Journal of Archaeological Science: Reports 13 (2017) 382–394

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

# Spatial distribution and functional relationship of local bedrock and stone constructions in the cultural landscape of ancient Anuradhapura (377 BCE–1017 CE), Sri Lanka

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A R T I C L E I N F O

*Keywords:*
Petrography
Stone architecture
Sacred buildings
Ornamental rocks
Quarrying

A B S T R A C T

The city of Anuradhapura, founded on the banks of the River Malwathu Oya, was the ancient capital of Sri Lanka between the 4th century BCE and the 11th century CE. The widespread architectural remains of the ancient city make it the most important archaeological site in the cultural landscape of the country. Most of the foundations, floor areas, pillars, and entrance units of the ancient constructions consist of stone materials, evidencing that stones were the principal building material in the ancient Kingdom of Anuradhapura. Numerous ancient rock quarries are located inside and outside the ancient city complex; most of them can be found along a N-S striking line of rock outcrops that runs through the historic city.

This study focuses on the importance of the availability of stone resources for the founding and development of early Anuradhapura settlement. For this purpose the building rocks in the ancient constructions are analyzed and the spatial distribution of their source areas examined using the petrological, chemical and mineralogical characterization of both building and source rock specimens.

The investigations document the predominant application of local gneissic rocks for construction elements such as pillars, stairs, balustrades and foundations. Contrastingly marble, which is not represented in the local lithology, was imported and utilized for ornamentation in sacred and residential buildings.

## 1. Introduction

The ancient city of Anuradhapura functioned as capital of the Singhalese kingdom in north-central Sri Lanka from the 4th century BCE to the 11th century CE. The comprehensive architectural remains point to the importance of Anuradhapura in the archaeological landscape of Sri Lanka. Until today, the ruins of sacred and residential constructions are evidence of the outstanding architectural and artistic culture during the Anuradhapura period (Bandaranayake, 1974).

This period's architecture is in Anuradhapura characterized by a mixed material tradition that used burnt bricks, timber and stones (Bandaranayake, 1974). The majority of foundations, floor areas, pillars, and entrance units of the buildings consist of stone blocks and provide evidence that rocks were the primary building material used for the construction of monumental buildings or elements. Gneissic rocks were the preferred building material in the ancient built environment of Anuradhapura.

The ancient city of Anuradhapura is located in a gently rolling plain. To the east of the city, the river of Malwathu Oya flows in a northerly direction. The basement rock of the area is dominated by metamorphic rocks (Kröner et al., 1994; Cooray, 1995). Superficial rock exposures are rare in the area due to a thick saprolite cover (Ball and Herbert, 1992; Schütt et al., 2013). The few rock exposures in the area occur west of the city along a linear outcrop, which runs from south to north. The majority of ancient architectural features, like the Citadel as the fortified center of the ancient city and numerous monasteries, were situated between the Malwathu Oya River and the rock outcrop line (Fig. 1).

Today the architectural remains of Anuradhapura still provide an impressive image of the wealthiness and the technical know-how of its

