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ORIGINAL PAPER

X-ray computed microtomography of Late Copper Age decorated bowls with cross-shaped foots from central Slovenia and the Trieste Karst (North-Eastern Italy): technology and paste characterisation

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Abstract

About 20 Late Copper Age bowls with cross-shaped foots from Deschmann's pile dwellings (Ljubljansko barje, central Slovenia) and Trieste Karst (North-Eastern Italy) have been investigated using X-ray computed microtomography (microCT) in order to study the vessel-forming technique, to characterise their pastes and to test the hypothesis that some Karst bowls could have been imported from nowadays central Slovenia or even more distant regions. In three selected virtual slices per sample, clay, lithic inclusions and pores have been segmented and quantified. In addition, the area, maximum length and width of each lithic inclusion have been calculated. Then, the microCT-derived results have been statistically analysed by principal component analysis (PCA). The orientation of pores and disjunctions in microCT volumes show that the basins of the bowls were built using mainly the coiling technique, while the base was shaped starting from a central piece, to which a layer of clay was added and then reshaped in order to produce the foots. The Slovenian bowls include both medium/coarse-grained and very fine- or fine-grained vessels mainly tempered with carbonate inclusions. The pastes of the Karst bowls are considerably heterogeneous. One bowl was most likely imported to the Karst but not from central Slovenia as it shows peculiar components, shape and decoration. The other two imported vessels show a very fine-grained paste comparable to the one of several samples from Deschmann's pile dwellings. Such technological similarity is confirmed by PCA of microCT data and petrographic observations. Our study confirms the existence of strong cultural connections between central Slovenia and the northernmost Adriatic coast during the Late Copper Age.

Keywords Late Copper Age decorated bowls · Central Slovenia · Trieste Karst (North-Eastern Italy) · X-ray computed microtomography · PCA of microCT-derived data · Technology · Paste characterisation

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Introduction

The three Deschmann's pile dwellings (*slo. Dežmanova kolišča*), located near Ig in the Ljubljansko barje (central Slovenia), are one of the main third millennium BC archaeological evidence in the south-eastern Alpine region (Fig. 1). In 2011, they were inscribed on the World Heritage List of UNESCO in the transnational serial property *prehistoric pile dwellings around the Alps*. The well-preserved ceramic finds from these sites have been included in various typo-chronological analyses to define the cultural development in this area during the Late Copper and Early Bronze ages (e.g. Dimitrijević 1956, 1966, 1979; Korošec 1958–1959; Bóna 1965; Ecsedy 1977; Parzinger 1984; Govedarica 1989; Maran 1998; Leghissa 2017). According to the latest typological analyses and a few absolute dates (Leghissa 2017, 2018), two main phases have been identified in Deschmann's pile dwellings. The oldest one (twenty-eighth–twenty-sixth century BC) is mainly characterised by pottery typical of the Late Copper Age Vučedol culture, widespread from the Balkans to south-eastern Central Europe, and pottery pointing to connections with other cultures, located especially in Central Europe. The younger phase (twenty-sixth century BC to twenty-fifth century BC) is defined by finds of the Ljubljana culture that has developed under the influences of Corded Ware (and Globular Amphora) as well as Somogyvár-Vinkovci and Bell Beaker cultures.

The Ljubljana culture is mostly attested in Deschmann's pile dwellings, but some typical elements are present also in many caves of the Trieste Karst (North-Eastern Italy; Fig. 1) and eastern Adriatic coast (Montagnari Kokelj 1981; Govedarica 1989; Gilli and Montagnari Kokelj 1993, 1994, 1996; Montagnari Kokelj and Crismani 1997; Montagnari Kokelj et al. 2002; Leghissa 2017, Fig. 181). Contacts between the two areas investigated in this contribution are already attested during the oldest phase of Deschmann's pile dwellings, but they undoubtedly increased during the development and spread of the Ljubljana culture (see Leghissa 2017 and the literature quoted there).

Decorated bowls with cross-shaped foots are reported from central Slovenia and the Trieste Karst. This type of vessel is common in the Vučedol culture, spread from the Balkans to

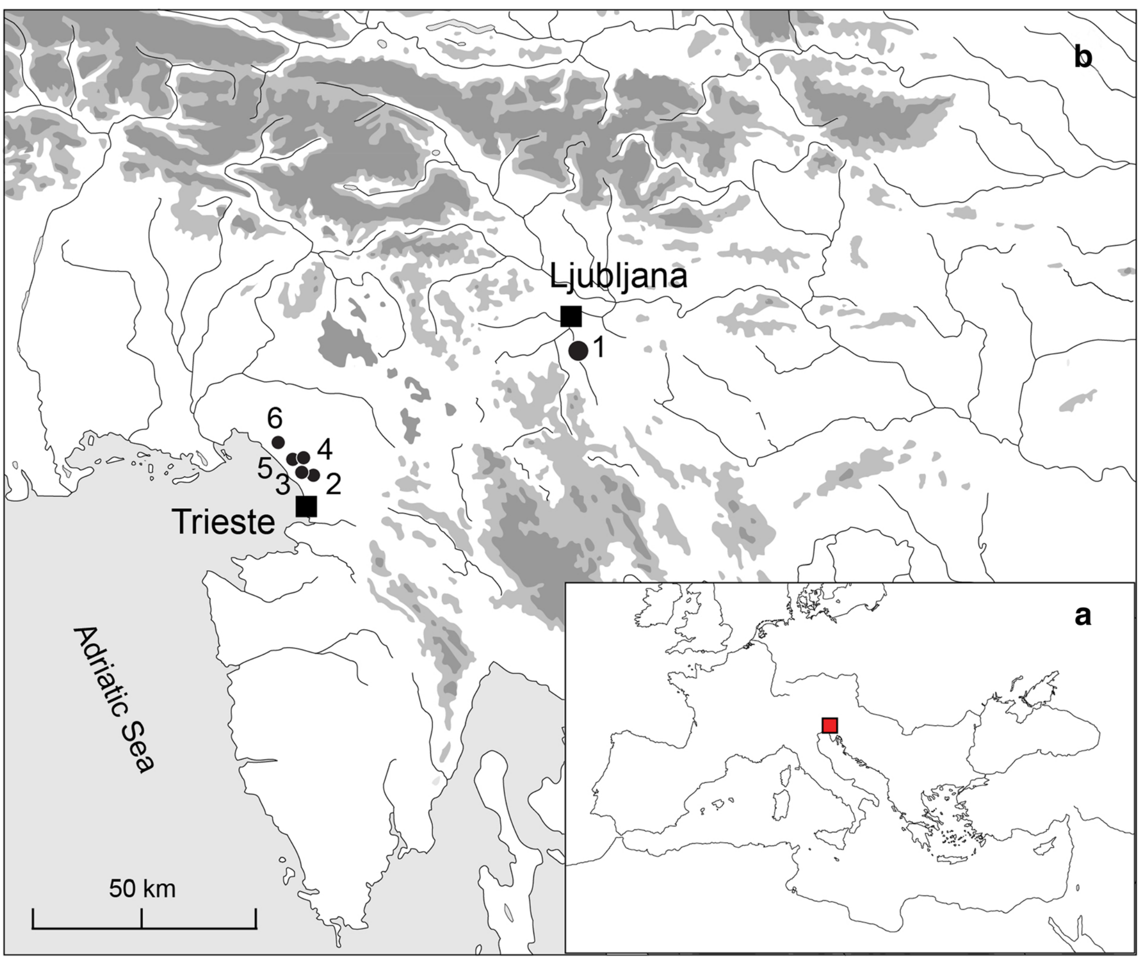

Fig. 1 Position of the archaeological sites where the investigated bowls have been discovered. 1, Deschmann's pile dwellings (Slovenia); 2, Ciclami cave; 3, Zingari cave; 4, Cotariova cave; 5, Pettine cave; 6, Edera cave. All cave sites are located in the Trieste Karst

south-eastern Central Europe, but it is also reported in other contemporaneous cultures in Central Europe. In Deschmann's pile dwellings, where this type is abundant, several variants are known, while only a few bowls were discovered in Trieste Karst. Despite the small number, the latter are heterogeneous as to shape and decoration.

Most of the known bowls from the Trieste Karst and a selection of bowls from Deschmann's pile dwellings (Fig. 1) have been studied using X-ray computed microtomography (hereinafter microCT) to define their production technology and to characterise their pastes. MicroCT has already been applied to the study of ancient pottery providing information about vessel-forming techniques and provenance (Kahl and Ramminger 2012; Bernardini et al. 2013, 2015, 2016; Sanger 2016; Machado et al. 2017). When the artefacts under consideration cannot be sampled, such as in our case, microCT is a precious tool to perform fabric characterisation of pottery, allowing the visualisation and quantification of lithic inclusions, clay matrix, pores and disjunctures generally related to firing shrinkage, loss of organic temper or the result of how the vessels were shaped into their final form (Bernardini et al. 2016).

We applied a similar approach to study the Copper Age bowls from Slovenia and the Trieste Karst, and we performed a multivariate statistical analysis of microCT-derived data. The obtained results have been used to discuss the origin of the few vessels found in the Karst area. In fact, they could have been imported to the Karst or they could have been locally produced following a model common in Deschmann's pile dwellings and beyond.

