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ORIGINAL ARTICLE

# Mid-Cretaceous calcarenite in stone products from the Roman colony of Emona, Regio X (modern Ljubljana, Slovenia)

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**Abstract**
Over the course of studying stone products from the Roman colony of Emona (Regio X), stratigraphically undefined calcarenite that was used to make simple sepulchral and architectural stone products was detected. The calcarenite used is late Aptian to early Cenomanian in age. The corresponding facies were found in the Lower Flyschoid Formation outcropping near the town of Medvode, within the local radius of Emona. The Roman quarry was likely located in this area near the Sava River. According to the collected data, the quarry was in operation mainly in the 1st century.

**KEYWORDS**
Cretaceous, microfacies, quarry production, Regio X, Roman time, stone products

## INTRODUCTION

Two sources of Cretaceous shallow-water bioclastic limestone are currently known in Regio X (Russell, 2013): the mid-Cretaceous (Albian–lower Cenomanian) Milna (sensu Brčić et al., 2017; Gušić & Jelaska, 1990; Tišljar et al., 1998), which supplied the Roman town of Pola (mod. Pula/Pola) (Džin, 2012); and the Upper Cretaceous (Coniacian–Campanian) Aurisina/Nabrežina limestone (Carulli & Onofri, 1969; Cucchi et al., 1985; Jurkovšek et al., 2016; Maritan et al., 2003; Sanders, 2001), which is known as the most important and widely used lithofacies in Regio X (Lazzarini & Van Molle, 2015; Previato, 2015, 2018). Colonia Iulia Emona was a Roman town in the north-eastern area of Regio X, which existed from the early

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1st to the 6th century where the modern city of Ljubljana, central Slovenia, stands today (Gaspari, 2014; Šašel Kos, 2012). The Upper Cretaceous Aurisina/Nabrežina limestone (Krašna, 2019; Previato, 2018) was, until now, the only known facies of Cretaceous limestone used in Emona. Quarried more than 70 km (by air) west of Emona, the Aurisina/Nabrežina limestone differs from the other limestones used in Emona in that it is not local in origin but had to be transported from the ancient quarries over the difficult foothills of the Alps (Figure 1a,b).

Stone products in Emona were largely produced from weather-resistant types of limestones, which allowed detailed shaping (Djurić et al., 2018; Mirtič et al., 1999). Various lithofacies of limestone of different ages used in Emona have already been recognised. Several locations of antique quarries have been proposed so far (Brodar et al., 1955; Müllner, 1879; Ramovš, 1990, 2002; Ramovš et al., 2000; Šašel Kos, 1997), but only the quarry in the modern village of Podpeč has yielded direct archaeological proof of its existence in antiquity (Djurić et al., 2022). Most stone products stratigraphically originate from the Lithiotis Limestone Member (Djurić et al., 2022) of the Podbukovje Formation (Dozet & Strohmenger, 2000), which outcrops in the Podpeč quarry, but Lower Triassic, Cretaceous and Miocene limestones are present as well (Djurić, 1997; Djurić & Rižnar, 2017; Šašel Kos, 1997). Recent analysis of the stone products from Emona shows some that products were incorrectly recognized as Lower Jurassic limestone from the Podutik area. Instead, they were made from Cretaceous limestone (hereafter referred as calcarenite) from an unidentified stratigraphic source unit and geographical location (Vodnik et al., 2017). So far, there have not been any systematic investigations of this calcarenite. Although foraminifera were mentioned (Visočnik et al., 2017), no one has attempted to make more specific taxonomic determinations or to determine the exact age of this stone, its stratigraphic position and its possible source. Thus, the aims of this research were to investigate the proportion of this newly detected calcarenite in the stone products of Emona, to determine its use, the microfacies, its stratigraphic position, and, most importantly, to determine whether suitable rocks can be found in the vicinity of Emona. To answer this last question, the calcarenites from the Lower Flyschoid Formation outcropping north of Ljubljana were sampled (Figure 1c).

## METHODS AND MATERIALS

In order to estimate the proportion of the mid-Cretaceous calcarenite in the stone products of Emona, 302 stone products represented by sepulchral and architectural elements (including building stone) made of sedimentary carbonates were investigated. Most of them are stored in the National Museum of Slovenia (inventory numbers marked as NMS) and in the City Museum in Ljubljana (inventory numbers marked as MGML and PN). A smaller number of stone products can be found outdoors in the city of Ljubljana (samples marked as KL). Together, these products cover the period from the 1st to the 4th century CE. Sampling was performed only on previously damaged parts of the stone products in order to minimize further deterioration of the stone monuments.

Thin sections (171 in number) were made from stone products kept in the City Museum of Ljubljana, and from products found outdoors in Ljubljana. These were analysed with a Keyence VHX 7100-S750E digital microscope, additionally equipped with a polarising lens. Thirty-four stone products (23 thin sections) belonging to stone products of previously stratigraphically indeterminate calcarenite are studied here in detail.

Archaeological characterisation of the stone products included determination of their use and possible chronology. For the analysis of the preferred use of a particular facies, stone products were grouped according to their use. The geological description of stone products was based on petrographic and sedimentological analysis, including macro- and microscopical