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http://dx.doi.org/10.1016/j.jasrep.2017.03.060
Received 11 April 2016; Received in revised form 6 March 2017; Accepted 8 March 2017
Available online 26 April 2017
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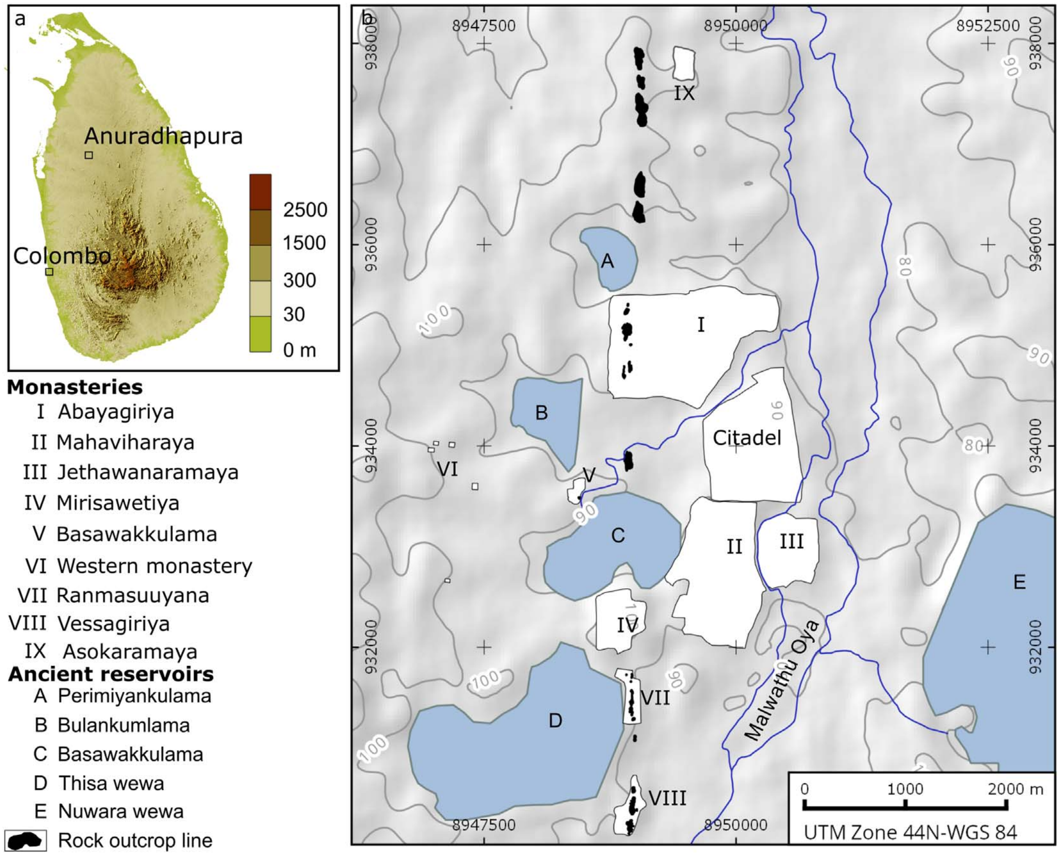


**Fig. 1.** Overview of the study site in north-central Sri Lanka (a) Location of Anuradhapura in Sri Lanka, (b) The ancient city of Anuradhapura, with the Citadel, monasteries and ancient reservoirs (locally Wewa or tank). Elevation data based on (Jarvis et al., 2008).

residents and kings. The high relevance of rocks as construction material from 200 BCE onwards was shown by Wagalawatta et al. (2016, 2015). The objective of this paper is to characterize the spatial distribution and functional relationship of local bedrock and built-in rocks of ancient constructions in the archaeological site of Anuradhapura. Geochemical and mineralogical compositions of local bedrock and rocks utilized as construction material are analysed to provide information on the material available. By combining survey data of utilized construction material with a petrographic characterisation of the local bedrock and built-in rocks of constructions, we aim to answer the question, if particular rocks are utilised in specific functional contexts in the built environment of the ancient city of Anuradhapura.

## 2. Study area

### 2.1. Natural setting

The city of Anuradhapura is located in the north-central lowlands of Sri Lanka (8°21′ N, 80°23′ E; 89 m asl). The climate is tropical with an average annual temperature of 27.1 °C and annual precipitation of 1198 mm (FAOCLIM, 2001). Due to its location north of the central highlands of Sri Lanka, which function as an orographic barrier, southwest (May–September) and northeast monsoon (December-February) provide only few rainfall (Schütt et al., 2013; Puvaneswaran and Smithson, 1991). The majority of annual rainfall occurs in the inter-monsoonal periods from March to May and October to November (Domroes and Ranatunge, 1993).