Materials and methods

In the present study, 23 bowls with cross-shaped foots have been studied: 14 from Deschmann's pile dwellings and 9 from five caves of the Trieste Karst (Table 1; Fig. 2). These vessels are among the most abundant ceramic forms in Deschmann's pile dwellings. Most of them can be typologically ascribed to the Vučedol culture phase and just a few ones to the later Ljubljana culture. They are generally richly decorated on the exterior, the interior and the rim with stab-and-drag, simple incised lines or rarely with impressions of cords wrapped around thin plates (i.e. the typical decoration technique of the Ljubljana culture; Leghissa 2015). In the Trieste Karst, a few bowls of this type were found. Despite their small number, they are outstanding for their rich and complex decorations showing incised lines or impressions of a twisted double cord, a technique mainly reported from contemporary Central European cultures (e.g. *Schnurkeramische Kultur* or Corded Ware culture; see Buchvaldek 1967; Furholt 2003).

Macroscopic observation

The surface of all samples has been observed using a stereomicroscope and/or a magnifying glass in order to identify visible lithic grains. Most vessels contain quite abundant limestone/calcite inclusions, while white mica and quartz grains have been recognised in a few bowls (Table 2).

Microfocus X-ray computed tomography

The vessels were imaged by X-ray microCT at the Multidisciplinary Laboratory of the Abdus Salam International Centre for Theoretical Physics (Trieste, Italy), using a system (Tuniz et al. 2013) specifically designed for the study of archaeological and palaeoanthropological materials (e.g. Bernardini et al. 2012, 2016; Tuniz et al. 2012, 2013; Bernardini et al. 2017; Duches et al. 2018).

The microCT acquisitions of most specimens were carried out by using a sealed X-ray source (Hamamatsu L8121-03) at a voltage of 110 kV, at a current of 90 μA and with a focal spot size of 5 μm. A few very dense vessels were analysed using a voltage of 140 kV, a current of 200 μA and a focal spot size of 20 μm. The X-ray beam was filtered by a 0.1-mm-thick copper absorber. A set of 1440 or 1800 projections of the artefacts was recorded over a total scan angle of 360° by a flat panel detector (Hamamatsu C7942SK-25; pixel size of 50 μm). The resulting microCT slices were reconstructed using the commercial software Digi XCT (Digisens) in 32-bit format and obtaining an isotropic voxel size from about 20 to 40 μm (Table 1).

Most of the samples have been analysed two times with different resolutions. Data sets with a resolution of about 20 μm have been used to perform the segmentation of the paste components, while the data sets with a lower resolution, including the whole vessels or a larger part of them, have been mainly used to study technological production traces.

Segmentations and microCT-derived data analysis

Using Avizo v.8 software, three virtual sections for each sample, taken at the centre and the edges of each data set, have been segmented in order to separate the clay matrix from the lithic temper materials and the pores following a procedure already applied by Bernardini et al. (2016). In the same work, a comparison between results from 2D segmentation of selected slices and 3D segmentation of extracted sub-volumes of archaeological pottery has shown that the much faster 2D segmentation generally gives comparable results (for details, see Bernardini et al. 2016).

After the segmentation process, we have first calculated, using the same software, the total area of clay matrix, pores and lithic inclusions (including both temper material and lithic components within the raw material) for all three virtual

Table 1 List of the studied Copper Age bowls with cross-shaped foots from central Slovenia and the Trieste Karst (North-Eastern Italy)

Inventory number	Site	Cultural attribution	Methods	Voxel size	References
B1482	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	41.01; 81.42	Korošec and Korošec 1969, T. 38: 1a, b; Leghissa 2017, T. 91: 1
B1963	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 43.15	Korošec and Korošec 1969, T. 44: 9a–c; Leghissa 2017, T. 107: 2
B1984	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	39.71	Korošec and Korošec 1969, T. 46: 12; Leghissa 2017, T. 95: 1
B1965	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 44: 11a–c; Leghissa 2017, T. 102: 2
B1939	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 47: 6a, b; Leghissa 2017, T. 93: 2
B1994	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 45: 6a, b; Leghissa 2017, T. 95: 5
B1505	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 42: 3a–c; Leghissa 2017, T. 96: 2
B5009	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 44.68	Korošec and Korošec 1969, T. 40: 4a, b; Leghissa 2017, T. 97: 3
NI19	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 39: 5; Leghissa 2017, T. 97: 4
B1479	Deschmann's pile dwellings	L. b. variant of V. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 40: 2a, b; Leghissa 2017, T. 103: 4
B1972	Deschmann's pile dwellings	L. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 47: 9; Leghissa 2017, T. 104: 3
B1973	Deschmann's pile dwellings	L. c.	μCT	39.71	Korošec and Korošec 1969, T. 49: 4; Leghissa 2017, T. 99: 2
B1490	Deschmann's pile dwellings	L. c.	μCT	21.42; 39.71	Korošec and Korošec 1969, T. 41: 7a, b; Leghissa 2017, T. 41: 7 a, b
B1497	Deschmann's pile dwellings	L. c.	μCT	39.71	Korošec and Korošec 1969, T. 38: 2a, b; Leghissa 2017, T. 109: 3
3469	Zingari cave	Influences of V. c.	μCT	30.95	Gilli and Montagnari Kokelj 1996, Fig. 34: 202
20591	Ciclami cave	Influences of V. c.	μCT	21.42; 42.19	Gilli and Montagnari Kokelj 1993, Fig. 51: 497
20592	Ciclami cave	Influences of V. c.	μCT	21.42; 38.99	Gilli and Montagnari Kokelj 1993, Fig. 37: 355
20419	Cotariova cave	Influences of V. c.	μCT	21.42; 43.33	Montagnari Kokelj et al. 2002, T. 27: 244
139461	Cotariova cave	Influences of V. c.	μCT	21.42	Montagnari Kokelj et al. 2002, T. 27: 245
SN	Cotariova cave	L.c.	μCT	21.42	Montagnari Kokelj et al. 2002, T. 27: 246
139462	Pettine cave	Influences of V. c.	μCT; OM	21.42	Marzolini 1983, Fig. 1: 22, 25
139463	Pettine cave	Influences of V. c.	μCT; OM	21.42	Marzolini 1983, Fig. 1: 11
139464	Edera cave	Influences of V. c.	μCT	21.42	Marzolini 1970, Fig. 2/1

L. b. Ljubljansko barje, *V. c.* Vučedol culture, *L. c.* Ljubljana culture

sections selected for all the artefacts. The ratio between the total areas of different pottery components can give interesting insights on how the paste of the vessels was produced (e.g. Bernardini et al. 2016).

Anyway, samples with a similar lithic inclusion/clay ratio could correspond to quite different pastes: the same ratio could be obtained considering a sample with very rare and big lithic grains or considering a vessel characterised by very abundant and small lithic inclusions. In order to overcome this bias, we have calculated, using Avizo v.8 software, the number, the area, the maximum length and the maximum width of every single lithic inclusion within the three virtual sections selected for all samples. After that, we have summed up the results for each vessel, putting together the data obtained from the segmentation and analysis of the three virtual sections.

To manage the resulting huge amount of data, we have divided our data sets (values for area, maximum length and width of all inclusions) into four intervals using Matlab R2016b.

The size of the intervals has been selected by taking into account minimum and maximum values of each variable and its distribution. This procedure was important to have the best