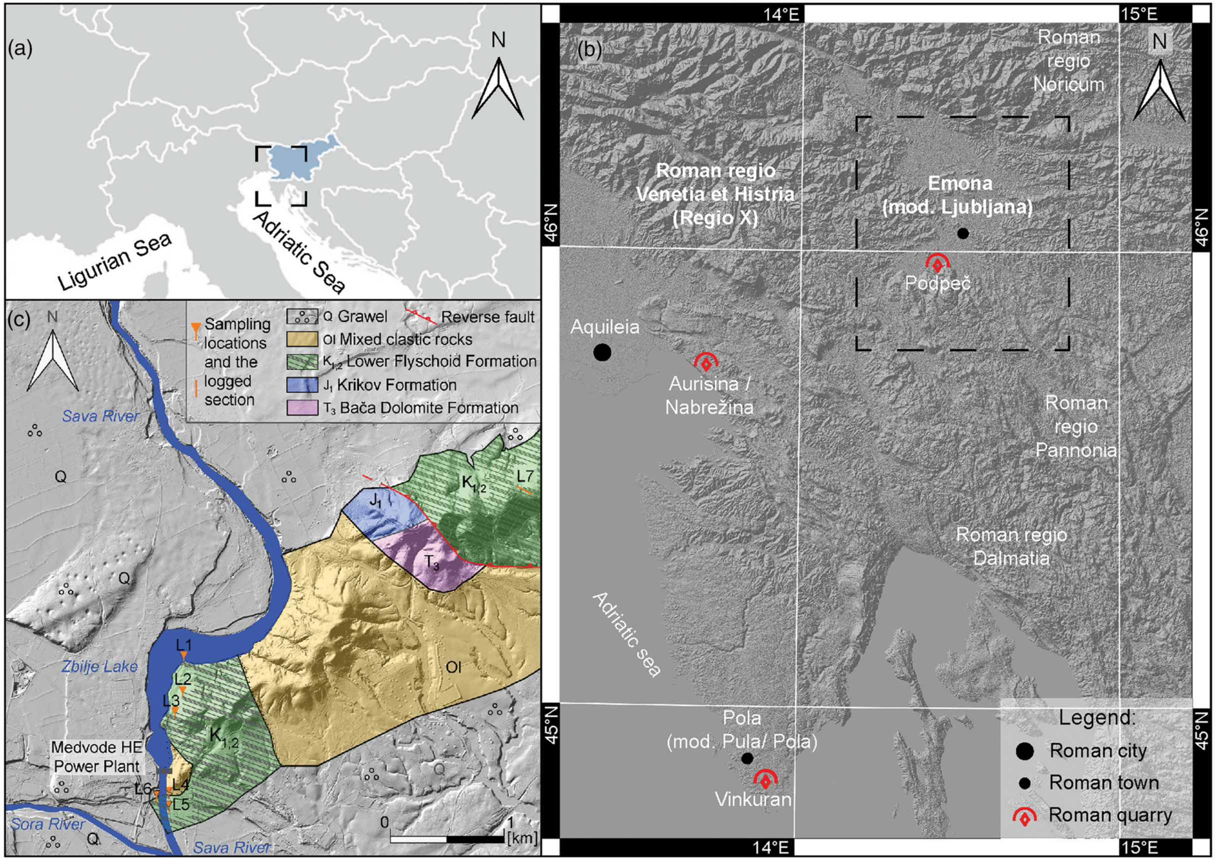


**FIGURE 1** Location of the studied area. (a) Geographical position of Slovenia with outlines of the wider studied area. (b) Geographical position of the wider studied area with marked Roman settlements and their main quarries. The area presented in Figure 4b is outlined with a dashed square. The source of the topography is ASTER global digital elevation model V002. (c) Outcrops of the lower Flyschoid formation north of Ljubljana, modified after geological map 1:250.000 of Slovenia (Buser, 2010), with positions of sampling sites and of the logged section (S). The source of the topography is a 1 m × 1 m resolution digital relief model (Surveying and Mapping Authority of the Republic of Slovenia, 2011)

structural (density and orientation of veins) and textural characteristics of the samples (bedding, lamination, grain orientation and grain sorting). The colour of the rock was described from the standard Munsell Rock Colour Chart (2008) on the (relatively) freshly broken-off parts of the stone products. The minimum thickness of the source bed required to produce a stone block of the necessary size was determined from the dimensions of the stone products. The samples were classified according to the terminology proposed by Dunham (1962), modified by Embry and Klovan (1971), with recommendations by Wright (1992) included. In order to enable the stratigraphic positioning and interpretation of the geological setting of the formation, the described microfacies were compared with the standard microfacies (Flügel, 2004; Wilson, 1975) and with the models of turbidite sedimentation (Tucker, 2001). Benthic and planktonic foraminifera were determined to constrain the relative age of the rock.

Based on the age and facies of the rock from stone products, we conducted a field campaign to sample suitable rocks in the vicinity of Ljubljana in order to create a reliable stratigraphic database that would allow us to test the hypothesis of local origin. Locations SE (Logatec and Vrhnika) and SW (Dobrepolje) of Emona/Ljubljana were checked in the field (see Figure 4b), but a suitable facies was not found. We thus focused on the exposures of the Lower Flyschoid Formation north of Ljubljana (for sampling locations see Figure 1c). Calcarenite beds were sampled near Lake Zbilje (L1: samples RKS1–RKS5; L2: sample LJ16; L3: sample LJ17), Verje (L4: sample LJ18; L5: sample LJ19) and Medvode (L6: samples LJ20–LJ22). A detailed sedimentological section (L7: samples S1–S17) was logged on the eastern slope of the Smlednik hill. All the samples from the outcrops were analysed in thin sections, using the same criteria as described above for the stone products. All studied samples are stored at the Geological Survey of Slovenia (archive of the leading author, R.B.) and are freely available for further study.

# RESULTS

## Characterisation of the studied stone products

### Archaeological characterisation

Among the 302 stone products that were investigated, 34 (11.26%) were made from mid-Cretaceous calcarenite. The products from the mid-Cretaceous calcarenite include parts of architecture (columns, architraves, thresholds, paving slabs) and urban infrastructure (sewer slabs), as well as votive (altars) and sepulchral (tombstones, ash-chests, urns, tombs) monuments. The columns, like almost all columns in Emona (Djurić et al., 2022), are of Tuscan order.

Among the preserved products, parts of columns and urns, as well as various prepared and untreated slabs, prevail. Together, these products account for 60% of all products and likely reflect the quarry's basic production output. It was found that the thin-bedded fine-grained calcarenite was favoured for the production of slabs. A list of all studied mid-Cretaceous calcarenite products is given in Table 1.

Chronologically, only tentatively definable products—tombstone MGML 0051183 (Slabe, 1967) and NMS L165 (Šašel Kos, 1997), Tuscan columns, and situla urns with bases, which roughly imitate those imported from Aurisina/Nabrežina—categorically belong to the 1st century, and likely point to activity at the quarry of mid-Cretaceous calcarenite at the time.

**TABLE 1** The studied mid-Cretaceous stone products from Emona, grouped according to use. The orientation of the bedding plane can in this case be determined from stylolites, grading or the orientation of fossils. The minimum thickness of the bed of origin is determined from the dimension of the artefact that is perpendicular to the bedding plane

| Product types (% of new limestone type in known quarry production of Emona) | Inventory number; (*) identifies the sampled products | Dimensions of stone products (cm); width, thickness, height | Minimal thickness of bed of origin | Facies type |
|---|---|---|---|---|
| Column bases (9%) | MGML 0057726 (*) | 49, 37, 26 | 26 | Limestone breccia |
| | MGML S0079972 (*) | 15, 16, 19 | 16 | Fine-grained calcarenite |
| | MGML 0057721 (*) | 45, 42, 26 | 26 | Corse-grained calcarenite |
| Column shafts (9%) | NMS L230 | 36, 33, 98 | 36 | Corse-grained calcarenite |
| | MGML 0057736 (*) | 41, 41, 62 | 41 | Fine-grained calcarenite |
| | MGML 0059819 (*) | 25, 25, 48 | 25 | Fine-grained calcarenite |
| Column capital (3%) | MGML 0060208 (*) | 40, 40, 28 | 28 | Fine-grained calcarenite |
| Entablature (3%) | MGML 0055255 (*) | 27, 46, 10 | 10 | Corse-grained calcarenite |
| Sewer construction slabs (12%) | PN 9102/1 (*) | 92, 73, 18 | 18 | Fine-grained calcarenite |
| | PN 9102/2 (*) | 110, 65, 23 | 23 | Fine-grained calcarenite |
| | PN 9102/3 (*) | 104, 62, 20 | 20 | Fine-grained calcarenite |
| | PN 9102/4 (*) | 87, 62, 15 | 15 | Fine-grained calcarenite |
| Paving slabs (6%) | KL3 (*) | 95, 53, 12 | 12 | Fine-grained calcarenite |
| | MGML S0097931 (*) | 113, 100, 13 | 13 | Fine-grained calcarenite |
| Threshold (3%) | MGML S0111023 (*) | 16,15, 15 | 15 | Corse-grained calcarenite |
| Ash-chests, urns and grave construction (32%) | NMS L49 | 103, 60, 55 | 55 | Corse-grained calcarenite |
| | NMS L77 | 50, 50, 38 | 38 | Corse-grained calcarenite |
| | NMS L256a | 55, 42, 15 | 15 | Corse-grained calcarenite |
| | NMS L256 | 65, 60, 47 | 47 | Corse-grained calcarenite |
| | NMS L254 | 45, 47, 45 | 45 | Corse-grained calcarenite |
| | NMS L268 | 47, 75, 33 | 33 | Corse-grained calcarenite |
| | MGML 0048568 (*) | 25, 20, 18 | 18 | Corse-grained calcarenite |
| | MGML 0053255 (*) | 37, 37, 36 | 36 | |