The topography of the area is generally flat, except for some isolated hills (inselbergs) which rise above the gently rolling plain (Fig. 1b). A saprolite layer up to several meters thick resulting from intensive chemical weathering under tropical climatic conditions overlies the bedrock in areas undisturbed by erosion (Schütt et al., 2013). A narrow ridge made up of granitic gneiss is the only prominent elevated morphological feature of the area. It raises up to 30 m with respect to the local elevation and strikes N-S crossing the ancient city. This bedrock outcrop line extends over more than 4 km and has a maximum width of 100 m (Figs. 1, 2).

Bedrock corresponds to high-grade meta-sedimentary and meta-igneous rocks of the Precambrian Wanni Complex (Fig. 2a). In the study area most rocks are trending in an N-S direction (Fig. 2b). Exposures of granitic gneiss outcrops are common as N-S striking belt through the ancient city of Anuradhapura (Fig. 2b). Granitic gneiss and charnockitic gneiss are the prominent rocks in the area (Fig. 2b). Rock exposures are rare. Marble does not occur in the study area. The nearest outcrops of marble are situated in Kanadarawa and Medagama, located 12 km Northeast and 42 km South of Anuradhapura.

### 2.2. Settlement history

Excavations in the Citadel have yielded information on the formation of permanent human settlements during the Early Iron Age (900–600 BCE) and the Basal Early Historic period (600–500 BCE) (all dates according to Deraniyagala, 2004). For these periods traces of iron technology, pottery, domestic cattle and horses as well as paddy-cultivation have been documented (Coningham, 1999; Deraniyagala, 2004). Evidence of writing appeared around 500 BCE for the first time in Sri Lankan history (Deraniyagala, 2004) (Table 1).

The initial urbanization of Anuradhapura began during the Lower Early Historic period (500–250 BCE) (Deraniyagala, 2004). According to the Mahavamsa chronicle, King Pandukabaya (reign 437–367 BCE) developed the rural settlement known as 'Anuradhagama' to the capital of his kingdom (Mahavamsa, 1912). From the beginning of the Mid-Early Historic period (250 BCE–100 CE), the administrative mechanism of the city became more refined and Anuradhapura extended its