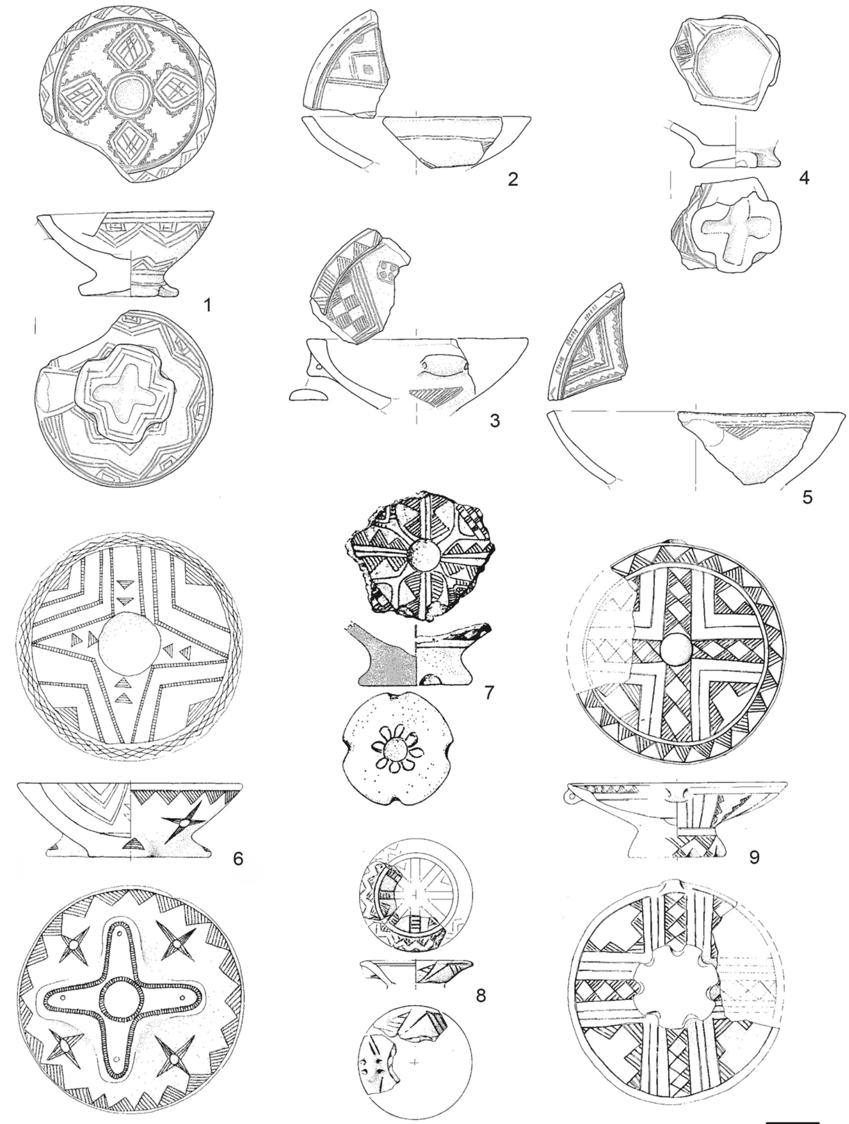

Fig. 2 Drawings of selected Copper Age bowls. 1, Deschmann's pile dwelling B1482; 2, Deschmann's pile dwelling B1984; 3, Deschmann's pile dwelling B1939; 4, Deschmann's pile dwelling B1505; 5, Deschmann's pile dwelling B1963; 6, Ciclami cave 20591; 7, Cotariova cave 20419; 8, Pettine cave 139463; 9, Ciclami cave 20592. Scale bar = 3 cm; for the references, see Table 1

representation of dimensional parameters describing the lithic inclusions within the paste, allowing a good separation between samples showing lithic grains of different sizes. As far as the area is concerned, the minimum value is 458 μm^2, the maximum value is 12,300,000 μm^2 and the intervals have been set as follows: very small inclusions, 0–50,000 μm^2; small inclusions, 50,000–100,000 μm^2; medium inclusions, 100,000–200,000 μm^2; and big inclusions, bigger than 200,000 μm^2. As far as the length is concerned, the minimum value is 29 μm, the maximum value is 5457 μm and the intervals have been set as follows: very small, 0–500 μm; small, 500–1000 μm; medium, 1000–1500 μm; and big, bigger than 1500 μm. As far as the width is concerned, the minimum value is 21 μm, the maximum value is 3653 μm and the intervals have been selected as follows: very small, 0–200 μm; small, 200–300 μm; medium, 300–400 μm; and big, bigger than 400 μm. The percentages of lithic inclusions falling within the defined size intervals have then been calculated.

In order to extract the maximum information possible from the data, principal component analysis (PCA) (e.g. Jolliffe 2002) has been performed using the programming language R (Kassambara 2017) and considering as variables inclusion/clay ratio and percentages of area, maximum length and maximum width. PCA is a multivariate analysis tool to reduce the dimensions of a given data set. It is based on the idea of rotating the original coordinate system to a new one. The direction of the new axes is then chosen to explain the maximum variance within the data set.

Optical microscopy

Small samples have been extracted from the two fragmented bowls of Pettine cave (139462, 139463) located in the Trieste

Table 2 Minerals identified through a stereomicroscope and/or a magnifying glass

Inventory number	Calcite	Limestone	Quartz	White mica	Observations
B1482	/	+++	/	/	/
B1963	+	/	/	/	/
B1984	/	/	/	/	Very fine-grained; no visible inclusions
B1965	/	/	/	+	/
B1939	+++	/	?	/	/
B1994	/	/	/	/	Very fine-grained; no visible inclusions
B1505	/	/	/	/	Very fine-grained; no visible inclusions
B5009	+++	/	/	/	/
NI19	+++	/	+	/	/
B1479	+++	/	/	/	/
B1972	/	+	/	/	/
B1973	+	/	/	/	/
B1490	++	?	/	/	Lithic fragments
B1497	+++	+++	/	/	Possible feldspar
3469	+++	+	/	/	/
20591	/	/	/	+++	/
20592	+++	/	/	/	/
20419	+	+	/	/	/
139461	++	+	/	/	/
SN	/	/	/	/	Very fine-grained; no visible inclusions
139462	/	/	/	/	Very fine-grained; no visible inclusions
139463	/	/	/	/	Very fine-grained; no visible inclusions
139464	+	+	/	/	/

+ = present; ++ = common; +++ = abundant

Karst, and they have been used to produce thin sections at the University of Padua. The thin sections have been observed via a polarising microscope at the Department of Mathematics and Geosciences of the University of Trieste. Unfortunately, we have not been allowed to take samples from the other artefacts.

Results

Pastes

The observation of the surfaces of the artefacts has allowed to identify lithic inclusions in many samples (Table 2) showing a

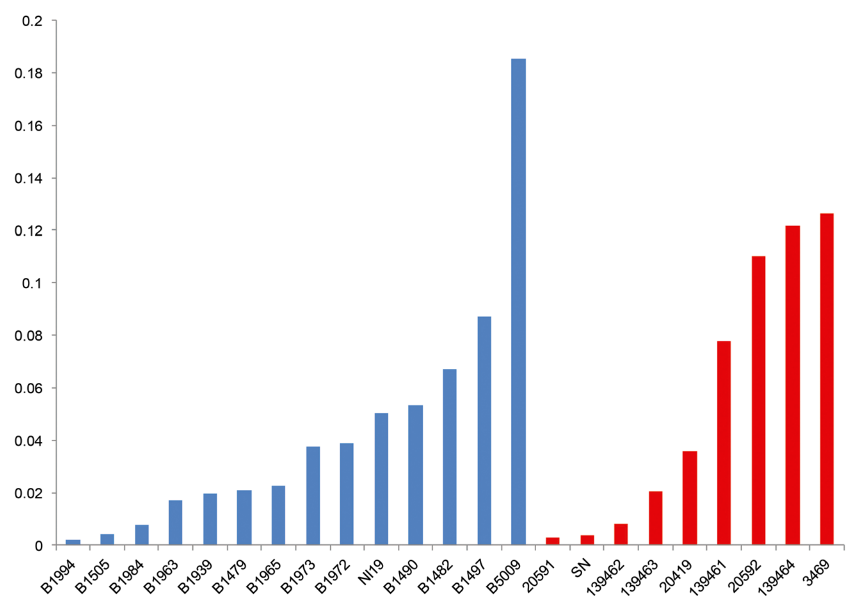

Fig. 3 Lithic inclusion/clay ratio for the Slovenian (light blue) and Italian samples (red)

coarse-grained paste. Among the identified inclusions, calcite and fragments of limestones are the most abundant, while quartz and white mica, probably muscovite, are rare. It is worth to mention bowl 20591 from the Trieste Karst because it differs from all other samples for the presence of abundant white mica. A few crystals of the same mineral have been recognised in sample B1965 from Deschmann's pile dwellings.

The segmentation of microCT data sets has allowed the virtual separation of the clay matrix, lithic inclusions and voids in 2D and their quantification. According to observations of microCT-derived virtual slices and the resulting lithic inclusion/clay ratios, fine- and coarse-grained pastes have been recognised in both Slovenian and Italian samples but no sharp distinctions can be made between sample groups (Fig. 3). The coarse-grained samples show abundant temper material with a size up to very fine gravel (from < 1 to 2–3 mm; lithic inclusion/clay ratio from about 0.04 up to 0.2), while the fine-grained vessels are variably tempered with lithic inclusions whose size is generally smaller than 1 mm (lithic inclusion/clay ratio lower than 0.04).

MicroCT data have revealed the presence of calcite, identifiable through the rhombohedral shape of crystals; clay pellets; grog fragments; rounded concentric inclusions often with a lighter centre, probably derived from the transformation of primary minerals during firing; low-density inclusions; and bone remains. The components identified in each sample are summarised in Table 3. It is not totally clear what the low-density inclusions correspond to, but their density is lower than that of clay, and they could be identified as charcoal fragments, macroscopically observed in some specimens.

Among Slovenian samples, some (Fig. 4; e.g. samples B1994, B1505, B1984, B1963, B1939, B1479 and B1965) are characterised by very fine- or fine-grained pastes with a lithic inclusion/clay ratio between 0.002 and 0.03 (Fig. 3). Small calcite crystals, clay pellets, rounded dense inclusions and bone remains have been identified in some samples (Fig. 4, Table 3). In sample B1939, a few small fish vertebrae have been identified and one of them has been virtually extracted (Fig. 5).

In medium- and coarse-grained vessels, calcite crystals have been often recognised (Table 3, Fig. 6).

Despite the small number of bowls discovered in the Karst area, they show quite heterogeneous features (Table 3, Fig. 7). Sample 20591 is different from all the other ones due to its very fine-grained (lithic inclusion/clay ratio 0.002) and dense paste where clay pellets and very rare and dense small inclusions have been imaged. A probable fish vertebra has been identified in sample 139464.