(Continues)

**TABLE 1** (Continued)

| Product types (% of new limestone type in known quarry production of Emona) | Inventory number; (*) identifies the sampled products | Dimensions of stone products (cm); width, thickness, height | Minimal thickness of bed of origin | Facies type |
|---|---|---|---|---|
| | | | | Corse-grained calcarenite |
| | MGML 0059817 (*) | 66, 66, 45 | 45 | Corse-grained calcarenite |
| | MGML S0106043 (*) | 23, 22, 20 | 20 | Corse-grained calcarenite |
| | MGML 0060192 (*) | 42, 42, 29 | 29 | Corse-grained calcarenite |
| Altars (9%) | NMS L64 | 36, 40, 39 | 36 | Corse-grained calcarenite |
| | NMS L67 | 46, 38, 70 | 46 | Corse-grained calcarenite |
| | NMS L70 | 47, 29, 69 | 47 | Corse-grained calcarenite |
| Tombstones (15%) | MGML 0048569 (*) | 16, 18, 18 | 18 | Corse-grained calcarenite |
| | MGML 0051179 (*) | 16, 47, 36 | 16 | Corse-grained calcarenite |
| | MGML 0051183 (*) | 17, 40, 75 | 17 | Corse-grained calcarenite |
| | MGML 0061375 (*) | 42, 64, 25 | 25 | Corse-grained calcarenite |
| | NMS L165 | 66, 22, 130 | 22 | Corse-grained calcarenite |

## Geological characterisation

The mid-Cretaceous calcarenite (Figure 2a) used to produce the stone products described above comprises fine-grained and coarse-grained facies of calcarenites and sedimentary limestone breccia with coarse-grained calcarenite matrix. The colour of both calcarenite facies and the limestone breccia matrix is light grey (hues N6–N7 in the Munsel Rock Colour Chart (2008), and, rarely, slightly brownish (colour 5Y 6/2) or slightly pinkish (colour 5YR 6/1). Along with their generally light grey colour, macroscopically distinguishing characteristics (see Supplement S1 for additional examples) include the presence of small (1 mm, rarely up to 3 mm) dark angular grains up to 1 mm in size. Microscopical investigation of these particles revealed that these are fragments of rudist shells. Echinoderm plates and foraminifera from the superfamily Orbitolinoidea are sometimes macroscopically evident in addition to the debris of rudist bivalves. The rock is densely veined. The calcitic veins have a reddish-orange or pale-yellow hue. Compaction stylolites are present in most samples.

One of the stone products (MGML 0057726) is a limestone breccia with coarse-grained calcarenite matrix. The macroscopically observed gravel-size lithoclasts (up to 5 cm) are light-grey mudstone, dark-grey wackestone with bivalve fragments, and black to dark-grey and red chert. Unfortunately, we could not obtain a sufficiently large sample to prepare a thin section from the stone product in order to a perform a detailed microfacies analysis of the lithoclasts without