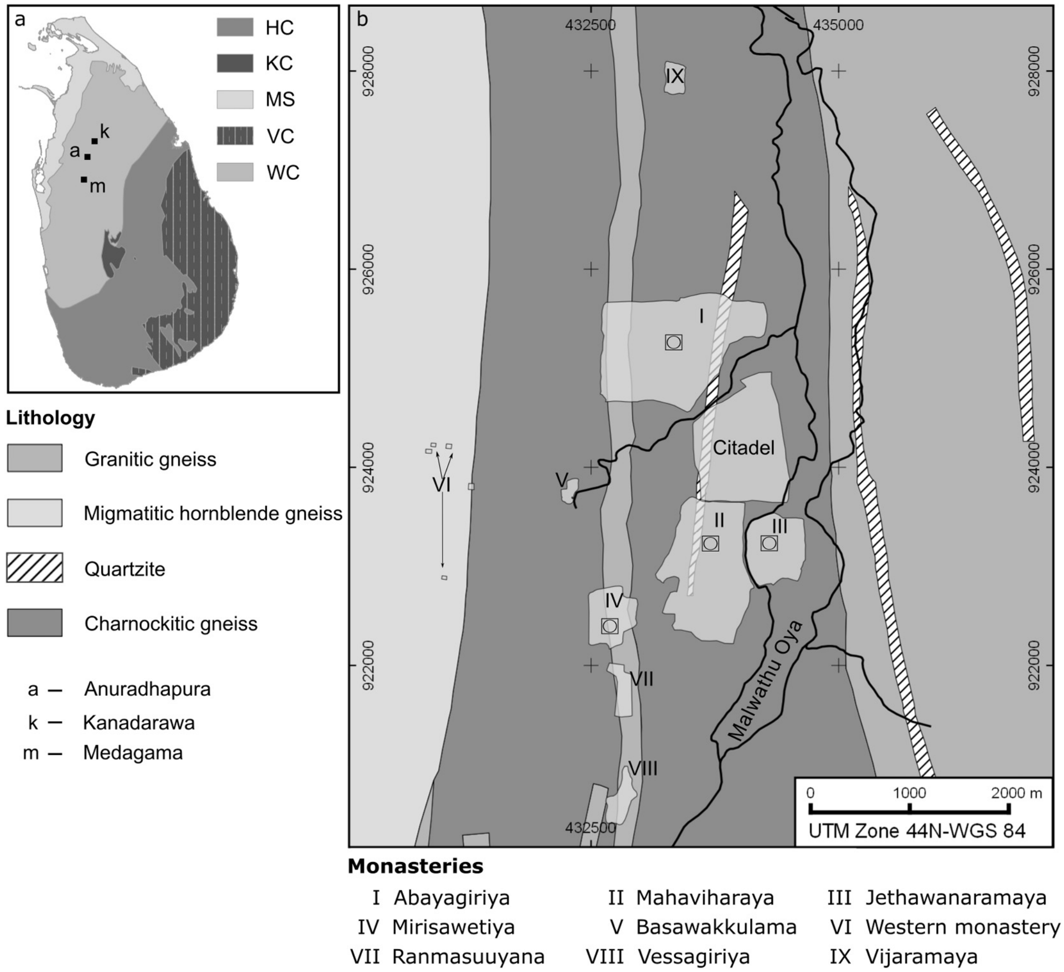


**Fig. 2.** The lithological character of Sri Lanka and the study area. (a) Location of Anuradhapura within the geological complexes of the island (HC - Highland Complex, KC - Kadugannawa Complex, MS - Miocene Sediment, VC - Vijayan Complex and WC - Wanni Complex) and (b) study area with its regional lithology and locations of ancient Buddhist monastic complexes in the ancient city area of Anuradhapura; (lithological regions based on GSMB, 1995, 2001, 2009b, 2009a).

**Table 1**
Cultural sequence and material evidence of ancient settlers in Anuradhapura (compilation after Deraniyagala, 2004; Deraniyagala, 1972; Coningham, 1999; Coningham, 2006; Seneviratne, 1987; Seneviratna, 1994; Cave, 1907; Mahavamsa, 1912, cultural sequence corresponds to Deraniyagala, 2004).

| Cultural sequence | Time | Occurrences |
|---|---|---|
| Early Iron Age | 900–600 BCE | Iron, horse, domestic cattle, paddy cultivation, wattle-and-daub constructions, wheel-made pottery |
| Basal Early Historic period | 600–500 BCE | Iron, cattle, horse, roofing tile, wheel-made pottery, Early Brahmi (writings), arrival of Vijaya |
| Lower Early Historic period | 500–250 BCE | Imported ceramics, more technologically advanced roofing tile, iron, burnt bricks, minor irrigations, using rock shelters as dwellings |
| Mid Early Historic period | 250 BCE–100 CE | Imported ceramics, more technological advanced roofing tile, iron, burnt bricks, coins, glass, first large tanks |
| Upper Early Historic period | 100–300 CE | Coins (local and Indo-Roman), decorated building stone, imported ceramics, major and minor monasteries, buildings with |
| Middle History | 300–1250 CE | whitewashed walls, massive irrigation systems, extended sovereignty over the hinterlands |

sovereignty over the entire hinterland (De Silva, 2000; Mendis and Weerasekara, 2013). During this period, the city rapidly developed its various residential and religious sectors (citadel, major and minor monasteries), including reservoirs and agricultural areas (Cave, 1907; Seneviratna, 1994, Seneviratne, 1987). The Upper Early Historic epoch (100–300 CE) is regarded as the period of growth; parallel to demographic expansion, a large-scale settlement developed with a water supply system based on major human-made reservoirs (Seneviratne, 1984). Imported ceramics from northern India to the Mediterranean region illustrate the supra-regional importance of the city at this time (Coningham, 2006, Coningham, 1999; Deraniyagala, 2004). Furthermore, Anuradhapura is regarded as one of South Asia's major sites of pilgrimage, attracting merchants from all over the Indian Ocean (Coningham, 1999; Coningham, 2006). The Chinese Buddhist monk Fa-Hsien, who visited Anuradhapura in the 5th century CE, reported that the city of Anuradhapura was a Buddhist center with around 60,000 monks living in monasteries in and around the city (Fa Hsien, 1923). After the invasion by South Indians in 1017 CE (Chulawamsa, 1953) Anuradhapura collapsed and a new kingdom was established with a capital in Polonnaruwa (c. 80 km south east of Anuradhapura).

