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ANALYTICAL APPROACHES AND DIGITAL METHODS IN ALLUVIAL ARCHAEOLOGY: THE 'ANCIENT SHIPYARD' OF PISA-SAN ROSSORE AS A CASE STUDY

1. Alluvial archaeology

Alluvial archaeology has developed as a field of environmental archaeology in recent years as part of a growing interest in wet environments[1], particularly for their ability to preserve 'archaeological memory'. One of the matters most debated concerns the study of archaeological records in alluvial contexts: since they belong to ever-changing landscapes, the interpretation of finds is difficult (Mayoral *et al.* 2012). The main critical aspect lies in recognizing the contexts of primary deposition, as the artifacts are conveyed into the archaeological deposit by the force of the alluvial flood flow. Ceramic assemblages are particularly undervalued; indeed, the literature reveals disagreement on the effectiveness of ceramic materials as dating artifacts, given their high degree of fragmentation, which makes chrono-typological associations challenging (Brown, Ellis 1995; Brown 1997, 59; Ferrarese Lupi, Lella 2013). This paper aims to propose some analytical approaches and digital methods for the study of ceramic assemblages resulting from alluvial floods (Tescione 2019[2]; Cicala, Tescione 2022).

2. The case study

To test the analytical approach, the archaeological site of the 'Ancient Shipyard' of Pisa-San Rossore (Italy) has been selected as a case study (Fig. 1). This site has been affected by a dense sequence of catastrophic and highly impactful alluvial floods, which have left their mark on its millennia-long fluvial history. Geomorphological analyses have allowed the identification of the presence of a riverbed, presumably the ancient course or meander of the Serchio River (*Auser* in Roman times), located approximately 1 km N of a bend in the Arno River and about 3-4 km from the current coastline (Camilli, Setari 2005, 14; Benvenuti *et al.* 2006). In pre-Roman times, this ancient channel had an uninterrupted flow into the sea, allowing ships to transport their cargoes in calm waters towards the city of Pisa. Subsequently, it would converge with the Arno River near Pisa (Camilli *et al.* 2009).

[1] In the form of Wetland Archaeology, for example.
[2] This paper is an excerpt from a doctoral thesis (Tescione 2019), currently being published.

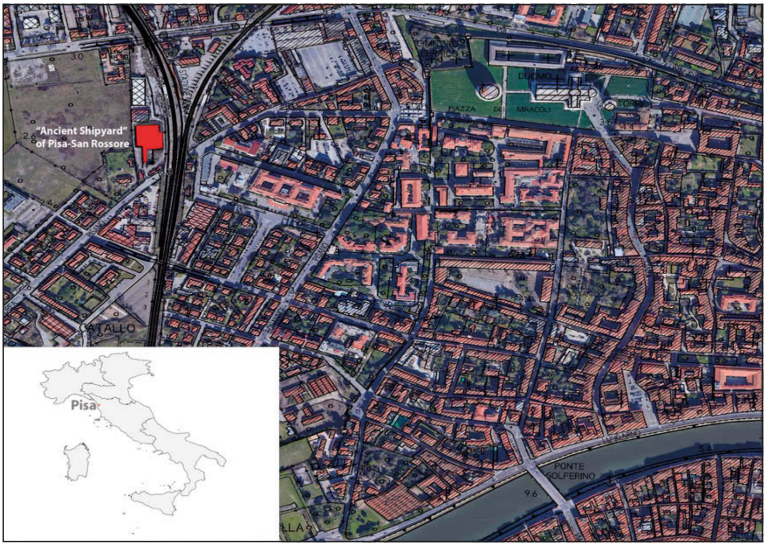

Fig. 1 – Placement of the case study.

Sedimentological analysis allowed the identification of four sandy lenticular lobes, incorporating ships and other archaeological remains. These lobes are associated with recurrent alluvial floods of the Arno (Benvenuti *et al.* 2006). Indeed, during exceptional alluvial floods linked to periods of heavy rainfall, the Arno, breaking its banks, would discharge large quantities of water and sediments into the dock area, overwhelming ships in transit or at rest and covering them with sand. Gradually, it filled the available space in the channel area, ultimately leading to its definitive abandonment. Over time, fluvial deposits have been added, causing erosive processes even on the channel bed itself. This resulted in the secondary deposition of some materials accumulated from previous floods. Inter-flood periods indicate the reuse of the river channel, as demonstrated by the presence of thin layers with clayey sediments recorded in each unit and documented by more recent archaeological materials from S to N (Camilli *et al.* 2005, 75; Benvenuti *et al.* 2006). The chronological calibration of the four lobes indicates that catastrophic alluvial floods of the River Arno occurred on a centennial pattern between the 3rd century BC (Pace 2020) and the 5th century AD (Camilli *et al.* 2006, 20). The formation processes of the alluvial floods are attributable to a combination of environmental factors (high-magnitude hydroclimatic events, sea level fluctuations, geomorphological and sedimentary processes) and anthropogenic features (deforestation, centuriation) (Camilli, Setari 2005, 16; Benvenuti *et al.* 2006).

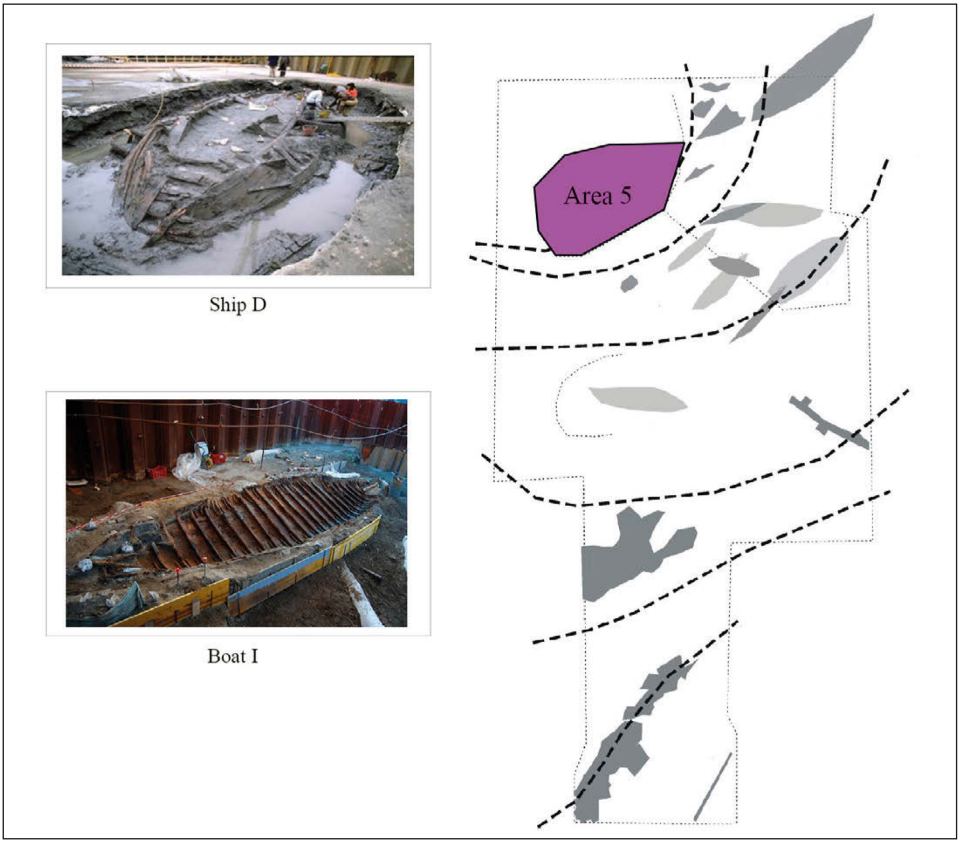

Fig. 2 – Area 5 positioning (re-elab. after Camilli *et al.* 2005, fig. 2): Ship D and Boat I at the time of the discovery (©Museo delle Navi Antiche di Pisa).