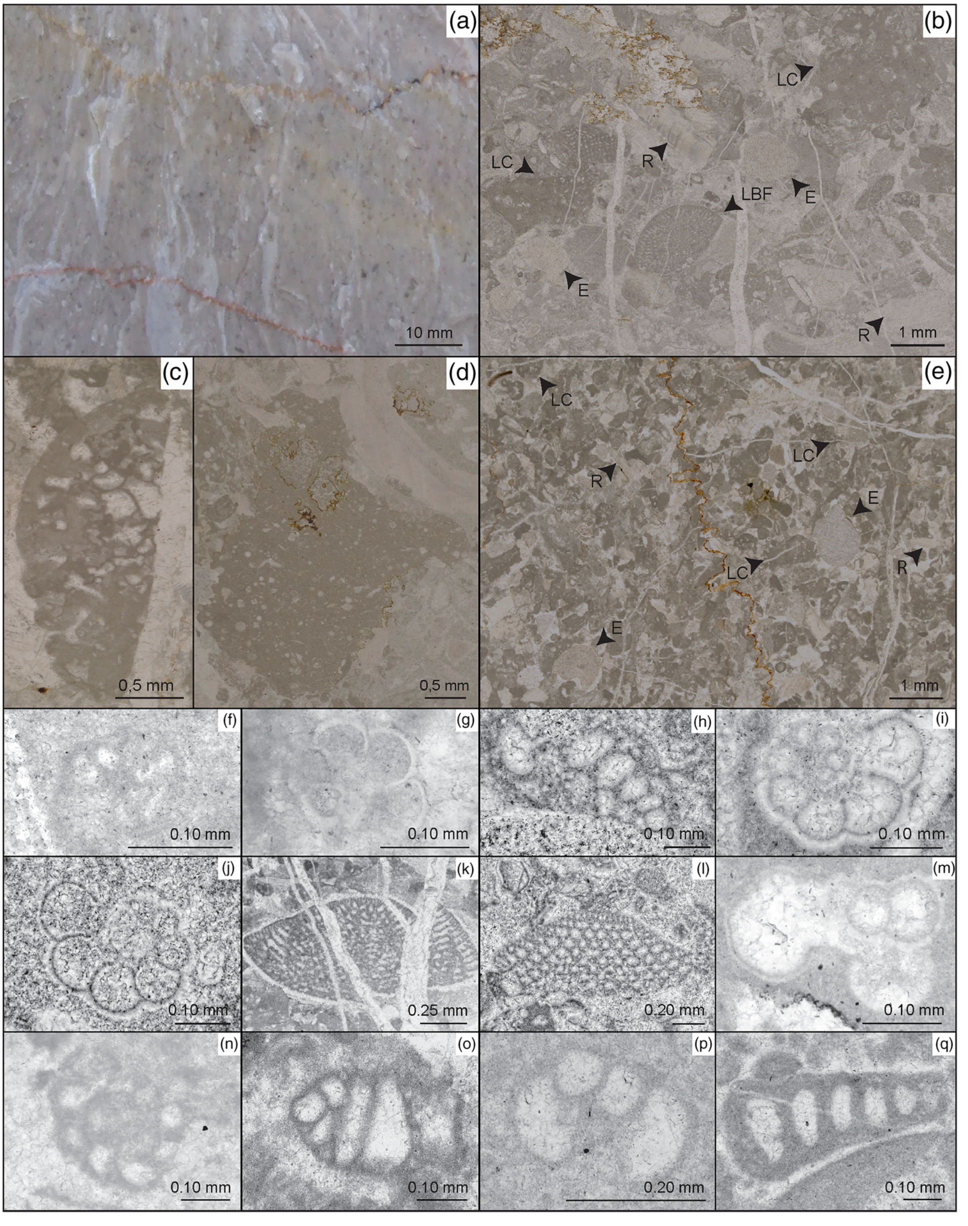


**FIGURE 2** Macrophotographs (a) and microphotographs (b–e) of the mid-Cretaceous calcarenite and foraminifera (f–q) from the stone products of Emona. (a) Macrofacies; note the light colour (N7) and the small black clasts (rudist shell fragments), somewhat characteristic for this calcarenite. Sample MGML 0061375. (b) View of coarse-grained calcarenite with marked bioclasts and lithoclasts (R, rudist bivalve; E, echinoderm debris; LBF, large benthic foraminifer *Mesorbitolina* sp.; LC, lithoclasts). Sample MGML 0061375. Most common lithoclasts (c–d): (c) Boundstone with *Bacinella irregularis* Radoičić. Sample MGML 0059817. (d) Lithoclast of wackestone with calcispheres, sponge spicules and calcispheres. Sample MGML 0061375. (e) View of fine-grained calcarenite with marked bioclasts and lithoclasts (R, rudist bivalve, E, echinoderm debris; LC, lithoclasts). Sample KL 3. (f) *Nezzazatinella picardi* (Henson). Sample MGML 0048568. (g) *Biticinella breggienensis* (Gandolfi). Sample MGML 0051179. (h) *Novalesia angulosa* (Margniez). Sample MGML 0052355. (i) *Ticinella* sp. sample MGML 0052355. (j) *Ticinella primula* (Luterbacher). Sample MGML 0057726. (k) *Orbitolina* sp. Sample MGML 0059817. (l) *Mesorbitolina* sp. Sample MGML 0059817. (m) *Whiteinella* sp. Sample MGML 0060192. (n) *Debarina hahounerensis* (Fourcade, Raoult and Vila). Sample KL 3. (o) *Pseudolituonella* sp. (cf. Reicheli). Sample MGML 60192. (p) *Nezzazatinella* sp. Sample KL 3. (q) *Novalesia distorta* (Arnaud-Vanneau). Sample KL 3

significantly damaging the artefact. The matrix of this breccia is petrographically identical to that of coarse-grained calcarenite, described below.

A more detailed investigation of thin sections revealed that the coarse-grained calcarenite is texturally packstone to grainstone. Grains comprise up to 70% of the surface of the thin section (Figure 2b) and range in size from 0.05 to 3.8 mm, while the average grain size is 1.5 mm. The rock is grain-supported and poorly sorted. At least half of the biogenic grains are echinoderm debris. The second most abundant biogenic grains are fragments of rudist shells. Benthic, and to a lesser extent planktonic foraminifera, are also present. In addition to biogenic grains, peloids and lithoclasts are found. The lithoclasts are irregular in shape and up to 0.5 mm in size. They include boundstone with *Bacinella*-type microproblematica (Figure 2c), bioclastic wackestone with calcispheres, sponge spicules and planktonic foraminifera (Figure 2d), and mudstone lithoclasts. The matrix contains spherical calcite and silica microfossils. The micritic matrix is partially washed out and the cement in both the washed-out areas in the packstone, and within the grainstone, is drusy mosaic.

The fine-grained calcarenite is texturally wackestone to packstone. Grains comprise up to a maximum of 50% of the thin section (Figure 2e). The grains range in size from 0.05 to 0.45 mm, with an average size of 0.21 mm. Sorting is moderately good. The predominant grains are intraclasts and peloids. Biogenic grains include small echinoderm plates, rare debris from rudist bivalves, and planktonic and rare benthic foraminifera. Similar microfacies of lithoclasts as described in the coarse-grained calcarenite are also present in the fine-grained calcarenite. In contrast to the coarse-grained calcarenite described above, orbitilinid foraminifera were not detected in fine-grained facies.

Based on the benthic and planktonic foraminifera present in the rock matrix, we constrained the age for both facies described above (Figure 2f–q). In the coarse-grained calcarenite benthic foraminifera *Nezzazatinella picardi* (Henson), *Mesorbitolina* sp., *Mesorbitolina texana* (Roemer), *Novalesia angulosa* (Margniez), *Debarina hahounerensis* (Fourcade, Raoult and Vila), *Pseudelituonella* sp., *Nezzazatinella* sp., *Novalesia distorta* (Arnaud-Vanneau) and planktonic foraminifera *Ticinella* sp., *Biticinella breggienensis* (Gandolfi) and *Whiteinella* sp. are present, while in fine-grained calcarenite benthic foraminifera *Nezzazatinella picardi* (Henson), *Novalesia angulosa* (Margniez), *Debarina hahounerensis* (Fourcade, Raoult and Vila), *Pseudolituonella* cf. *reicheli* Marie, *Nezzazatinella* sp., *Novalesia distorta* (Arnaud-Vanneau), and planktonic foraminifera *Ticinella* sp., *Biticinella breggienensis* (Gandolfi) and *Whiteinella* sp. can be found. The age of the assemblage for both facies is late Aptian–early Cenomanian.

## Characterization of possible source formations in the local and regional radii of emona

The shallow-marine carbonates south of Ljubljana have been studied previously. These successions (see Figure 4b) correspond to the shallow lagoonal parts of the inner platform (Dozet & Šribar, 1997; Šribar, 1979). Their observations have been confirmed by the field survey performed by the leading author (R.B.).

