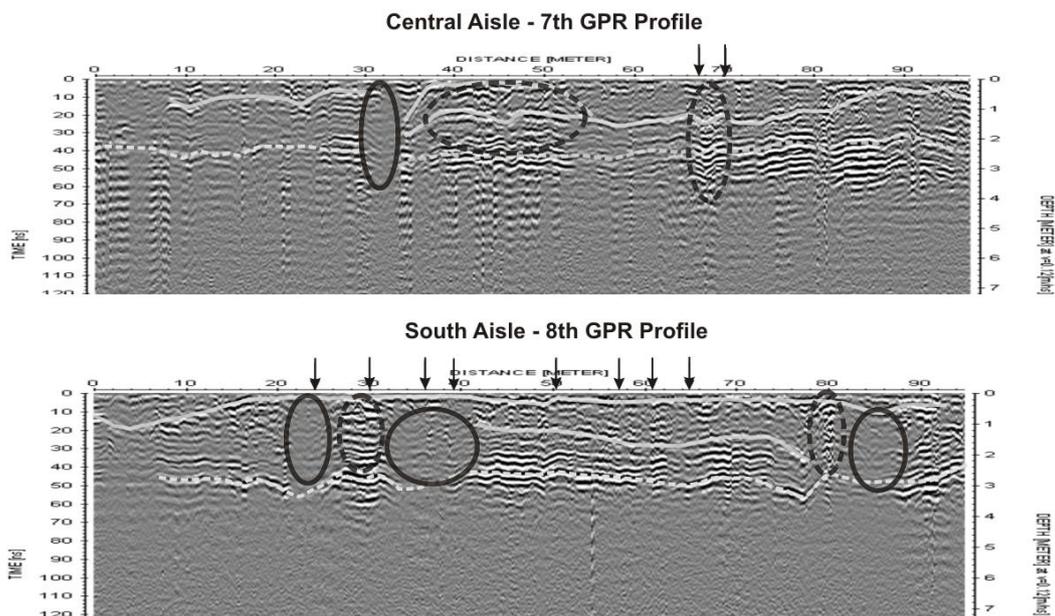


Figure 6 - GPR profiles with interpretation (interfaces with lines, local features with circles). The arrows show positions of observed depressions.

The stratigraphy presents a complex reflection profile with heterogeneities involving coarse grained laminated stratum that dominates the upper 3m of the profile and an underlying fine grained structureless stratum that could correspond to the saline water table (Figure 6). In the

upper 2m of the profile two interfaces have been recognised (solid lines) and another interface has been identified at approximately 3m depth representing a strong reflection signal horizon (dashed line). The profiles are considered to be in agreement with the conductivity contour maps indicating, coarser stratum at the eastern parts of the substratum up to a depth of 3m indicated by strong reflection signals that gradually fade westward.

The GPR profiles are indicative of substratum ground deformation that at locations could relate to liquefaction processes, (Maurya et al., 2006). The upper stratum presents convolutions especially in the upper horizons, indicative of plastic deformation. Sharp vertical discontinuities of weak signal have been identified across the coarse grained laminated stratum (host sediment), indicative of conductive areas permeable to saline water probably related to sand vents (solid line circles), Dimensions vary from 0.5m to 5m and extend clearly down to a depth of 3m suggesting liquefied sediment source below 3m depth. In addition, laminations of the coarse grained material dip towards the centre of these sharp vertical discontinuities exhibiting a concave up geometry. This concave up geometry is in conformity to surface depressions, indicative of the downward settlement of the sediments after release of pressure, (Takahama et al., 2000). For profile 8 in the south aisle and profile 7 for the central aisle the correlation of the surface depressions with the substratum discontinuities has been possible, indicative of their direct association. For the profiles of the north aisle correlation has not been possible since the floor remains artificially covered by gravel and soil and surface depressions have not been recorded.

5. Discussion and Conclusions

Correlation between the stratigraphy described by Pallas (1959, 1960, and 1965) and the geophysical survey provides a better understanding of the subsurface lithostratigraphy on which the Early Christian Basilica was founded. The foundation ground horizon of the construction according to the trial trenches is located approximately 1m below the Basilica floor and is composed mainly of sand with local intercalations of clay. This horizon relates well with the horizon identified at the western part of the central aisle GPR profile (profile 7) extending at ~1m depth. The conductivity contour maps appear to be in agreement with the stratigraphy described by Pallas (1965) in trial trenches 1 and 2 - that is sand with local clay intercalations.

It could also be suggested that the clay intercalations have a dominant character in the western part of the foundation ground in contrast to the eastern part that appears to be coarser grained. The stratigraphy that overlies the foundation surface (<1m) in trial trenches 1, 2 and 3, is dominated by an artificial fill composed of sand and pebbles containing fragments of ceramics, mortar and lithic fragments representing the works of levelling the ground for the construction of the temple. This horizon has been identified in the GPR profiles with strong signal reflections. However it is difficult to identify its continuity since the horizon presents intense convolution and is frequently interrupted by vertical discontinuities possibly associated with sand vents. The angular boulders and sand horizon that according to archaeological trenches extends from ~1.45 to at least 3m depth at locations to the SW of the Basilica, is suggested that could correspond to the strong reflection signal horizon that appears in all the GPR profiles at an approximate depth of ~2-3m. The thickness of this horizon varies from ~1 to 1.5m and it is not continuous.

The GPR profiles have provided indications that could support ground liquefaction and information on its characteristics (Maurya et al., 2006). The existence of numerous sharp vertical discontinuities in the upper 3m of the profiles with dimensions that range from 0.5m to 5m characterised by weak reflection signals are indicative of sand vents. This indication is further supported by the geometry observed in the lateral margins of the vents, where the host sediment presents laminations dipping towards the centre of the vents that in combination with concave-up geometry observed in the upper parts of the vents, is indicative of the sediment settlement (draw – in process) (Takahama et al., 2000). The sand vents and observed geometry have been successfully correlated with the surface linear and circular depressions. Since the sand vents discontinuities

appear to fade out below ~3m, a liquefaction sediment source below ~3m depth is suggested. Special care has to be taken for the two linear structures-zones under the northern aisle and the northern part of the central aisle of the temple, striking in a direction parallel to the Basilica that have been detected by electromagnetic measurements. These zones in depths between 1.0 - 2.5m consisted of coarse material have to be interpreted and be considered if they relate to the liquefaction phenomenon.

We further suggest that the liquefaction is earthquake-induced. The geomorphology of the area can be characterised as a coastal lagoon with the Christian Basilica founded on a coastal dune separating the coast from the inner basin. According to the classification of geomorphological units to their earthquake-induced susceptibility (Kotoda et al., 1988), the location is characterised as highly susceptible. The dimensions of the vents and surface depressions are indicative of violent venting due to rapid hydraulic pressure increase in the liquefied sediment (Obermeier 1996). Since the Early Christian Basilica is considered to have been destroyed by the earthquake of 551-552 AD (Pallas 1960, Papazachos & Papazachou 1989 and references therein), it is possible that its destruction could relate to earthquake-induced ground liquefaction.

In summary, preliminary correlation of the stratigraphy with GPR profiles and conductivity contour maps has provided sufficient indications that allow us to suggest that the surface structures observed on the Basilica floor are the surface expression of earthquake-induced ground liquefaction. However, further research is required for a better understanding of the factors controlling the ground failure mechanism and its relation to the post 5th century AD seismicity of the region.

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