Excavation campaigns have revealed a complex stratigraphic sequence, documenting the history of a landing for approximately 1200 years, from the 6th century BC to the 7th century AD (Camilli 2012, 14-18). The extreme complexity of the stratigraphic sequence of the archaeological site has made it necessary to select a sample area. Analysis thus focused on the ceramic assemblage derived from Area 5 deposits, located in the NW sector of the archaeological site (Fig. 2). This area constitutes the northernmost segment of the San Rossore riverbed. What it represents is not confined to the final phase of the channel's life: analysis of the deposit confirms the succession of alluvial events that characterize the entire history of the paleochannel. The most remarkable events in the stratigraphic sequence of Area 5 are represented by the sinking of Ship D and Boat I. Ship D was a river barge, 14 m long and 6 m wide, overwhelmed by a flood in the Late Roman period[3] and Boat I was a Roman *linter*, whose wreckage has been dated from ^{14}C analyses to the first half of the 3rd century AD.

3. Analytical approaches and digital methods

3.1 *Stratigraphic data processing*

The quantity and diversity of data produced from the excavation of the Boat I and Ship D deposit allowed the application of GIS technology (using the QGIS platform), which offered several advantages: the easy general and analytical consultation of the context; the processing of quantitatively significant calculations and queries; the spatial location of artifacts; and the production of various graphical outputs related to the demanded themes. One of the initial applications was to the stratigraphic reconstruction, which, due to its high level of difficulty, required the combined use of various research tools (Fig. 3).

The first step involved data acquisition, reprocessing and the standardization of the various data produced by different operators in different years. The initial task included integrating the overall plan of the archaeological site and, consequently, Area 5, into a GIS, linking the overall plan to specific UTM coordinates using the geodetic datum EPSG:3003 (Monte Mario/Italy zone 1). One of the primary challenges was creating quoted raster images for all identified archaeological units, processing altitudinal isosurfaces for each unit. The next step involved the association of the single unit and phase with a specific polygon-type shapefile. These operations aimed to have a greater number of graphic elements to reconstruct the paleo-landscape. The characteristics of each archaeological unit were also recorded in a PostgreSQL database, integrated into the GIS platform. This allowed the sedimentological peculiarities observed for each unit to connect archaeological analysis conducted in Area 5 with geological reports (Benvenuti *et al.* 2006). A real 'stratigraphic information system' has been created through the fusion of archaeological data with the tools provided by the GIS platform (Desachy 2008, 151).

The second phase involved the topographic representation of the stratigraphic sequence by creating a Digital Elevation Model (DEM) using the QGIS2threeJS plug-in. Combined with available geomorphological data, this phase allowed for a better definition of the formation processes of the stratigraphic sequence. The trends, sedimentological characteristics and thickness

[3] The recent dendrochronological and radiometric analysis dated the shipwreck to the 7th cent. AD (Mariotti *et al.* 2007), but analysis of the ceramic assemblage placed the wreck in the 5th cent. AD (Tescione 2019).

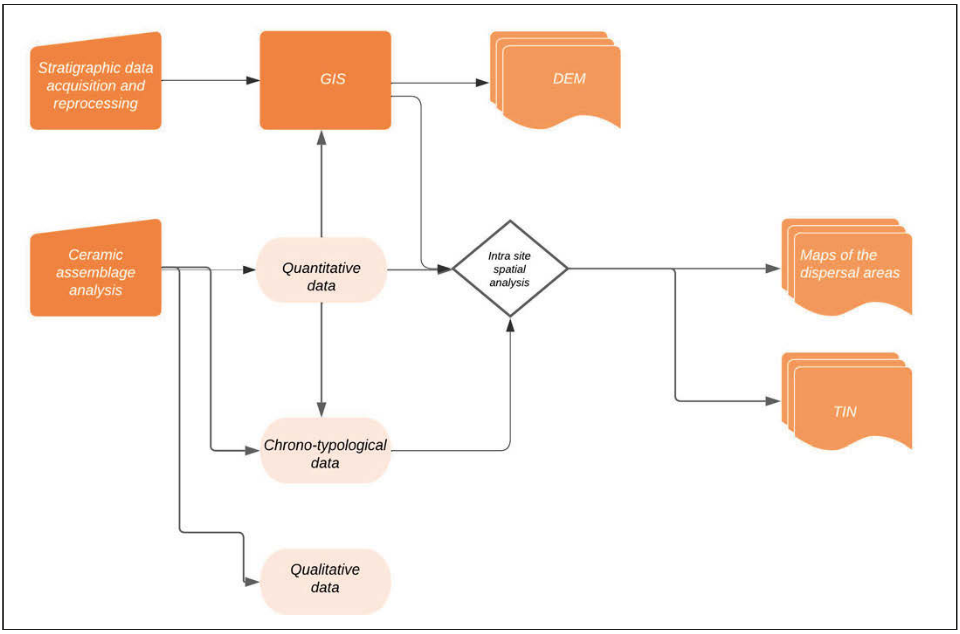

Fig. 3 – Workflow of the analytical approaches (elab. by T. Tescione).

of the archaeological layers helped to determine the genesis of the ceramic assemblages and, furthermore, the magnitude and power of the alluvial flood flows. The use of 3D models in stratigraphy and sedimentology has proven to be a valuable contribution to improve the understanding of archaeological sites (Semeraro 2008, 47; 2011, 134; Campaña Lovano *et al.* 2016, 337).

3.2 *Quantitative analysis: comparative systems*

The study of the ceramic assemblage of Area 5 has proven to be a significant opportunity for an experimental verification of some quantitative analysis procedures applied in archaeology. The goal was to assess with similar data the achievable results and to determine to what extent different systems meet the objectives of reliable quantification (for a similar approach, De Simone *et al.* 2015). Therefore, a ceramic assemblage from a single archaeological unit (282) was used as a sample to understand which system was optimal and, at the same time, to identify the variables associated with each applicable method (Tab. 1).

The quantification method based on weight estimation was not applied because it requires a high degree of specialization, such as specific knowledge of fabrics, glazes, and other non-typological elements, which is not easy to

Ceramic class	N.Fr.	%N.Fr.	MNI	%MNI	EVE	%EVE
Common ware	23	6,91%	4	6,78%	3	13,89%
Cooking ware	48	14,41%	16	27,12%	1,6	7,41%
African cooking ware	29	8,71%	13	22,03%	1,1	5,09%
Italian sigillata	19	5,71%	5	8,47%	0,8	3,70%
African red slip ware	2	0,60%	2	3,39%	0,3	1,39%
Thin-walled pottery	9	2,70%	5	8,47%	0,8	3,70%
Lamp	2	0,60%	1	1,69%	0	0,00%
Amphorae	201	60,36%	13	22,03%	14	64,81%

Tab. 1 – Quantitative analysis. Comparative systems on a sampled ceramic assemblage from an archaeological unit (282).

employ in a context like a case study, characterized as it is by a wide variety of ceramic classes and productions. The quantitative analysis involved the use of methods for calculating the quantity of ceramics (counting of fragments) and systems for evaluating the quantity of vases based on MNI (Minimum Number of Individuals) and EVE (Estimated Vessel Equivalents). EVE is based on a calculation of the percentage of the circumference of the rim and bottom of fragments referable to the same ceramic class or type (Orton *et al.* 1993, 203-218). The MNI method involves counting the morphologically significant fragments for each ceramic class or type (Raux 1998). The significant variations observed between the quantification method based on fragment counting and those based on MNI and EVE were linked to the brokenness index. In our case, the high presence of amphorae, as numbers of fragments, could be associated to the corresponding great breakage value that characterizes this ceramic class. Minor fluctuations were observed between the results of the MNI and EVE, confirming the good stability of these two systems.