The thick carbonate successions of the Adriatic Carbonate Platform, however, are not the only possible local source. The Lower Flyschoid Formation studied in the area near the town of Medvode and Verje, Smlednik hills and Lake Zbilje (see Figure 1c) is characterized by limestone breccias, carbonate–chert breccias, coarse-grained and fine-grained calcarenites, marlstone, rare beds of chert (for detail section log see Supplement S2). Marlstone is thin-bedded to laminated and often contains nodules of black, green to black, and reddish chert up to several centimetres in size. Marlstone forms packages up to 5 m thick or is intercalated as thick beds up to 5 cm between thicker beds of calcarenite. Chert beds are up to 10 cm thick and green to black in colour. Calcarenite beds are on average 20 cm thick, and only a few are as large as 50 cm thick. Limestone breccias outcrop in several thick horizons up to 5 m. These breccias are clast supported, often graded and were formed as the result of high-density turbidity flow transport (Rožič, 2005). The lithoclasts are almost exclusively limestone: oolithic grainstone, grainstone with debris of rudist bivalves and echinoderms, boundstone lithoclasts with *Bacinella* sp. microproblematica, light-coloured micritic limestone, and wackestone lithoclasts with calcispheres, sponge spicules and planktonic foraminifera. We have focused on describing the petrographic and microfacies analysis of calcarenite beds. In general, calcarenites can be divided into coarse-grained (Figure 3a) and fine-grained (Figure 3b) facies. The former are clast-supported, poorly sorted and often graded (Figure 3c), with an average grain size of 1.5 mm. The latter are mud-supported, better sorted, and have an average grain size of 0.35 mm. Lamination can be observed in both varieties. Abraded and resedimented bioclasts are the dominant grains in coarse-grained calcarenites. They are represented by echinoderms, fragments of rudist bivalves, and benthic and planktonic foraminifera, whereas lithoclasts and peloids are subordinate in coarse-grained calcarenite and predominate over bioclasts in fine-grained calcarenites. Their proportions vary greatly between samples. Among the lithoclasts described are mudstone, *Bacinella* sp. boundstone, wackestone with calcispheres, sponge spicules and planktonic foraminifera (Figure 3d), grainstone with rudist debris, oolithic grainstone and crystalline limestone.

Spherical pelagic microfossils made of calcite (calcispheres) and silica (radiolaria) were described from the matrix. Among the foraminifera, planktonic species predominate in the fine-grained calcarenite, while benthic foraminifera are more likely to be found in the coarse-grained calcarenite. Late Aptian–early Cenomanian age was determined based on the foraminifera present in the rock matrix: *Novalesia angulosa* (Margniez), *Whiteinella* sp., *Mesorbitolina* sp., *Pseudolituonella* sp. and *Debarina hahounerensis* (Fourcade, Raoult and Vila) (Figure 3e–l).

# DISCUSSION

## Identification of the provenance of the mid-cretaceous calcarenite

The use of Lower–Upper Cretaceous limestones is reported from numerous Roman towns and settlements in Regio X (Djurić & Rižnar, 2017; Džin, 2012; Lazzarini & Van Molle, 2015; Previato, 2018). The greatest part of the Cretaceous limestones was used in those cities that were adjacent to nearby quarries and which supplied the cities with the most important stone materials. Two important sources are known from databases of Roman quarries (Braemer, 2004; Dworakowska, 1983; Russell, 2013). The Roman town of Pola (modern Pula/Pola) was mainly supplied by a local quarry in Vinkuran/Vincural (Crnković, 2003; Džin, 2012). The stone there belongs to the light-grey to white-coloured (N8) Lower to Upper Cretaceous (upper Albian–lower Cenomanian) Milna Formation (sensu Gušić & Jelaska, 1990), which consists of bioclastic wackestone to grainstone (Tišljar et al., 1998; Vlahović & Tišljar, 2003). The succession evidenced in the quarry starts with microbial laminites of biolitite texture, followed by a succession of well-sorted limestone consisting mainly of rudist debris, generally packstone to grainstone in texture, that exhibits a shallowing-upward cycle and intercalations of rudist biostromes and *Chondrodonta* bivalves floatstone to rudstone in texture (Tišljar et al., 1998; Vlahović & Tišljar, 2003).

The Roman city of Aquileia also used the Cretaceous limestone from the nearby quarries of Aurisina/Nabrežina (Previato, 2018). The Upper Cretaceous (Coniacian–Campanian) Aurisina limestone (Cucchi & Piano, 2013) can be stratigraphically divided into the Sežana and Lipica