Table 3 Paste components identified through microCT. *D.p.d.* Deschmann's pile dwellings

Inventory number	Site	Grain size	Calcite	Grog	Clay pellets	Bones	Concentric inclusions	Low-density inclusions
B1482	Dpd	Coarse	x	/	/	/	/	/
B1963	Dpd	Fine	x	/	x	/	x	/
B1984	Dpd	Very fine	?	x	x	/	x	x
B1965	Dpd	Fine	?	/	/	/	x	/
B1939	Dpd	Fine	?	/	x	Fish vertebrae	/	x
B1994	Dpd	Very fine	/	/	/	/	x	/
B1505	Dpd	Very fine	?	/	x	/	x	x
B5009	Dpd	Coarse	x	/	x	/	/	/
NI19	Dpd	Coarse	x	/	x	/	/	/
B1479	Dpd	Fine	x	x	x	/	/	/
B1972	Dpd	Fine	x	/	x	/	x	/
B1973	Dpd	Fine	?	/	x	x	/	/
B1490	Dpd	Medium	x	/	x	x	x	/
B1497	Dpd	Coarse	x	/	/	?	/	x
3469	Zingari cave	Coarse	x	/	/	/	x	/
20591	Ciclami cave	Very fine	/	/	x	/	/	/
20592	Ciclami cave	Coarse	x	/	x	/	/	/
20419	Cotariova cave	Coarse	x	/	x	x	/	/
139461	Cotariova cave	Fine	x	/	/	/	/	/
SN	Cotariova cave	Fine	/	?	x	/	x	/
139462	Pettine cave	Fine	?	/	x	/	x	/
139463	Pettine cave	Fine	x	x	x	/	x	/
139464	Edera cave	Coarse	x	/	/	Fish vertebra?	x	/

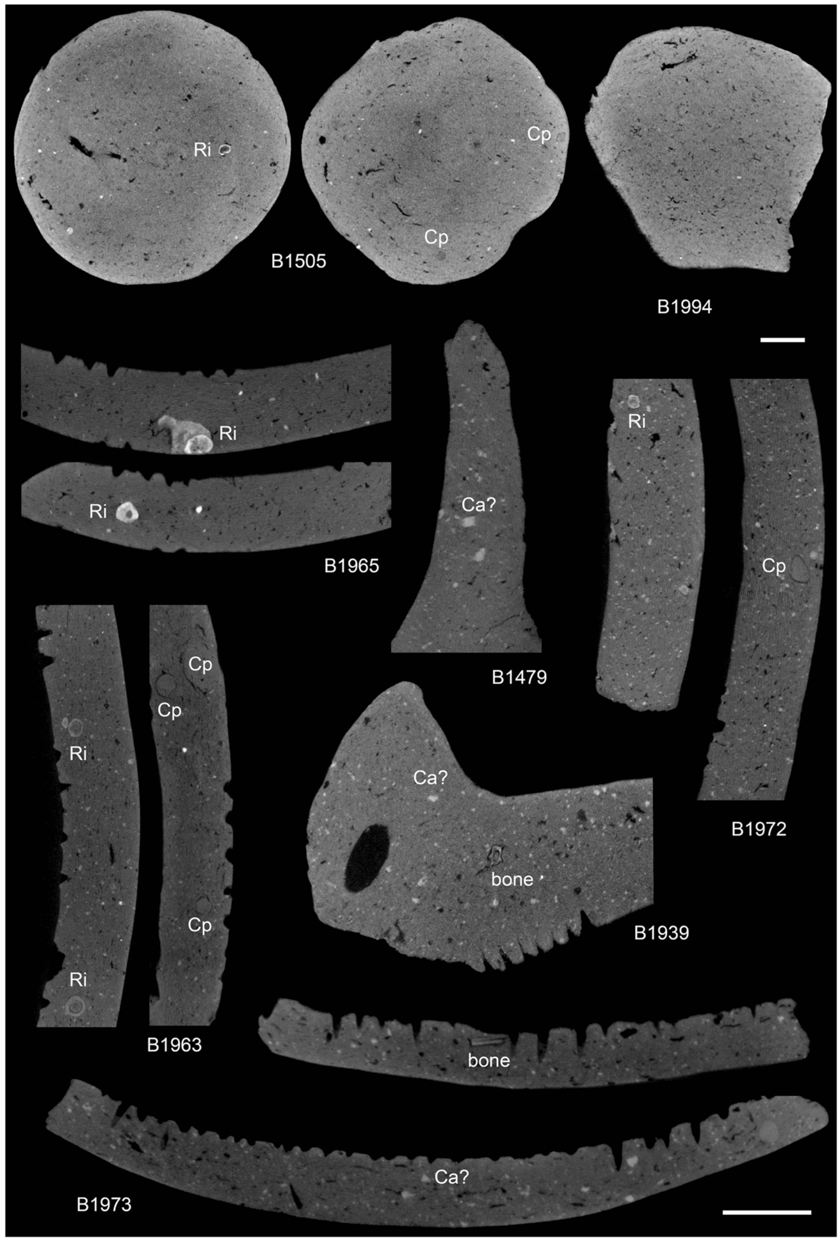

Fig. 4 Virtual sections of selected fine-grained bowls from Deschmann's pile dwellings. Ca, calcite; Cp, clay pellet; Ri, rounded inclusion; scale bars = 1 cm

Only the two bowls from Pettine cave were sampled to produce thin sections. Sample 139462 shows a brown fabric characterised by quite abundant angular quartz with a grain size from silt to medium sand, quite abundant flint fragments up to 0.5 mm large and abundant grog fragments. The grog fragments present different fabric and colours, suggesting they were obtained by crushing different vessels. In addition, a quartzite fragment containing muscovite crystals has been identified (Fig. 8). Sample 139463 shows a reddish paste containing similar components, such as quartz, angular flint grains, muscovite and grog fragments, but also rare calcite. It is worth mentioning that some grog fragments contain abundant flint fragments (Fig. 8).

Technology

Discontinuities and pores within the paste can give information about the bowl-shaping techniques. Lindahl and Pikirayi (2010) have demonstrated that the orientation of pores within the ceramic body, from one wall surface to the other, can be used to distinguish vessel-forming techniques, in particular between U and N coiling and modelling techniques. The U coiling technique gives curved convex sub-parallel discontinuities, while N coiling technique produces sub-parallel pores with a diagonal orientation. In vessels produced by modelling techniques, the discontinuities are parallel to the wall surfaces.

According to virtual cross sections of the rims of the investigated bowls, the upper part of the vessels was produced

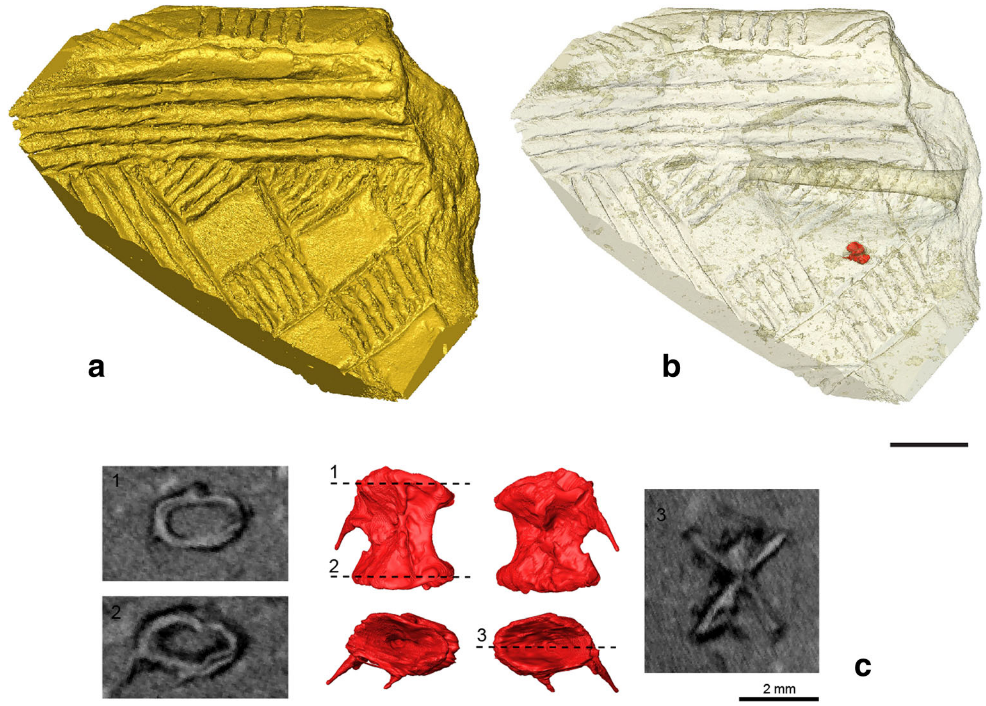

Fig. 5 Virtual extraction of a fish vertebra from sample B1939. **a** Virtual rendering of the artefact. **b** Virtual rendering of the artefact with the paste in transparency and the vertebra in red. **c** Extraction of the vertebra and selected virtual sections. Where not specified, the scale bar corresponds to 1 cm

using both the coiling and the modelling techniques. Samples B1994, B1490 and 139464 show pores with diagonal orientation and were therefore produced by N coiling technique, while sample 3469 shows pores parallel to the surfaces of the vessel, produced by a modelling technique (Fig. 9).

In virtual sections of both Italian and Slovenian samples, the core of the base is surrounded by a circular concentric layer of paste. This suggests the base was shaped starting from a central piece, to which a layer of clay was added and then reshaped in order to produce the foots (Fig. 10). The upper part of the bowl was probably separately produced and then joined to the base as it is suggested by the discontinuities in longitudinal virtual sections of sample B1482 (Fig. 11).

Analysis of microCT-derived data

After the segmentation of clay, lithic inclusions and pores in three slices per sample (Supplementary Table 1), we calculated the area, the maximum length and the maximum width of every single lithic inclusion. Table 4 shows the number of lithic inclusions divided into four size intervals considering their area, maximum length and maximum width.