The difficulties in applying the EVE method to all ceramic categories – it does not consider those classes or forms not represented by significant morphological elements – led to a determination against using quantitative procedure. EVE works best with material produced in reasonable numbers or derived from a single workshop (Orton 1993, 164-176; Orton *et al.* 1993, 171-173). Counting based on the MNI involves calculating the same vessel two to three times (especially in the case of standardized forms), while quantification in EVE eliminates this overrepresentation (Raux 1998, 14). For this reason, ceramic fine classes (Italian sigillata, African red slip ware, thin-walled ceramics), characterized by typological seriality, are overestimated as MNI. The Seville Protocol has been tested (Adroher *et al.* 2016) and it is based on the sum of the rim/bottom circumferences, adding a breakage coefficient (Modulo de Ruptura, MR). The method was not adopted because it is particularly effective for serial productions, such as amphorae, and less suitable for others. Furthermore, this approach takes into account only the rims and bottoms, prejudicing the quantitative analysis and producing an underestimation of the data.

Given the challenges of different systems, the MNI has been adopted as it proved to be the most useful method considering the preservation state of the artifacts (largely intact or almost entirely reconstructible), excavation methods (given the extent of the investigated area) and the quantity of cataloged artifacts. The research also attempted to recontextualize the material data through fragment counting (according to the system outlined in the Beuvray Protocol) (Arcelin, Truffeau Libre 1998, VII).

The analysis of a large portion of the Area 5 deposit[4] allowed the overall cataloging of 36,117 ceramic fragments, characterized by a broad chronological range (from the late Republican era to the late Roman period). In addition to these records, another 7,014 fragments of brick products (roof tiles, bricks, *tubuli*) must be added. In all analyzed ceramic assemblages, there is a prevalent presence of amphorae, confirming the distinctive feature of the landing area as a scenario of bustling transshipment and trade activity of goods to and from Pisa.

3.3 *Qualitative data*

Another aspect of the research included an analysis of the formation processes of ceramic assemblages, considering the indices of completeness and fragmentation of materials. Procedures were developed with an eye to the methodologies discussed in the literature (Ceci, Santangeli Valenzani 2016, 19-23), and by evaluating the parameters and conditions of use most suitable for the case study. The completeness of a vessel, which depends on depositional and post-depositional events, appears similar in artifacts involved in the same processes. In this research, the index was based on the percentage of preserved rim or base. From this type of analysis, a higher incidence of records characterized by a completeness index between 1-25% and an increase in intact or almost intact materials (with an index between 76-100%) is observed in alluvial deposits. These results can be attributed to the greater violence and speed of depositional phenomena (i.e., alluvial flood flows) that overwhelmed the ceramic assemblages in primary and, sometimes, secondary deposition (more fragmented) to form new concentrations in the recovery archaeological units.

The fragmentation index, although largely influenced by the physical characteristics of the fabric (Ceci, Santangeli Valenzani 2016, 20-21), was calculated by taking into consideration not the weight of the artifacts

[4] The huge amount of ceramic materials made it necessary to analyze just a selection of the assemblages; for this reason, the findings deriving from the archaeological units of phases 1 to 7 have been chosen.

Deposits	Volume	N. Fragments	Mean of the completeness index	Alluvial magnitude index
Phase 1	131,660 m^3	155	42,5	3097,88235
Phase 2	150, 710 m^3	1252	38,13	3952,53082
Phase 3	2,770 m^3	3207	62,77	44,1293612
Phase 4	7,830 m^3	1441	41,7	187,769784
Phase 5	13,280 m^3	1066	37,59	353,285448
Phase 6	16,429 m^3	356	37,53	437,516653
Phase 7	43,850 m^3	609	32,94	1331,20826

Tab. 2 – The reconstruction of the alluvial magnitude index calculated on the ratio between the volume of the deposits (expressed in cubic meters) and the mean of the completeness index.

but rather the number of fragments (N. Fr.) and the quantity of represented vessels (MNI) within each phase. The fragmentation index proves to be particularly high during phases associated with alluvial floods even if it is greatly influenced by post-depositional, excavation and post-excavation events. These analytical approaches have also contributed to estimating the magnitude of the alluvial flows, understood as the potential energy required for the formation of the artifact dispersal areas.

With this is mind, firstly, the volume of each analyzed phase was reconstructed. Secondly, the ratio between the volume of the phases (expressed in cubic meters) and the mean of the completeness index allowed for the reconstruction of the alluvial magnitude (Tab. 2). Specifically, phase 2 (alluvial deposit of the wreckage of Ship D) presents a high-impact event characterized by considerable kinetic energy, capable of uniformly removing numerous ceramic assemblages (as evidenced by the discovery of 1252 ceramic fragments) and channeling a significant amount of clayey-sandy material into Area 5 deposit. Moreover, this phase is associated with the sinking and overturning of Ship D, a vessel of considerable size. The previous alluvial floods (associated with phases 3 to 5) are marked by less substantial and impactful deposits compared to those recorded for the phase 2. Considering the ratio between volume and completeness index of ceramic materials, it is possible to hypothesize that for these flows, an energy expenditure 20 times less than that used by the depositional event of phase 2 was involved. Therefore, a hydrogeological regime characterized by medium-intensity flooding events can be hypothesized for phases 3 to 5.

During the cataloging step of the pottery, the types of surface appearance were recorded, identifying visible evidence with the naked eye, such as the presence of organic residues, traces of combustion, mortar concretions and so on. This analytical approach allowed the identification, as far as is possible, of the original provenance deposit of the finds, characterized by a wide range of entries into archaeological deposition. This is the case of some bricks with signs of burning, also found in other areas of the archaeological site, attributable both to hearths for cooking on boats and to a phenomenon of dumping fragmented and unusable material (Camilli *et al*. 2006, 33, 50). The Area 5 deposits have yielded various kinds of production waste (34 fragments), especially over-fired or under-fired bricks (22 specimens), suggesting a production area nearby. Furthermore, the presence of different kilns could also be indicated by a brick fragment with traces of glass and a spacer. In both cases, it is presumed that they come from production workshops believed to have been in operation between the 2nd and 3rd centuries AD (Remotti 2012, 25). Moreover, the proximity to a watercourse may have favored the presence of one or more manufacturing facilities, enabled both by the availability of raw materials (in this case, water supply and the availability of clay banks) and by the long and medium-distance dissemination of products.

3.4 *Chronological quantifications*

A detailed analysis of quantitative data from a diachronic perspective has provided interesting insights into understanding the morphogenetic dynamics that contributed to the formation of archaeological deposits. The chronological heterogeneity of ceramic classes has led to the adoption of a quantification system capable of presenting a non-flattened temporal image and, more importantly, useful for detecting the chronological distribution of artifacts within the layer (Ferrarese Lupi, Lella 2013). The most suitable chronological quantification method for the case study seemed to be that employing the sum of weighted averages (Terrenato, Ricci 1998, 92-94; Ceci, Santangeli Valenzani 2016, 74-76), applied both to the entirety of the ceramic records and relatively to the MNI derived from the archaeological unit of each phase. This method has provided an interesting chronological overview of the entire depositional history related to Area 5, but at the same time, it has allowed the dating of other 'phanto' activities: events not reported in the examined stratigraphy but documented in other sectors of the archaeological site.