The earliest trace of paddy cultivation in Anuradhapura is documented for the Early Iron Age (900–600 BCE) (Deraniyagala, 2004) (Table 1). According to inscriptional evidences, the land-use pattern in ancient Anuradhapura was characterized by rice cultivation intertwined with other crops that were less dependent on the availability of water (Paranavithana, 2001). Today rice cultivation represents the main present-day land use in the Anuradhapura region (Bandara, 2003). Rice is predominantly cropped in lower topographic positions


Fig. 3. Stone-made structures in the ancient city of Anuradhapura. (a) Restored monastic building with stone-made foundation, door and window frames, guard stones and balustrades in Abayagiriya monastery. (b) Ancient Bodhi tree shrine decorated with marble stones in the Abayagiriya monastery. (c) Marble sculptures (ancient Buddha statues in the restored temple of Ruwanweliseya in the Mahavihara monastery). (d, e) Migmatitic hornblende gneiss pillars were used in the entrance of a double-platform monument in the Western monasteries. (photographs taken by Wagalawatta et al., 2015).

or on the alluvial soils (Gilliland et al., 2013). Shifting cultivation, locally known as “Chena cultivation” (Dharmasena, 1994; Silva, 1977, Kingwell-Banham and Fuller, 2012) frequently occurs on the upper slopes, close to the divides (Gilliland et al., 2013).

### *2.3. Ancient architecture of Anuradhapura*

The preserved floors of residential and workplace wattle-and-daub constructions, dating to the Early Iron Age represent the earliest architecture of Anuradhapura, (Coningham, 2006, Coningham, 1999) (Table 1). After the arrival of Buddhism, natural rock shelters were frequently utilized as the dwelling places of Buddhist monks (Mahavamsa, 1912). Today these sites are easy to recognize due to the drip ledges created over the roof portal, which controlled rainwater trickling into the rock shelter (Bandaranayake, 1974; Coningham, 1995).

According to the archaeological evidence, burnt bricks gradually rose to prominence as main construction material during the Mid-Early Historic period and were the prime material since the Upper Early Historic period (Deraniyagala, 2004, Deraniyagala, 1972) (Table 1). The utilization of stone blocks as construction materials did not start before the Upper Early Historic period (Coningham, 2006, Coningham, 1999; Deraniyagala, 2004).

Most of the preserved building structures in the ancient monasteries of Anuradhapura were probably constructed after the 5th century CE (Bandaranayake, 1974). While the lost structures of the upper floors, especially the roofs and upper walls, probably consisted of perishable materials, mainly timber (Bandaranayake, 1974; Ranaweera, 2013). Stone materials are the major architectural feature of both buildings and non-building structures in Anuradhapura during the Middle History. In Anuradhapura stone blocks were predominantly integrated in the foundations, platforms, floor areas, and pillars of sacred and residential buildings (Brown, 2013). In non-building architectural features stone blocks were utilized for irrigational constructions, sculptures, ancient bridges and ramparts (Coningham et al., 2007; Schroeder, 1990; Shannon and Manawadu, 2007). The utilization of rocks as construction material is also documented in other historic sites in Sri Lanka, pointing to the utilization of local outcropping materials. In Polonnaruwa migmatitic hornblende biotite gneiss are the prevailing rocks used in constructions (De Jayawardena, 2015). Granitic gneiss and marble dominate as construction material in the fortress of Sigiriya (Katupotha and Kodituwakku, 2015).