In Fig. 12, we have plotted the percentages of inclusions falling within the different size intervals considering their area, maximum length and maximum width. Comparing Table 4 and Fig. 12, the differences between samples can be observed.

When the area of inclusions is considered (Fig. 12), several samples (B1479, B1939, B1963, B1965, B1972, B1973 and 139461–139464, SN) show a higher percentage of very small inclusions and a gradual decrease in the percentage of small, medium and big inclusions. Sample 20591 has a peculiar paste characterised by rare very small and small inclusions without any medium and big ones. Other samples, such as samples B1497, N19 and 3469, show a completely different distribution of inclusions with a prevalence of very big lithic grains. Finally, other samples show similar percentages of inclusions belonging to all four classes or a prevalence of very small inclusions coupled with a similar lower percentage of inclusions belonging to other classes (20419 and 20592).

Considering the maximum length of inclusions, a prevalence of very small inclusions (< 500 μm) has been detected in most samples. However, in some samples with a coarse grain size, the percentage of small inclusion (500–1000 μm) is similar to that one of very small inclusions (Fig. 12). The distribution of inclusions considering their maximum width is quite well comparable to that one obtained, taking into consideration the areas (Fig. 12).

To visualise and summarise the pottery fabric information given by microCT-derived inter-correlated data, PCA has then been performed, considering percentages of lithic inclusions, area, length, width and inclusion/clay ratio as variables. Figure 13a shows the relationships between variables and the quality of their representation. Variables positively correlated are grouped together, while those negatively correlated are located in opposite quadrants. The quality of representation can be expressed by a value of square cosine ($\cos^2$). The distance between the end points of variables measures the quality of the variables. The best representation of a variable is given when its end lies on the correlation circle, a condition corresponding to the maximum square cosine value, that is 1. In Fig. 13a, variables are well represented and three main groups of variables are positively

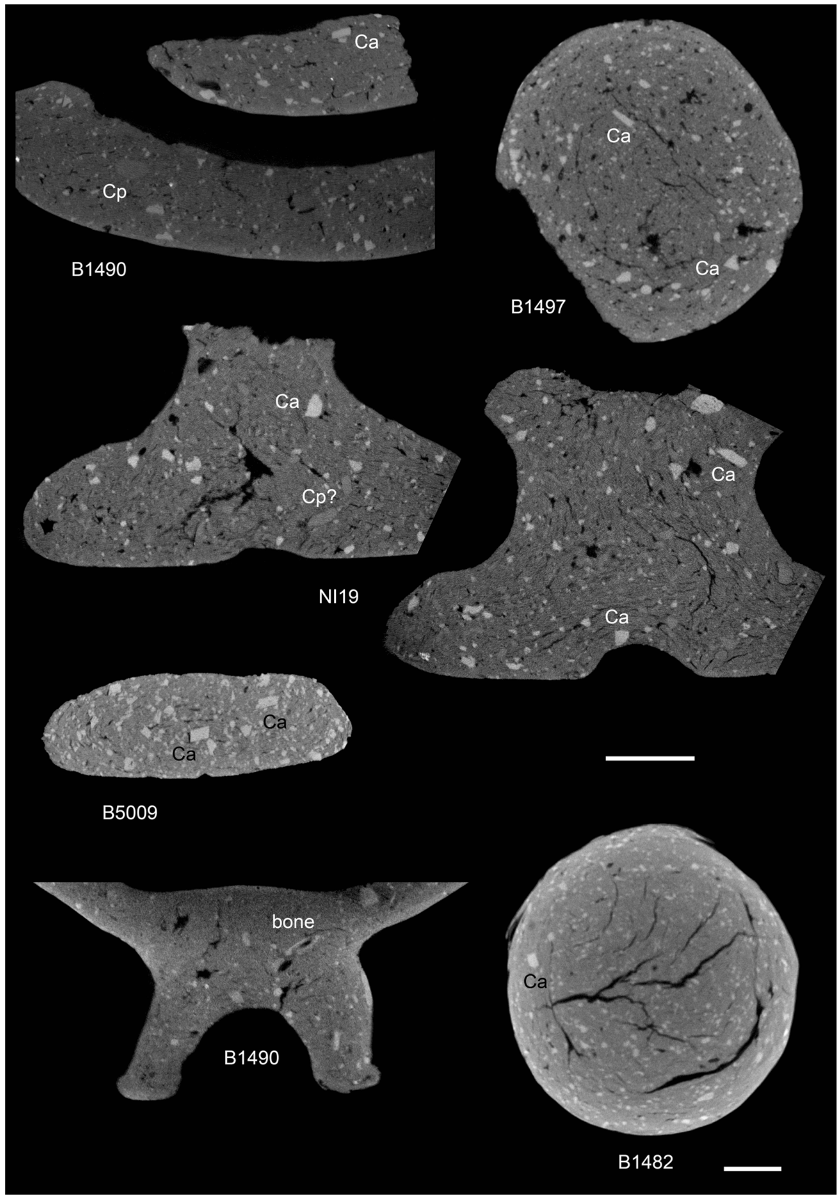

Fig. 6 Virtual sections of selected coarse-grained bowls from Deschmann's pile dwellings. Ca, calcite; Cp, clay pellet; scale bars = 1 cm

correlated: very small area-very small length-very small width, small area-small width and small length-medium area-medium length-medium width-big area-big length-big width.

In the bivariate plot of Fig. 13b, we can observe the position of the samples with respect to principal components 1 and 2 and the variables. When a vessel falls close to a given variable, it has a high value of such a variable, while its value is low if it is located on the opposite side of the same variable.

The samples falling in the top right quadrant are characterised by very fine-grained fabric with prevalent very small inclusions. Most of them are from the Karst with exception of sample B1963, that is very close to the bottom right quadrant. In this quadrant, there are mainly fine-grained Slovenian samples and two bowls from Pettine cave (Trieste Karst). This group of materials is characterised by a high total clay area because they lie on the opposite side of the lithic inclusion/clay ratio variable. Samples with medium and big inclusions and a big lithic inclusion/clay ratio mainly fall in the top left quadrant. Even if this diagram simply provides a description of pottery fabric and lithic inclusions, it is interesting to note that in the bottom quadrants, all the samples, with the exception of two Italian bowls, are from Deschmann's pile dwellings.

Discussion and conclusions

The orientation of pores and disjunctions in microCT volumes has allowed recognising the bowl-forming process in several

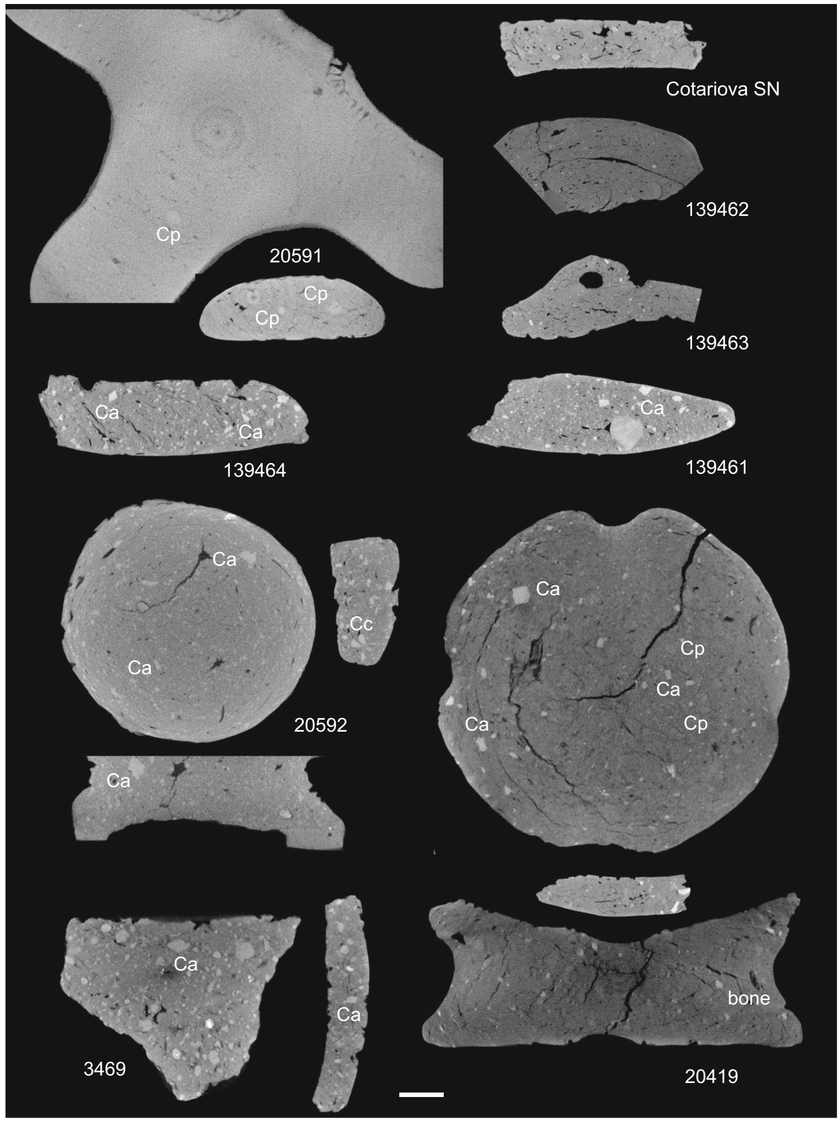

Fig. 7 Virtual sections of all analysed bowls from the Karst. Ca, calcite; Cp, clay pellet; scale bar = 1 cm

artefacts. The basin was produced using mainly the N coiling technique, recognised in the rim of three artefacts (B1994, B1490 and 139464), but also the modelling one (3469; Fig. 9). The base was shaped starting from a central piece, to which a layer of clay was added and then reshaped in order to produce the foots.