The most noteworthy result is the redating to the second half of the 5th century AD of the alluvial flood that caused the wrecking of Ship D (Phase 2, Fig. 4). This event had been assigned to the mid-6th century AD within Phase XII of the entire archaeological site (Martinelli, Pignatelli 2008; Camilli 2012, 17), although in a previous research work, older chronological values (the early 5th century AD) had been proposed, partly on the basis of radiocarbon dating (Mariotti Lippi *et al.* 2007). The alluvial flood flows of the 4th century AD (Phase 3-4) do not have parallels in the general periodization of the San Rossore area, which during this period seems to have been experiencing a «relatively calm» period, although it is specified that «the entire excavation area is currently completely devoid of data» (Camilli 2012, 17). However, the recognized flood is confirmed in the unpublished excavation

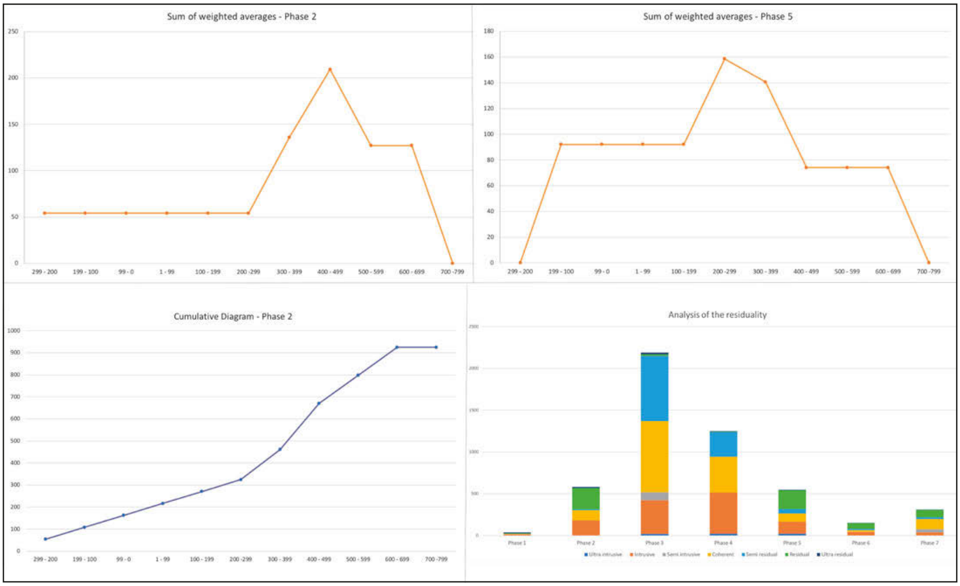

Fig. 4 – Chronological quantifications: sum of the weighted averages, cumulative diagram, analysis of residuality (elab. by P. Rosati, T. Tescione).

reports of Area 5, where an alluvial event is identified in the mid-4th century AD. The wreck of Ship I (mid-3rd century AD, Phase 5, Fig. 4) has affinities with Phase VII of the general periodization of the archaeological site, assigned to 250-280 AD (Camilli 2012, 16).

Another means of chronological analysis was the cumulative diagram, in which each century has a value equal to its own score, always in percentage of finds, added to that of the previous centuries. The resulting saturation curves appear 'steeper' in situations of heavy accumulation, while they have a flatter trend in periods characterized by a low input of material (Ceci, Santangeli Valenzani 2016, 83). In this case as well, it was possible to define periods with higher ceramic accumulation as the result of catastrophic events. The accumulation of 5th century AD ceramic materials in the Phase 2 deposition could be relevant to the presence of a major alluvial event in the fluvial history of San Rossore. The chronological quantification was completed by comparing the trend lines of the chronologically coherent materials with those of all other ceramic assemblage (residual or intrusive) to define the area of residuality (Ceci, Santangeli Valenzani 2016, 83). It was necessary to establish a margin of error associated with the calculation of the 'average' dating by subtracting the mean value from the maximum and minimum chronological range of the entire ceramic assemblage. The analysis of the residual records allowed the restitution of the overall values of chronologically coherent materials, and those which are residual and intrusive. This facilitates, firstly, the reconstruction of the formation processes of the deposits as related to individual phases and, secondly, the definition of the chrono-typological associations of ceramic assemblages. Graphs (Fig. 4) related to moments of fluvial stasis (Phases 1-6) show low indices of residuality and intrusivity, indicative of limited erosive processes. In diagrams related to alluvial deposits (Phases 2 to 5), there is an increase in the indices of residuality and intrusivity, confirming the different morphogenetic process of the deposits compared to those of fluvial stasis.

3.5 *Intra site spatial analysis*

This part of the research program focused on the hypothetical reconstruction of the origins of the deposits' materials, their arrival influenced by the interaction of natural factors (alluvial flows, river currents) and human activities (navigation and trade). There is still a clear difficulty in recognizing which artifacts were part of a commercial cargo, intentionally thrown or accidentally fallen on the riverbed, and which formed part of onboard equipment, or are attributable to contexts adjacent to the shoreline.

The considerable number of archaeological finds required the creation of a digital catalog, done by developing a relational database (using FileMaker software) with separate tables for different categories of data. The data from the 'Materials' table of the database was converted into a Microsoft Excel worksheet to be integrated into the GIS platform (within the PostgreSQL software). The table of records and the shapefile containing the limits of the Archaeological Unit were related by linking ceramic artifacts to the respective stratigraphic unit. Within the 'spatial' database, a new ID_T field was created and the ceramic records were associated with it through a join association. Additionally, each artifact corresponds to an attribute table, with a progressive ID field from 1 to n (based on the number of materials for each US). The quantity and morpho-typological complexity of the cataloged ceramic context made it impractical to consider individual georeferenced fragments. As a result, due to the small number (a total of 289 artifacts) and limited typological-functionality variety (mostly transport containers), this type of archaeological record was not very representative of the analyzed ceramic sample.

To visualize the concentration of the recorded finds within the phases analyzed, a statistical approach was adopted using a tool integrated into the QGIS software called Random Points Inside Polygons (Variable) for a randomized representation of artifacts. In addition, two graphic solutions were adopted for the representation of artifact dispersal areas: point spatial analysis maps and heatmaps. In both graphs, for example, the concentration in the alluvial deposits associated with the sinking of Ship D (Phase 2, Fig. 5) appeared highly significant, visible on the N and NE sides of the wreck. In this case, it seems possible that the alluvial flow encountered two obstacles in its path, represented by the N limit of the river channel bank (presumably not far away) and the NE boundary of the ship, generating a backflow. The latter may have eroded previous ceramic contexts, accumulating material in more recently formed deposits. Moreover, there is a clear ceramic concentration in this case, consisting of 715 MNI and 1560 fragments, a significantly higher quantity than observed for the other deposit related to a period of a river calm (Phase 1-6).

Some of the most effective graphical representations have used artifact distributions based on membership classes for the different phases recognized. The composition of these ceramic assemblages has been influenced by the different alluvial dynamics that led to the formation processes of the deposition and the post-depositional events. For example, in Phase 4 (alluvial deposit, Fig. 6), accumulations of amphorae are evident in the N and NW sectors outside the space occupied by the wrecks. This concentration can be attributed to alluvial flows including material previously deposited in the interior space of Boat I (Phase 5), channeling part of its cargo and other associated archaeological material outside. The presence of amphorae and other tradeable pottery (Phase 5, Fig. 6) might suggest that, after the sinking of the Boat I, the alluvial flood flow caused the dispersal of some materials, likely present inside the vessel, towards the NW side and the exterior space behind the stern.