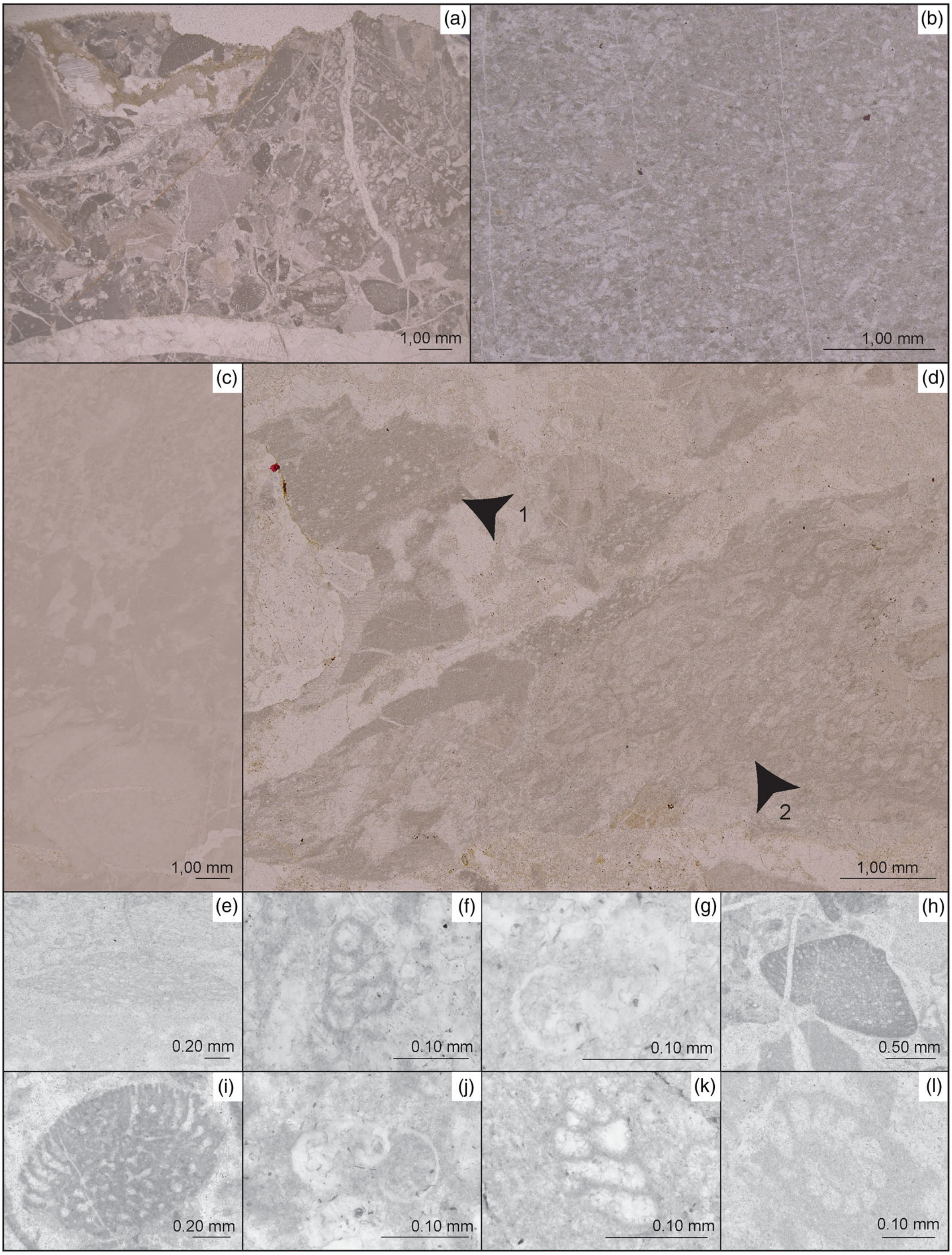


FIGURE 3 Microfacies and foraminifera of calcarenites from the lower Flyschoid formation locations around the Lake Zbilje, Medvode, Verje and the Smlednik hill. (a) Coarse-grained calcarenite. Sample RKS 5. (b) Fine-grained calcarenite. Sample RKS 3. (c) Gradation in coarse-grained calcarenite. Sample S1 14.4. (d) The most common lithoclasts: 1, lithoclasts with calcispheres and sponge spicules; 2, lithoclasts with *Bacinella* sp. microproblematica. Sample RKS 8. (e) *Mesorbitolina* sp. Sample RKS 7. (f) *Novalesia angulosa* (Magniez). Sample RKS 3. (g) *Whiteinella* sp. Sample RKS 5. (h–i) *Mesorbitolina* sp. Sample RKS 5. (j) *Whiteinella* sp. Sample RKS 5. (k) *Pseudolituonella* sp. S1 4.2. (l) *Debarina hahounerensis* (Fourcade, Raoult and Vila). Sample S1 14.4

Formations (Jurkovšek et al., 2016). Both formations belong to the inner parts of the platform (Cucchi et al., 1987; Jež & Otoničar, 2018; Jurkovšek et al., 2013). The main Roman quarry (Previato, 2018) is located in the Santonian–Early Campanian (Maritan et al., 2003) part of the Lipica Formation. The Santonian–Campanian part of the Lipica Formation consists of thick-bedded and massive limestone with rudist biostromes and bioherms floatstone to rudstone in texture (Jurkovšek et al., 2016). The main types of Roman Aurisina/Nabrežina quarry stone include the commercially named 'Aurisina granitello' and 'Aurisina Roman stone' limestones, which consists of bioclastic packstone to grainstone with rudists debri, benthic foraminifera, echinoderms and green algae (Cucchi et al., 1987; Sanders, 2001), and the rudist floatstone to rudstone (Cucchi et al., 1987; Sanders, 1999, 2001), commercially known as 'Aurisina fiorita'.

While the rudist floatstone to rudstone of the Roman quarries at Vinkuran/Vincural and Aurisina/Nabrežina can be macroscopically distinguished from each other according to their macrofossil content (various rudist species), the facies of bioclastic packstone to grainstone are very similar in colour and composition. Divisions according to the provenance of the stone products can be determined based on foraminifer assemblage (Velić, 2007).

The presently studied stone products from Emona differ from the limestone quarried near Aurisina/Nabrežina and Pola/Pula. The limestone from Aurisina/Nabrižina is younger in age and can thus be readily excluded as a possible source of the studied products. The Milna Formation contains similar predominant grains, as well as similar foraminiferal assemblages. However, the Milna Formation lacks the lithoclasts that originate from the distal parts of the slope.

Lower Cretaceous carbonate deposits are well exposed in SW Slovenia (Buser, 2010). Lithostratigraphically, the Lower Cretaceous carbonates in this area belong to the Valanginian–Aptian Brje Formation, while the Povir Formation is Aptian–Cenomanian in age (Jurkovšek et al., 2013, 2016). Both formations were deposited in lagoonal environments of the shallow-marine Adriatic Carbonate Platform (Buser, 1989; Picotti et al., 2019; Vlahović et al., 2005). Taking into consideration only the closer surroundings of Emona/Ljubljana, these two formations outcrop SW of Ljubljana between Logatec and Vrhnika (Pleničar, 1963), and SE of Ljubljana around Dobrepolje (see Figure 4b) (Buser, 1965). The facies and the microfossil content of the limestone from these locations were described in detail by Šribar (1979), Cousin (1981) and Dozet and Šribar (1997). The concept of lithostratigraphic division (Jež & Otoničar, 2018; Jurkovšek et al., 2016) has not yet been applied to Cretaceous carbonates in the locations SE (Logatec and Vrhnika) and SW (Dobrepolje) of Emona/Ljubljana. However, Šribar (1979) and Dozet and Šribar (1997) described microfacies very similar to those from the Brje and Povir Formations. As these formations lack the suitable facies and corresponding foraminifera assemblage found in the calcarenites used to produce the studied stone products, they were excluded as the possible source unit.

Calcarenite and sedimentary limestone breccia beds formed by high-density turbidity flow deposits (Rožič, 2005), however, are a constituent of the Aptian–lower Cenomanian Lower Flyschoid Formation from western and central Slovenia (Cousin, 1981; Rožič, 2005) that was deposited within the Slovenian Basin. The latter was a deep-marine paleogeographic domain located adjacent to the Adriatic Carbonate Platform (Caron & Cousin, 1972; Rožič, 2005; Rožič et al., 2014; Samiee, 1999). The Lower Flyschoid comprises hemipelagic and pelagic marlstone and claystone, interchanging with gravity deposits, mostly calciturbidites (Buser, 1986, 1989; Koch et al., 1989; Rožič, 2005). Carbonate deposits are present within the Lower Flyschoid and the Gora Formations in the form of thin- to very thick-bedded and even massive calciturbidites (Caron & Cousin, 1972; Rožič, 2005; Rožič et al., 2014; Samiee, 1999). The composition of the clasts, which comprise time-equivalent as well as older rocks, corresponds to the carbonate platform margin, the middle part of the slope, and even the basin floor (Rožič, 2005; Samiee, 1999). So far, the sedimentology and stratigraphy of the Lower Flyschoid Formation have only been studied in western Slovenia (Caron & Cousin, 1972; Koch