MicroCT analysis of the bowls with cross-shaped foots from Deschmann's pile dwellings has showed the use of two main paste types. The first one includes bowls with a medium or coarse-grained paste tempered with abundant and generally poorly sorted carbonate/calcite inclusions, identified through both macroscopic and microCT observations (B1482, B1490, B1497, B5009, N19). The lithic temper material has a size up to very fine gravel (from <1 to 2–3 mm), and the paste lithic inclusion/clay ratio spans from about 0.04 up to 0.2. The big lithic inclusions (> 200,000 μm^2) are prevalent (B1497, N19) or abundant (B1490, B5009; Figs. 3, 6 and 12). In the PCA bivariate plot, such vessels fall relatively close to each other in the top left quadrant, with the exception of sample B1482 (Fig. 13).

The second group is larger and includes very fine- or fine-grained vessels. Some of them show a paste almost without temper (B1994, B1505, B1984), while the others generally contain well-sorted fine calcite/limestone grains with a prevalence of very small inclusions (< 50,000 μm^2). Consequently, the inclusion/clay ratio is very low and spans between 0.002 and 0.03. Grog, clay pellets, rounded dense inclusions and bone remains have been identified in some of them (Figs. 3, 4 and 12, Table 3). A few small fish vertebrae have been identified in sample B1939. Most of the samples fall in the bottom right quadrant of PCA bivariate plot (Fig. 13).

The two main pastes were used regardless of the bowl size and quality of decorations and manufacture. Calcite and limestone fragments, used as tempered material, are already reported from pottery assemblages of the Ljubljansko barje dated to

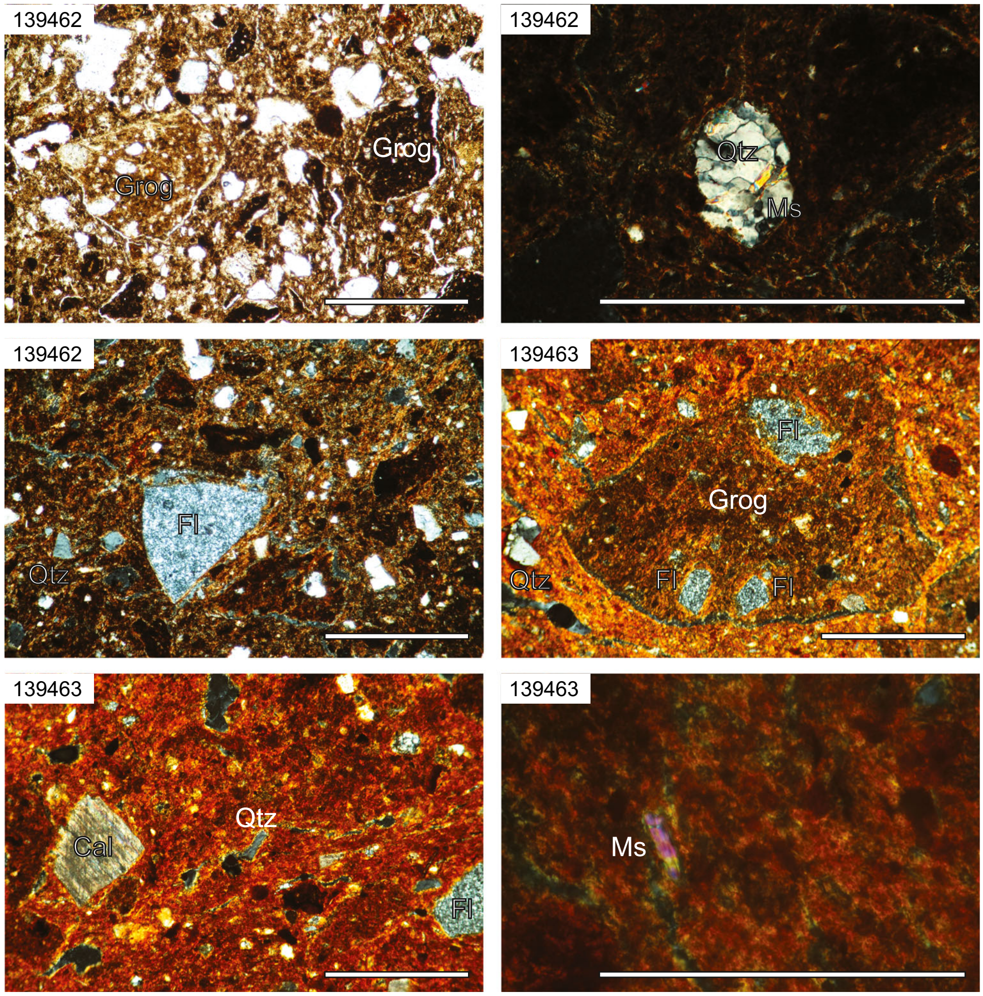

Fig. 8 Microphotographs of thin sections produced from bowls 139462 and 139463 from Pettine cave. The top left image was taken using plane-polarised light while all the others using crossed polars; scale bars = 0.5 mm. Cal, calcite; Fl, flint; Ms, muscovite; Qtz, quartz

the fifth and fourth millennia BC, and they could be easily gathered from the karst outcrops south of the Ljubljansko barje (Žibrat Gašparič 2013). The presence of fish remains within the paste would suggest that the clay raw material of sample B1939 was likely collected from local lake deposits.

The results of microCT analysis support the hypothesis that the bowls were locally produced using different recipes. This is not surprising if we consider that the investigated material come from three pile dwellings in use for a few centuries. Non-destructive chemical analysis by prompt-gamma activation analysis (PGAA) of the same vessels and natural clay samples from Ljubljansko barje is in progress to confirm such interpretation.

Even if the group of bowls from Trieste Karst includes only nine vessels, they show very heterogeneous pastes.

Sample 20591 from Ciclami cave is different from all the investigated Slovenian and Italian artefacts. Its decoration shape and technique are not reported from the bowls with cross-shaped foots from Deschmann's pile dwellings. Its paste is rich of muscovite mica, very dense and without carbonate

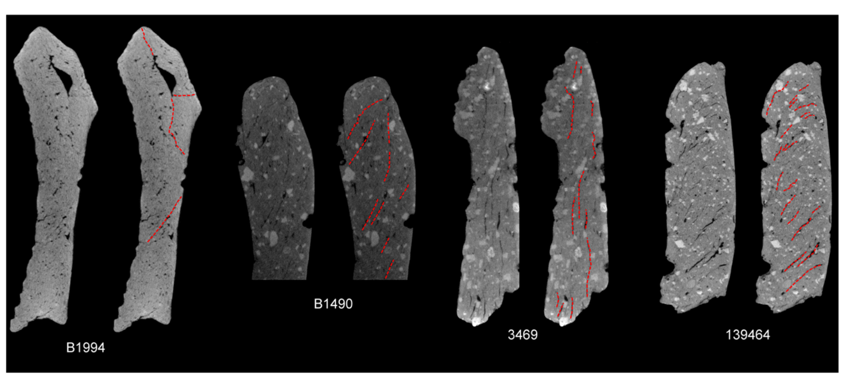

Fig. 9 Virtual transversal sections of the selected rims of investigated bowls showing technological traces highlighted by dotted red lines

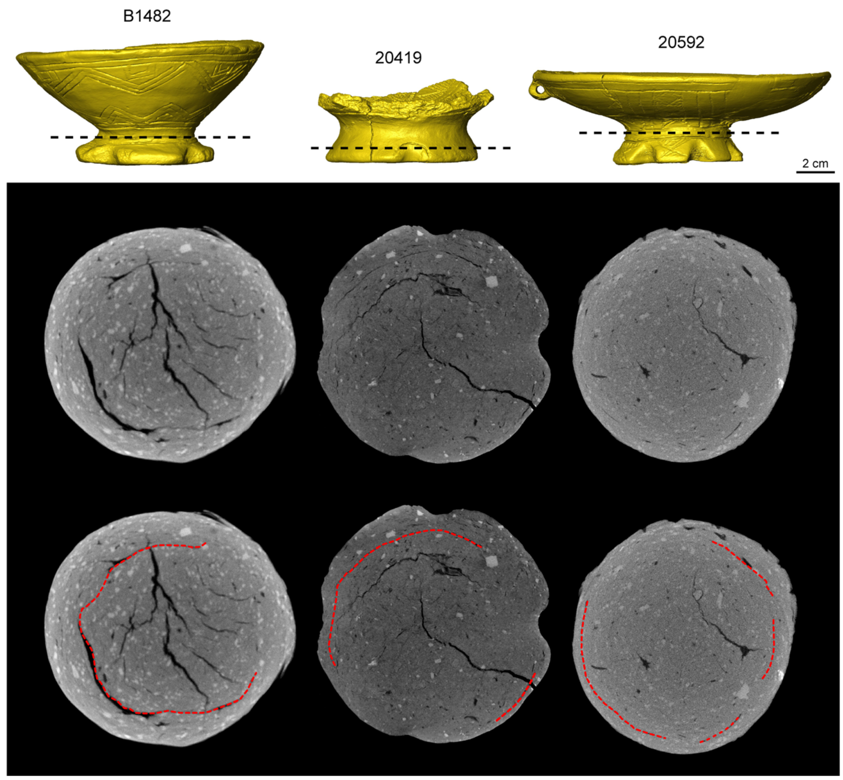

Fig. 10 Virtual transversal sections of the base of selected bowls from Slovenia (B1482) and Italy (20419 and 20592). Technological traces are highlighted by dotted red lines

inclusions and contains only a few dense very small and small lithic grains (lithic inclusion/clay ratio 0.002). Neolithic pottery from the Trieste Karst is very rich in calcite inclusions, and abundant muscovite has not been reported so far (Spataro 1999; Bernardini et al. 2016). For all these reasons, bowl 20591 has likely been imported to the Karst area. According