Another analytical approach used the graphical representation of ceramic material related to the chrono-typological variables identified within individual phases. This method allowed us to highlight both ceramic clusters contemporaneous with the formation of the deposit and those which were intrusive or residual, channeled into recovering contexts by alluvial flood flows within the same phase. For example, the ceramic deposits of Phase 2 (Fig. 7) show a concentration of residual materials inside or outside Ship D, with a significant trend from N-NW to SE, a typical orientation of alluvial flows. The chronologically coherent materials (AD 300-500, Fig. 7) tend to be dispersed outside the ship; it is conceivable that the alluvial flow, documented in this phase, caused the scattering of artifacts contemporaneous with the deposition of Shipwreck D. In Phase 2 (alluvial deposits), the late Roman period materials show a greater variety of typology and function, which could indicate that the alluvial flow brought down not only tradeable material but also other ceramic contexts, probably related to the use of the harbor or belonging to commercial-residential units not far from the river channel.

The various alluvial dynamics identified in the stratigraphic sequence of Area 5 have influenced the formation of contexts and had an effect on some

Fig. 5 – Dispersal area of ceramic assemblage (based on the MNI) from the deposits of Phase 2: heatmap and point spatial analysis map (elab. by P. Rosati, T. Tescione).

Fig. 6 – Map with ceramic distributions based on membership classes (Phase 4 and 5) (elab. by P. Rosati, T. Tescione).

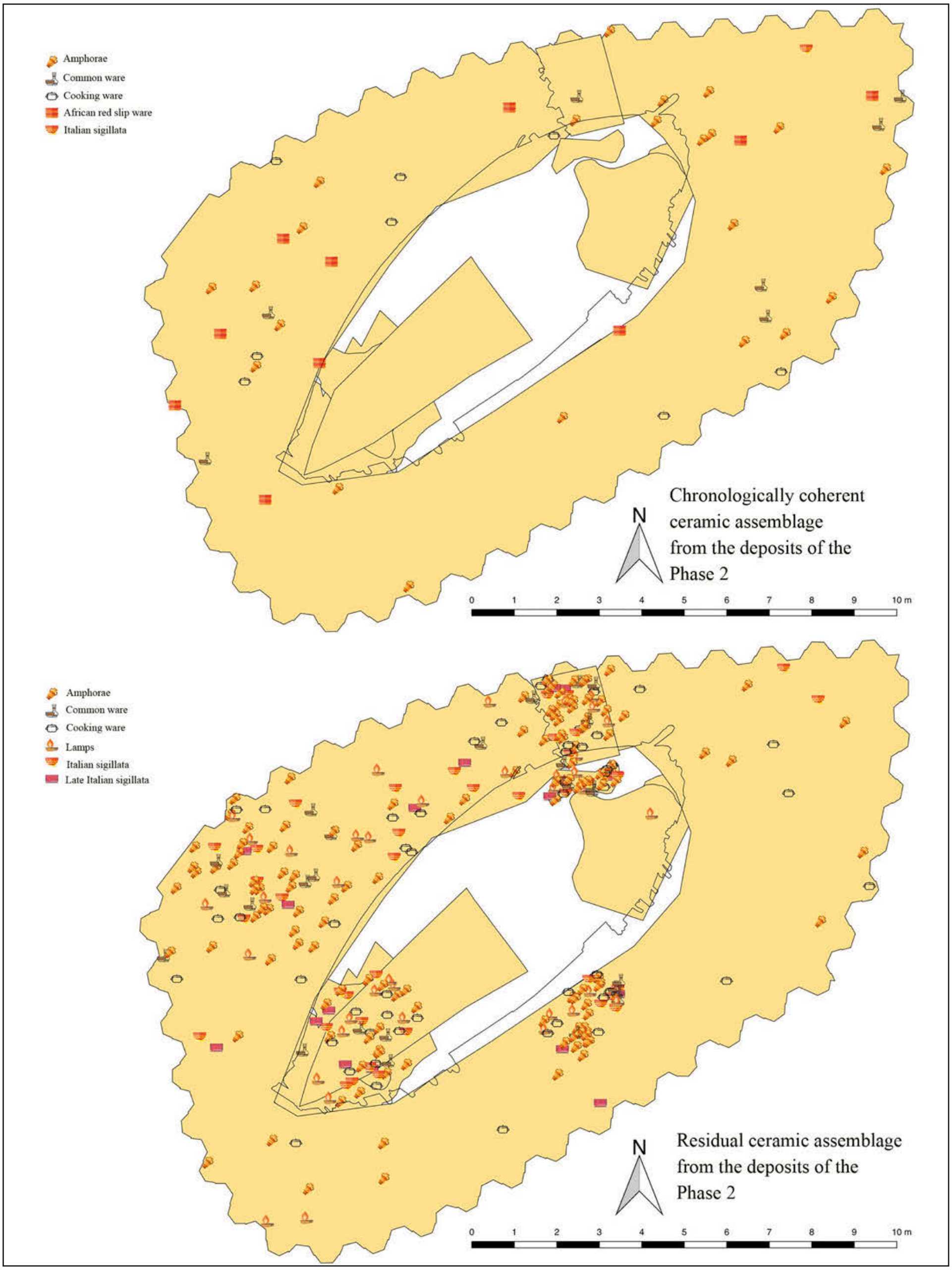

Fig. 7 – Map with ceramic distributions based on chronologically coherent and residual material (Phase 2) (elab. by P. Rosati, T. Tescione).

intrinsic characteristics of the ceramic, such as the completeness index. We have generated thematic plans showing the dispersion of artifacts with different completeness indices, recorded during the cataloguing process for some ceramic classes (preserving rims and bases). The results related to deposits linked to the wreckage of Ship D and Boat I are particularly interesting. In the map of Phase 2 (alluvial deposits and sinking of Ship D), accumulations of materials with a high completeness index are evident to the NE of Ship D (Fig. 8).

A detailed chrono-typological analysis of the materials resulting from this concentration reveals that only 33% of the artifacts are contemporaneous with the formation of the deposit in the 4th-5th centuries AD. The higher percentage of intact artifacts appears to be residual compared to the genesis of the Phase 2 deposition. This confirms that this accumulation is related to a backflow that impacted (naval?) deposits of earlier formation, channeled into the recovering deposition due to a high-magnitude event (Phase 2). The analysis of Phase 5 (alluvial deposit and sinking of Boat I) highlights a ceramic assemblage characterized by high completeness indices inside the wreck (Fig. 8). The high completeness indices associated with these ceramic assemblages, characterized by a certain functional uniformity (amphorae) and chronological differences (containers from the late high-medium and late Imperial periods), suggest that the alluvial flood flow (Phase 5), in addition to sweeping over Boat I, impacted deposits of earlier formation, characterized by the presence of tradeable material, channeling them into the Area 5 deposits.

The analyses presented so far fall within a rather basic function of the GIS platform, allowing the visualization of data recorded in the PostgreSQL database. The second step of the research program concerns the interpolation of data with descriptive-statistical procedures. Here, the Triangulated Irregular Networks (TIN) method was adopted (Lim, Pilesjö 2022), based on irregularly sampled data represented according to Delaunay Triangulation (Tsai 1993; Semeraro *et al.* 2012; see Ducke, Suchowska 2021, p. 521 for other bibliographic references). The system, based on a vector-type structure composed of triangular datasets (Campana, Forte 2003), is used in environmental archaeology for building predictive models (Vogelsang, Wendt 2018) and applied to river graphical rendering (Marozas, Zack 1990; Clevis *et al.* 2006).