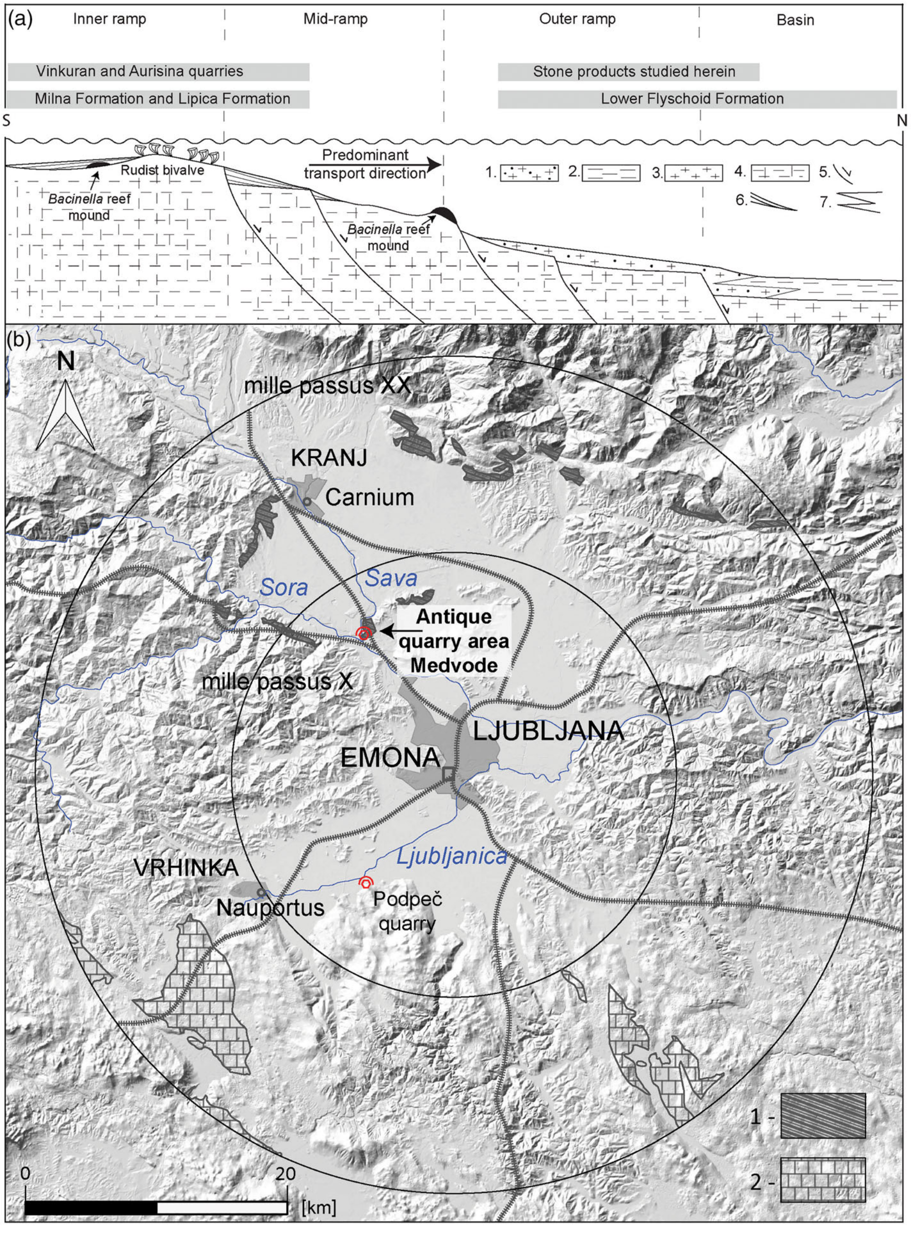


**FIGURE 4** Provenance of mid-Cretaceous calcarenite. (a) Schematic interpretation of the sedimentation environment (after Flügel, 2004; Fuček et al., 2003; Jurkovšek et al., 2016; Koch et al., 2002; Rožič, 2005; Tišljar et al., 1998) of the Lower–Upper Cretaceous stone source formations and stratigraphic attribution of Cretaceous stone products in Regio X (marked in grey). We note that Aurisina limestone is younger, but the sedimentary model remains rather uniform throughout the time period discussed herein: 1, deeper marine resediments (breccia and calcarenite); 2, pelagic sediments (limestone, marlstone, claystone, chert); 3, older deeper marine rocks; 4, older shallow marine carbonates; 5, normal faults; 6, shallow marine sediments progradation; 7, deeper marine sediments progradation). The figure is not to scale. (b) Lower to mid-Cretaceous deposits (1, deeper-marine carbonates; 2, shallow-marine limestone) in the surroundings of Emona, modified after Buser (2010), with Roman towns, main rivers, traces of Roman roads from Šašel Kos (1997), radii for local and regional provenance (see Djurić & Rižnar, 2017; Flügel & Flügel, 1997) and newly proposed quarry area drawn in. The source of the topography is a 1 m × 1 m resolution digital relief model (Surveying and Mapping Authority of the Republic of Slovenia, 2011)

et al., 1989; Rožič, 2005; Rožič et al., 2014; Samiee, 1999); however, the Lower Flyschoid Formation also outcrops closer to Ljubljana in smaller areas around Zbilje Lake, Medvode, Verje and on the Smlednik hill. These successions were studied herein.

The age, texture, grain composition, presence and composition of lithoclasts, colour, and thickness of the stone products and calcarenite beds in the Lower Flyschoid Formation appear to be consistent with the rocks observed in the stone products. In particular, the presence of planktonic foraminifera and distal lithoclasts in the stone product samples attest to the deposition of the calcarenite in open marine environments (Figure 4a).

The lithological successions similar to those of the Lower Flyschoid Formation and Emona's mid-Cretaceous stone products are known from more distant areas in Slovenia (Cousin, 1981; Koch et al., 1989; Rožič et al., 2014; Sartorio et al., 1992), while regional correlations for the studied lithofacies described in the stone products of Emona appear at the margins of the transitions from platforms to basins (Borgomano, 2000; Bosellini, 2002; Dragičević & Velić, 2002; Sartorio et al., 1992, 1997; Vlahović et al., 2005). However, by reviewing the age and facies in the regionally known Roman quarries (Braemer, 2004; Dworakowska, 1983; Russell, 2013) located on the Dalmatian coast (Škegro, 2006), in Istria/Istra (Džin, 2012) and in Puglia (Calia et al., 2002), none was found to correlate with the studied stone products lithofacies deriving from the regionally known marginal areas of the platforms (Bosellini, 2002; Dragičević & Velić, 2002). Therefore, no presently known source of stone quarried in Antiquity has been found that corresponds to the examined stone products. Assuming that the stone used by the Romans was of local origin, the calcarenites from the Lower Flyschoid Formation appear to be the source (see Supplement S3 for all locations studied). The closest known outcrops that match in terms of facies and bed thickness to the studied stone products from Emona are located at the sampling site near the modern town of Medvode (Figure 4b); (see Supplement S4 for additional data), which was/is connected to Emona (mod. Ljubljana) via a navigable section of the Sava River (Gaspari, 2012; Umek, 1986).

## The importance of mid-cretaceous calcarenite in emona's stone trade

Many factors influence the extraction of stone, such as bedding thickness, density of discontinuities in the rock, hardness of the rock, dip of the beds, accessibility of the outcrop, and the means and costs of transportation (Djurić, 1997; Djurić et al., 2022). The current databases of Antique quarries mentioning the supply of stone to Emona (Djurić, 1997; Djurić & Rižnar, 2017; Russell, 2013) already include several proposed quarry sites, of which the Podpeč quarry is by far the largest (Djurić et al., 2022).