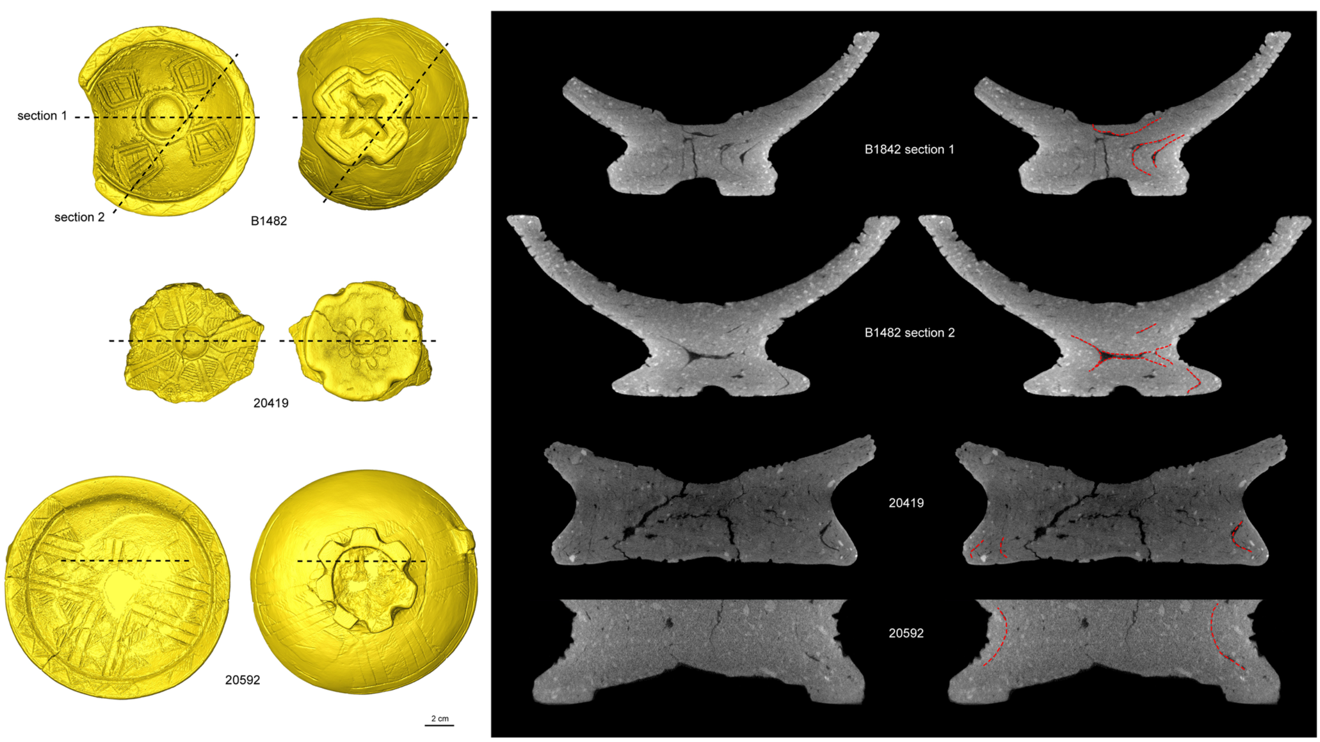

Fig. 11 Virtual longitudinal sections of the base of selected bowls from Slovenia (B1482) and Italy (20419 and 20592). Technological traces are highlighted by dotted red lines

Table 4 Number of lithic inclusions divided into four size intervals considering their area, maximum length and maximum width

Name	Area				Maximum length				Maximum width			
	Very small 0–50,000 μm²	Small 50,000–100,000 μm²	Medium 100,000–200,000 μm²	Big > 200,000 μm²	Very small 0–500 μm	Small 500–1000 μm	Medium 1000–1500 μm	Big > 1500 μm	Very small 0–200 μm	Small 200–300 μm	Medium 300–400 μm	Big > 400 μm
B1505	30	32	18	10	60	27	3	0	20	30	24	16
B5009	220	155	180	206	345	288	86	42	136	184	150	291
B1482	237	309	306	157	509	449	47	4	156	313	249	291
B1490	73	66	75	70	134	113	25	12	49	69	53	113
B1479	78	68	32	20	130	59	7	2	55	55	48	40
B1939	126	99	46	20	218	70	2	1	82	96	73	40
B1963	255	54	16	7	309	22	1	0	185	109	25	13
B1965	24	17	4	7	40	9	2	1	13	21	7	11
B1972	257	118	44	13	353	73	4	2	183	148	67	34
B1973	101	87	58	30	198	68	4	6	80	89	62	45
B1984	1	7	9	7	8	12	1	3	0	6	9	9
B1994	3	5	1	2	7	3	1	0	2	6	0	3
B1497	193	185	339	453	413	545	162	50	173	141	257	599
NI19	66	94	106	116	145	165	52	20	34	83	84	181
3469	59	80	65	102	130	126	29	21	29	72	69	136
20591	86	9	0	0	89	6	0	0	77	14	3	1
20592	28	85	185	489	82	347	239	119	22	35	103	627
20419	10	30	46	109	33	92	45	25	3	27	32	133
139461	562	74	40	28	626	66	8	4	478	143	31	52
SN	33	4	6	1	38	6	0	0	25	11	5	3
139462	54	27	18	15	79	31	4	0	34	36	22	22
139463	116	47	16	10	153	31	4	1	95	60	19	15
139464	345	140	69	68	457	131	22	12	264	169	87	102

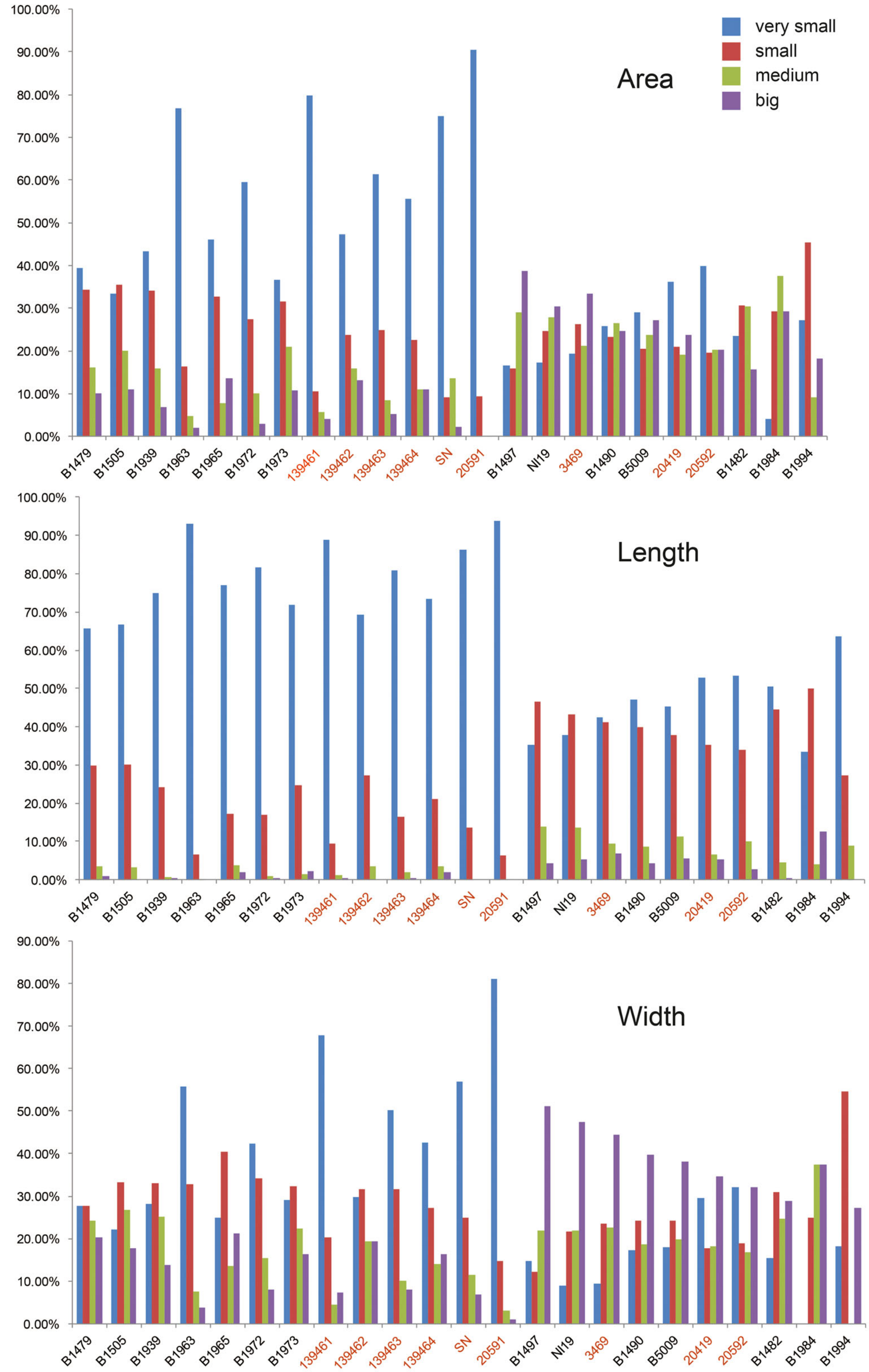

Fig. 12 Histograms showing the percentages of very small, small, medium and big lithic inclusions considering their area, length and width. Red labels, Karst samples; black labels, Slovenian samples