Unlike other types of analytical procedures, TIN are applicable in situations like this case study, where both the sampling of data and the scattering of records are irregular. Each triangle is defined on a map using grid nodes derived from a GIS statistical procedure. The apices of the triangles form nodes which indicate the direction of flow. Circulation is marked by the colour-coding, with red indicating a blockage. The circulation index produced represents the scale of the impact of the alluvial flood flow on the ceramic assemblages. This type of analysis, graphically rendered using heatmaps,

Fig. 8 – Map with ceramic distributions based on the completeness index (Phase 2 and 5) (elab. by P. Rosati, T. Tescione).

highlights the proximity of the recorded finds to primary deposition contexts or obstacles to the main flow, slowing down the movement of artifacts channeled into Area 5 by the alluvial force. Analyses related to Phase 4 are particularly interesting (Fig. 9), revealing a cluster of ceramic records near Boat I. Considering the distance from potential obstacles (shipwrecks and basin limits), Delaunay triangles could indicate a connection between these finds and the deposition of Boat I. Moreover, Unit 5370, located to the NW of Boat I, yielded 393 NMI, of which 50% consists of pottery from the late 2nd to early 3rd century AD, the date of the shipwreck itself.

The TIN analysis for the ceramic assemblage of Phase 2 (Fig. 10) showed a concentration of artifacts near the external NE side of Ship D. This cluster, especially that of 5th century AD material (Fig. 10), is extremely valuable in reconstructing the ceramic assemblage contemporaneous with the ship's sinking. However, it is difficult to associate these artifacts with the cargo of Ship D if the recent radiometric analyses dating the vessel to the mid-6th century AD are correct (Martinelli, Pignatelli 2008).

4. Concluding remarks

Alluvial archaeology, as an emerging discipline, characterized by a strong interaction between geological and archaeological analysis. The analytical approaches presented have emerged from this interdisciplinary approach. The effectiveness of the various procedures has been tested within a case study of particular significance, namely the archaeological site of the Ancient Shipyard of Pisa-San Rossore.

Ceramic assemblages have been considered as geological clasts, contributing to the definition of the formation processes of the analyzed deposit (in synergy with the results of geomorphological interpretations), the chronological framework of alluvial floods, the dynamics of flows (confirming the data from geological analysis), and, especially, the original deposition of the ceramic assemblage found in secondary deposition. In this regard, the combination of different analytical approaches and digital methods has proven particularly useful, ranging from quantitative analyses for chrono-typological determination of ceramic assemblages to intra-site spatial analyses, which have been effective in defining alluvial flood flows and the ceramic assemblage.

The creation of a 'stratigraphic information system' through the use of a GIS platform has facilitated the reconstruction of the formation processes within the stratigraphic sequences. The quantitative and qualitative analyses of the ceramic assemblages have made it possible to clarify the depositional and post-depositional process dynamics. The results of the chronological analyses have made a useful contribution to the discussion of the problem relating to the original provenance contexts of the residual and intrusive artefacts.

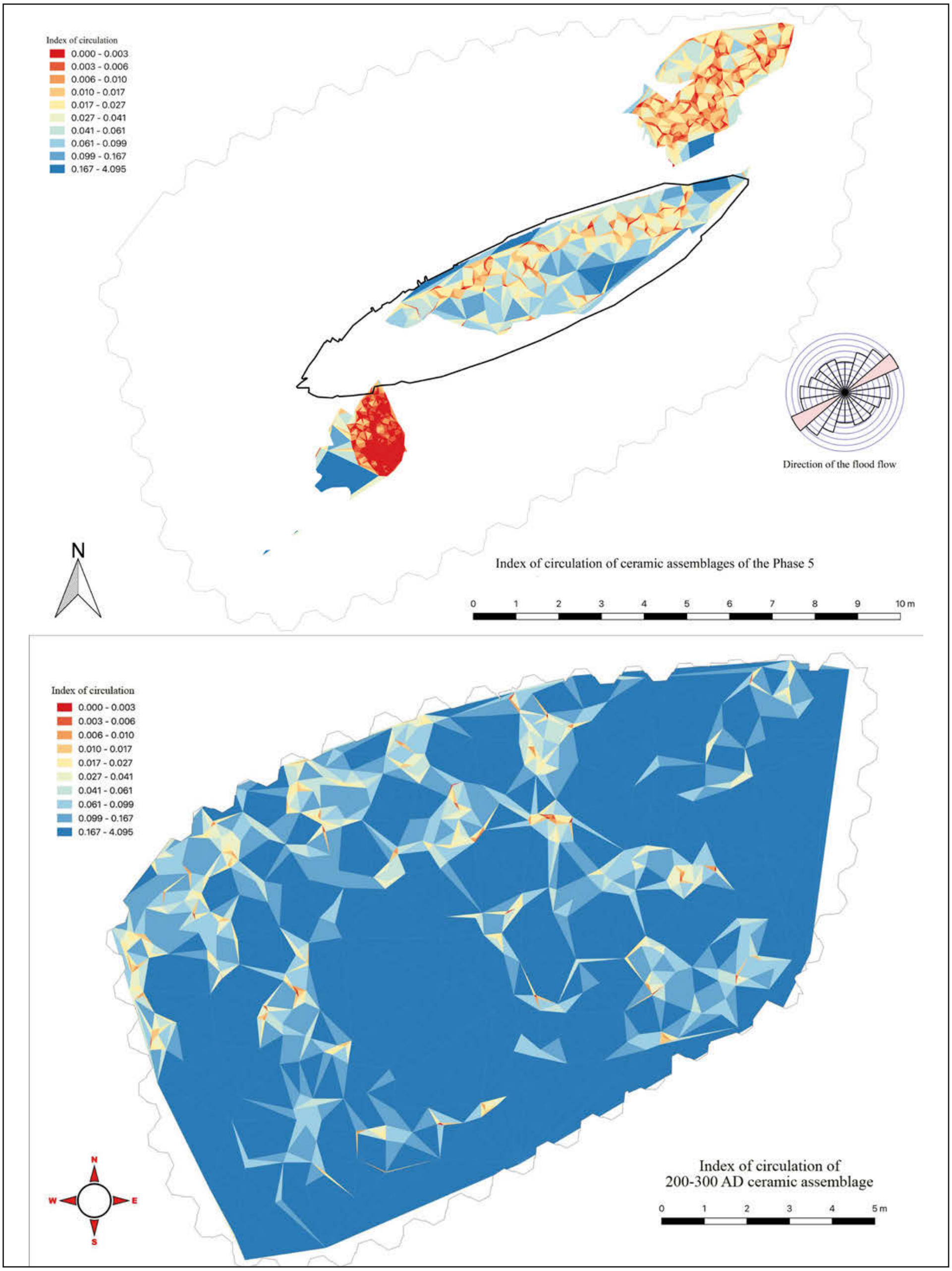

Fig. 9 – Map with ceramic distributions represented according to Triangulated Irregular Networks (TIN) (Phase 5 and 3rd century AD ceramic assemblage) (elab. by P. Rosati, T. Tescione).