The proportion of mid-Cretaceous calcarenite in the total number of preserved columns (bases, capitals, shafts) in Emona is low (10.8%). Nevertheless, it is higher than the proportion of imported columns from the Aurisina/Nabrežina quarries (7.7%). The ratio of cinerary urns reveals a different situation: urns imported from Aurisina/Nabrežina (36.4%) are twice as numerous as those from the mid-Cretaceous calcarenite (18.2%). A similarly large difference is observed in the preserved tombstones, where the proportion of products from Aurisina/Nabrežina limestone (18.2%) is almost one-third higher than that of mid-Cretaceous calcarenite products (15.2%). If we consider only tombstones from the 1st century, the share of the Aurisina/Nabrežina limestone products (23.1%) is considerably higher than that of products from the mid-Cretaceous calcarenite (15.4%). For the other types of products, the share of both Cretaceous lithofacies is roughly equal (Figure 5a). The workmanship of the studied products was not of the quality of the workmanship of the imported products. While comparable to those made in Podpeč (Djurić et al., 2022) the studied stone products are even coarser in shape. Although it is difficult to assess due to the lack of previous data (only a few early stone products from Podpeč are known), the production of building stone in the

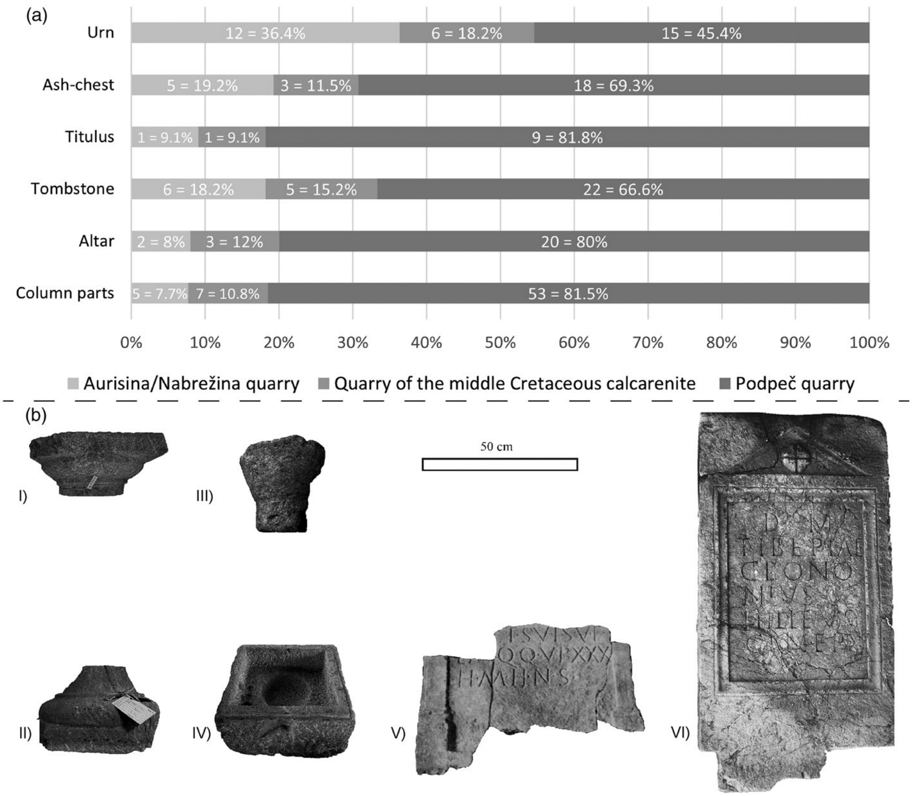


**FIGURE 5** Mid-Cretaceous stone products from Emona. (a) Proportion of product types arranged according to provenance. (b) Chronologically tentatively definable products to 1st century CE (I–VI), made from mid-Cretaceous calcarenite. Inventory numbers of presented stone products: (I) MGML 0060208; (II) MGML 0057721; (III) MGML S0106043; (IV) NMS L256; (V) MGML 0051183; (VI) NMS L165

form of untreated slabs should also be noted. This indicates that thin-bedded calcarenite was also present in the quarry, which can also be interpreted from the estimated thickness of the bed of origin.

As argued above, the most plausible source of the mid-Cretaceous calcarenite points to the provenance from the Lower Flyschoid Formation north of Emona/Ljubljana. Based on the epigraphic analyses (Šašel Kos, 1997; Visočnik & Županek, 2018; Visočnik et al., 2017) and other tentatively definable stone products (Figure 5b), extraction of the rock began in the first half of the 1st century and lasted through the duration of the 2nd century (with production likely peaking in the 1st century). Production times are too long to assume that the rock was only taken from the surface. The products also indicate a relatively wide range of uses (see Table 1), and a well-thought-out extraction scheme (the extraction of thinner beds seems to favour the production of paving and raw slabs). Based on the basic shaping of the studied stone products and the wide range of types of stone product (including building stone for urban infrastructure and architecture), it is reasonable to assume that the stone was quarried locally and worked in a quarry that supplemented the (early) needs of Emona's inhabitants. This reinforces the Lower Flyschoid Formation north of Emona/Ljubljana as the most plausible source. However, due to the construction of the HE Power Plant (see Figure 1c), a highly altered surface and riverbed prevented us from gathering data on other input factors, such as geomorphological or direct archaeological evidence of the quarry's very existence.

# CONCLUSIONS

A significant portion of the stone products from Emona were made from a calcarenite of Late Aptian–Lower Cenomanian (mid-Cretaceous) age. The calcarenite is macroscopically characterised by its light grey colour (N6–N7) and the presence of small black grains representing rudist debris. At the thin-section level, the calcarenite is texturally packstone to grainstone. Its most notable characteristics are the presence of planktonic foraminifera in the matrix and the presence of various lithoclasts derived from the carbonate margin or the transition from slope to basin. Appropriate geological setting areas were reviewed against reported Roman quarries to date. Since this lithofacies in stone products has until now only been reported in the present article, a new source had to be found. The detailed optical microscopy of both primary outcrops and stone products presented herein have allowed us to correlate the stone products with the outcrops of the Lower Flyschoid Formation within the radii of local origin. The long production timeline indicates the continuous extraction of stone, probably from a quarry that supplemented the main production of the Podpeč quarry for Emona. A suitable place for the extraction was identified within the radius of local origin on the banks of the Sava River, where calcarenites of the Lower Flyschoid Formation outcrop at the surface (see Figures 1c and 4b). The presumed local origin is further confirmed by a wide range of uses (sepulchral and architectural elements, including building stone). The newly defined quarry most likely operated primarily in the early stages (1st and early 2nd centuries CE) of the construction and equipping of the Colonia Iulia Emona and its cemeteries.

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## PEER REVIEW

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## DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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