to available data, its technological features are different to those so far identified in the analysed artefacts from Deschmann's pile dwellings too. Bowls with similar decorations are known from Austria, Czech Republic, Slovakia, Hungary, Serbia, etc., as far as Ukraine (see Leghissa 2017, p. 172). The most similar bowls are some vessels from Moravia in the Czech Republic (Medunová-Benešová 1977, T. 47: 1a–c, 5a, b, 6a, b; 48: 1a–c; 49: 1a–c; 48). Nevertheless,

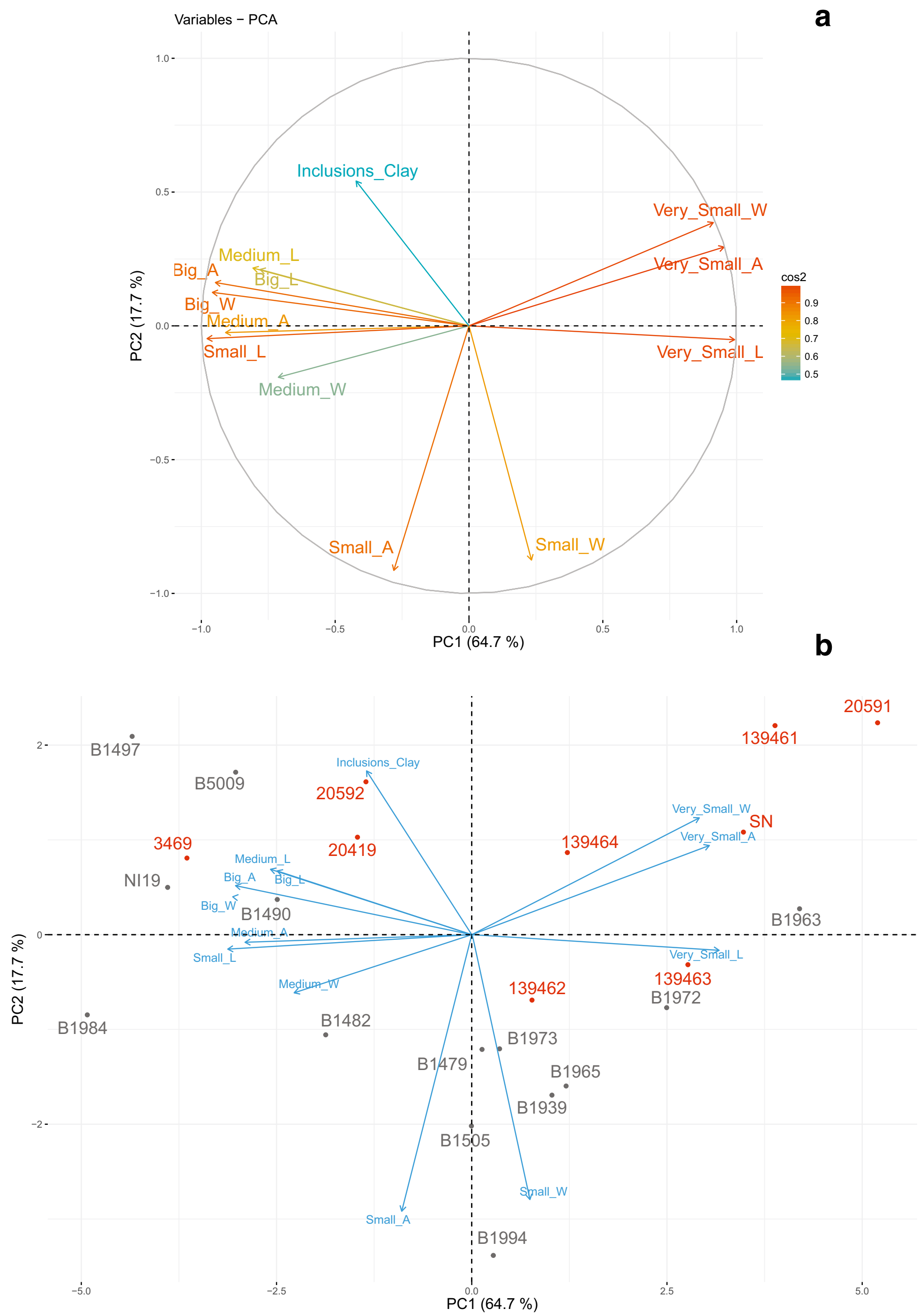

Fig. 13 **a** Variable correlation plot showing the relationships among variables and the quality of their representation. **b** Bivariate plot showing the variables and the position of investigated samples from Slovenia (black labels) and Trieste Karst (red labels). A, area; L, length; W, width; Inclusions_ Clay, lithic inclusion/clay ratio

the precise origin of bowl 20591 from Ciclami cave cannot be precisely identified without further investigations.

According to microCT results, the bowls 139462 and 139463 from Pettine cave show a fine-grained paste (lithic inclusion/clay ratios 0.008 and 0.02, respectively) with a prevalence of very small lithic inclusions (Fig. 12) comparable to that of several samples from Deschmann's pile dwellings (Fig. 3). In vessel 139463, calcite crystals and grog fragments have been identified, such as in the Slovenian samples B1479 and B1984. The two bowls fall into the bottom right quadrant of PCA plot, very close to the fine-grained group of Slovenian samples, and they are the only two Italian artefacts included in the two bottom quadrants of the same diagram, indicating a similitude with a large group of bowls from Deschmann's pile dwellings. These data could suggest a possible origin from central Slovenia or surrounding areas, and optical microscopy supports this hypothesis. Abundant grogs and angular flint grains, quartzite and muscovite crystals are a pottery component that is rare or so far not reported in the prehistoric ceramics of the Trieste Karst (Spataro 1999; Bernardini et al. 2016), while they have been identified in those of Ljubljansko barje. Among the pottery fabric groups of Resnikov prekop, a fifth millennium Neolithic site very close to Deschmann's pile dwellings, fabric groups 3 and 4 are rich in flint and muscovite (Žibrat Gašparič 2013).

Nevertheless, it is worth stressing that the decoration (i.e. impressions of twisted cord) of the two bowls from Pettine cave is not reported among the bowls with cross-shaped foots from Deschmann's pile dwellings but only, very rarely, on other types of vessels. For this reason, we cannot exclude that the Pettine bowls could have been imported from a different region, as supposed for the Ciclami bowl 201591. Chemical data obtained by PGAA (in progress) could help in answering to this question.

The coarse-grained samples (3469, 20419 and 20592) are mainly calcite-tempered pottery with lithic inclusion/clay ratios from about 0.035 to 0.12 and a prevalence or high percentage of big inclusions (> 200,000 μm^2) (Fig. 12). They are technologically similar to the Slovenian bowls with a medium- or coarse-grained paste. This is confirmed by the PCA plot where Karst samples fall into the top left quadrant (Fig. 13). However, sample 3469 is the only one where the orientation of pores suggests it was shaped using a modelling technique.

The last three bowls from the Trieste Karst (SN, 139461 and 139464) contain prevalent very small inclusions but the calcite-tempered 139461 and 139464 artefacts show high lithic inclusion/clay ratios (0.07 and 0.12, respectively) due to the presence of a few very large inclusions. Conversely, the bowl SN does not contain calcite and has a low lithic inclusion/clay ratio (0.03). They fall into the top right quadrant of PCA plot. The possible presence of a fish vertebra in sample 139464 would suggest that the clay raw material was gathered from a lacustrine environment, such as the one of Ljubljansko barje at that time.

The origin and function of the bowls with cross-shaped foots is still debated (see e.g. Kulcsár 2009; Kaiser 2013), but the small number and beautiful decoration of those from the Trieste caves suggest that they could have been used as valuable ceremonial items. The probable origin of part of them from central Slovenia or even more distant regions would indicate that sometimes not only aesthetic and technological models but also the objects themselves moved from other regions to the Karst. The strong connections between central Slovenia and the Karst during the first half of the third millennium BC are confirmed by other classes of artefacts, such as copper and polished stone axes (Bernardini et al. 2014a, 2014b; Bernardini 2018 and the references quoted there).

From a methodological point of view, the present paper provides one of the first examples of statistical analysis of ceramic microCT-derived data, allowing a non-destructive objective description of pottery fabrics.

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