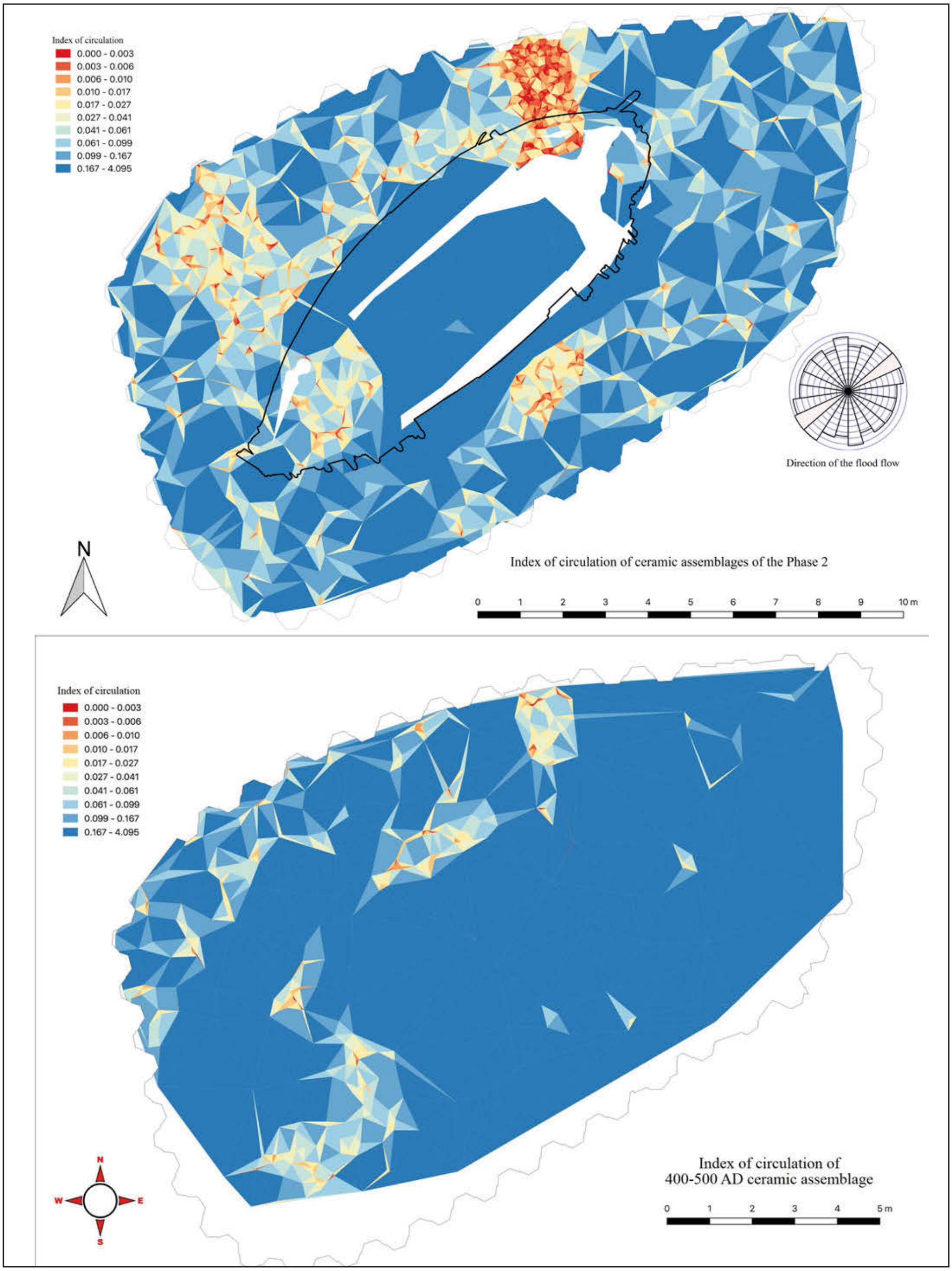

Fig. 10 – Map with ceramic distributions represented according to Triangulated Irregular Networks (TIN) (Phase 2 and 5th century AD ceramic assemblage) (elab. by P. Rosati, T. Tescione).

The subsequent definition of the chrono-typological differences within the ceramic material, established through the elaboration of thematic plans, allowed the recognition of the dispersal area and finds concentrations, highlighting the hypothetical flow directions (useful for hypotheses on the reconstruction of primary deposits placement of residual or intrusive finds). Finally, the data obtained proved to be a useful contribution to the overall reconstruction of the hydrogeological processes making it possible not only to understand the depositional dynamics, but also to reconstruct the recurrence and magnitude of flood events. The proposed methodology explored so far is intended to represent only a part of the path towards the development of a convincing analysis of ceramic assemblages deriving from alluvial floods, with its potential to contribute significantly to the understanding of ancient landscapes and settlements.

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REFERENCES

Adroher A.M., Carreras C., Almeida R., Fernández A., Molina J., Viegas C. 2016, *Registro para la cuantificación de cerámica arqueológica: estado de la cuestión y una nueva propuesta. Protocolo de Sevilla (PRCS/14)*, «Zephyrus», 58 (julio-diciembre), 87-110 (https://doi.org/10.14201/zephyrus20167887110).

Arcelin P., Truffeau-Libre M. (eds.) 1998, *La quantification des céramiques: conditions et protocole. Actes de la table ronde du Centre archéologique européen du Mont-Beuvray (Glux-en-Glenne 1998)*, Glux-en-Glenne, Bibracte.

Benvenuti M., Mariotti-Lippi M., Pallecchi P., Sagri M. 2006, *Late-Holocene catastrophic floods in the terminal Arno River (Pisa, Central Italy) from the story of a Roman riverine harbour*, «The Holocene», 16, 6, 863-876 (https://journals.sagepub.com/doi/10.1191/0959683606hl978rp).

Brown A.G. 1997, *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change*, Cambridge, Cambridge University Press.

Brown A.G., Ellis C. 1995, *People, climate and alluviation. Theory, research design and new sedimentological and stratigraphic data from Etruria*, «Papers of the British School at Rome», 63, 45-73.

Camilli A. 2012, *Ambiente, rinvenimenti e sequenza. Un breve riassunto aggiornato dello scavo delle navi*, in Remotti 2012, 13-18.

Camilli A., De Laurenzi A., Setari E. 2006, *Alkedo. Navi e commerci della Pisa romana*, Catalogo della mostra, Pontedera, Bandecchi&Vivaldi.

Camilli A., Puma P., Remotti E. 2009, *Dismounting, conserving, displaying ships. The MNAP-Museo delle Navi Antiche di Pisa and the activity of Centro di Restauro del Legno Bagnato di Pisa*, in S. Bertocci, S. Parrinello (eds.), *Wooden Architecture in Karelia, Tiber Architecture as a Phenomen of National Culture*, II, Firenze, Edifir, 270-277.

Camilli A., Remotti E., Pallecchi P. 2005, *Stratigrafia fluviale, portuale e terrestre: la sequenza dello scavo delle navi di Pisa, S. Rossore*, in B.M. Giannattasio, C. Canepa, L. Grassi, E. Piccardi (eds.), Aequora, pontos, jam, mare...*Mare, uomini e merci nel Mediterraneo antico*, *Atti del Convegno internazionale (Genova 2004)*, Firenze, All'Insegna del Giglio, 74-86.

Camilli A., Setari E. 2005, *Le navi antiche di Pisa. Guida archeologica*, Milano, Mondadori Electa.

Campaña Lozano I., Benito-Calvo A., Pérez-González A., Ortega Martínez A.I., Bermúdez de Castro J.M., Carbonell E. 2016, *Using 3D models to analyse stratigraphic and sedimentological contexts in archaeo-palaeo-anthropological Pleistocene sites (Gran Dolina Site, Sierra De Atapuerca)*, in S. Campana, R. Scopigno, G. Carpentiero, M. Cirillo (eds.), *CAA 2015, Keep the Revolution Going*, *Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology (Siena 2015)*, Oxford, Archaeopress, 337-345.

Campana S., Forte M. 2003, *Remote Sensing in Archaeology*, *XI ciclo di lezioni sulla ricerca applicata in archeologia (Certosa di Pontignano 1999)*, Firenze, All'Insegna del Giglio.

Ceci M., Santangeli Valenzani R. 2016, *La ceramica nello scavo archeologico: analisi, quantificazione e interpretazione*, Roma, Carocci Editore.

Cicala L., Tescione T. 2022, *Velia. Fenomeni alluvionali e trasformazioni dell'abitato*, in M. Cipriani, E. Greco, A. Salzano (eds.), *Dialoghi sull'archeologia della Magna Grecia e del Mediterraneo (V edizione). Catastrofi, distruzioni, storia*, *Atti del V Convegno internazionale di Studi (2020)*, Paestum, Pandemos, 117-128.

Clevis Q., Tucker G.E., Lancaster S.T., Desitter A., Gasparini N., Lock G. 2006, *A simple algorithm for the mapping of TIN data onto a static grid: Applied to the stratigraphic simulation of river meander deposits*, «Computers & Geosciences», 32, 749-766 (https://doi:10.1016/j.cageo.2005.05.012).

Desachy B. 2008, *De la formalisation du traitement des données stratigraphiques en archéologie de terrain*, Thèse, Université de Paris 1 Panthéon-Sorbonne, École doctorale d'Archéologie, Anthropologie, Ethnologie, Préhistoire.

De Simone G.F., Martucci C.S., Boemio G., D'Italia S. 2015, *Pottery as a proxy indicator for diet change in Late Antique Campania*, in R. Gül Gürtekin-Demir, H. Cevizoğlu, Y. Polat, G. Polat (eds.), *Keramos, Ceramics: A Cultural Approach*, *Proceedings of the First International Conference at Ege University (Izmir 2011)*, Kızılay-Ankara, Bilgin Kültür Sanat Yayınları, 218-228.

Ducke B., Suchowska P. 2021, *Exploratory network reconstruction with sparse archaeological data and XTENT*, «Journal of Archaeological Method and Theory», 29, 508-539 (https://doi.org/10.1007/s10816-021-09529-3).

Ferrarese Lupi A., Lella P. 2013, *Gaussian curves for visualizing chronological patterns of ceramic finds and residuality*, «Archaeometry», 55, 2, 296-311 (https://doi.org/10.1111/j.1475-4754.2012.00680.x).

Lim J., Pilesjö P. 2022, *Triangulated Irregular Network (TIN) models*, in J.P. Wilson (ed.), *The Geographic Information Science & Technology Body of Knowledge* (https://doi.org/10.22224/gistbok/2022.2.7).

Mariotti Lippi M., Bellini C., Trinci C., Benvenuti M., Pallecchi P., Sagri M. 2007, *Pollen analysis of the ship site of Pisa San Rossore, Tuscany, Italy: The implications for catastrophic hydrological events and climatic change during the late Holocene*, «Vegetation History and Archaeobotany», 16, 453-465 (https://doi.org/10.1007/s00334-006-0070-x).

Marozas B.A., Zack J.A. 1990, *GIS and archaeological site location*, in K.M.S. Allen, S.W. Green, E.B.W. Zubrow (eds.), *Interpreting Space: GIS and Archaeology*, London, CRC Press, 165-172.

Martinelli N., Pignatelli O. 2008, *Datazione assoluta di alcuni relitti dal contesto delle navi di Pisa. Risultati preliminari delle indagini dendrocronologiche e radiometriche col* ^{14}C, «Gradus», 3, 2, 69-78.

Mayoral V., Borja Barrera F, Borja Barrera C., Martínez del Pozo J.A., de Tena M. 2012, *The evolution of an agrarian landscape. Methodological proposals for the archaeological study of the alluvial plain of Medellin (Guadiana basin, Spain)*, in S.J. Kluiving, E.B. Guttmann-Bond (eds.), *Landscape Archaeology between Art and Science. From a Multi- to Interdisciplinary Approach*, Amsterdam, Amsterdam University Press, 97-114.

Orton C.R. 1993, *How many pots make five? An historical review of pottery quantification*, «Archaeometry», 35, 2, 169-184.

Orton C., Tyers P., Vince A.G. 1993, *Pottery in Archaeology*, Cambridge, Cambridge University Press.

Pace G. 2020, *ll cantiere delle navi antiche di Pisa San Rossore: importazioni ed esportazioni nel commercio del Mediterraneo. Il contesto di età repubblicana*, Tesi di dottorato, Università di Pisa.

Raux S. 1998, *Méthodes de quantification du mobilier céramique: état de la question et pistes de réflexion*, in Arcelin, Truffeau-Libre 1998, 11-16.

Remotti E. (eds.) 2012, *Il bagaglio di un marinaio*, Roma, Aracne Editrice.

Semeraro G. 2008, *'Accedere' allo scavo archeologico. Sistemi (e problemi) di elaborazione dei dati*, in G. De Felice, M.G. Sibilano, G. Volpe (eds.), *L'informatica e il metodo della stratigrafia*, *Atti del Workshop (Foggia 2008)*, Bari, Edipuglia, 39-54.

Semeraro G. 2011, *Banche dati, GIS e Web GIS: breve storia delle tecnologie applicate ai beni archeologici nel Laboratorio di Informatica per l'Archeologia dell'Università di Salento*, «Scires-IT» 1, 1, 125-144 (http://dx.doi.org/10.2423/i22394303v1n1p125).

Semeraro G., Pecere B., Mianulli A. 2012, *Applicazioni GIS alla ricerca archeologica: il santuario di Tag Silg a Malta*, «Scires-IT», 2, 1, 83-104 (https://dx.doi.org/http://dx.doi.org/10.2423/i22394303v2n1p83).

Terrenato N., Ricci G. 1998, *I residui nella stratificazione urbana. Metodi di quantificazione e implicazioni per l'interpretazione delle sequenze: un caso studio dalle pendici settentrionali del Palatino*, in F. Guidobaldi, C. Pavolini, P. Pergola (eds.), *I materiali residui nello scavo archeologico*, Testi preliminari e Atti della tavola rotonda (Roma 1995), Roma, Collection de l'École Française de Rome 149, 89-104.

Tescione T. 2019, *L'archeologia delle alluvioni: problemi di analisi dei contesti ceramici. Un caso di studio dal Cantiere delle Navi Antiche di Pisa-San Rossore*, Tesi di dottorato, Università degli studi di Napoli Federico II.

Tsai V.J.D. 1993*, Fast topological construction of Delaunay triangulations and voronoi diagrams*, «Computers and Geosciences», 19, 10, 1463-1474 (https://doi.org/10.1016/00983004(93)90062-A).

Vogelsang R., Wendt K.P. 2018, *Reconstructing prehistoric settlement models and land use patterns on Mt. Damota/SW Ethiopia*, «Quaternary International», 48, 140-149 (http://dx.doi.org/10.1016/j.quaint.2017.06.061).

ABSTRACT

This paper aims to present analytical approaches and digital methods for the analysis of ceramic assemblages resulting from catastrophic alluvial flood flows. The study has been developed based on the principles of 'alluvial archaeology', a recently-developed field of archaeology. In this research program, ceramic records have been treated on a par with clasts in the geomorphological analyses of alluvial sediments. To test the different analytical procedures the 'Ancient Shipyard' of Pisa-San Rossore has been selected as a case study. This archaeological site represents a river channel, affected by several alluvial flood events. The analysis achieved several objectives, including the definition of the formation processes of the deposition (in synergy with the results of geomorphological data), the chronological framework of alluvial floods, the dynamics of flows, and locating the original deposition of the ceramic assemblage. In this regard, the combination of different approaches has proven particularly useful, ranging from computational analyses for chrono-typological determination of ceramic assemblages to intra-site spatial analyses, which have been useful in defining alluvial flood flows and the subsequent movement of ceramic assemblages.