Ancient quarries are predominantly situated along the rock outcrop line, which consist of granitic gneiss and intersects the area in an N-S direction (Fig. 2). The quarries are mostly located (i) at boulders exposed on the surface (at the side or on the top), (ii) directly at surface level, or (iii) associated with rock shelters (Wagalawatta et al., 2015). Further quarries are found at the bottoms of the Basawakkulama tank

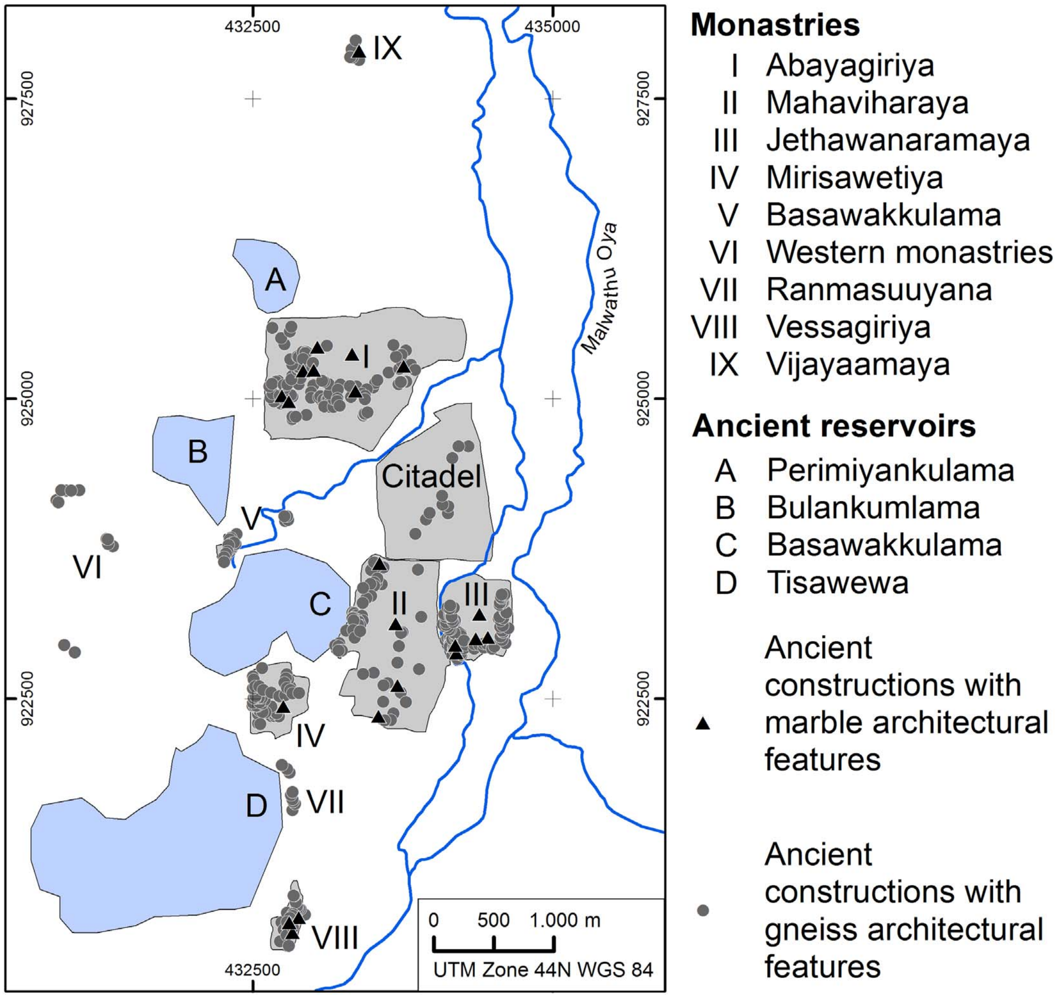


**Fig. 4.** Spatial distribution of ancient constructions consisting of gneissic rocks and of marble.

and the tank Tisawewa. Pit quarries are located west of the city where migmatitic hornblende gneiss occurs below a saprolithic layer. The Western monasteries were built in close proximity to these quarry pits (Wagalawatta et al., 2015).

## 3. Material and methods

### 3.1. Field work and data recording

During field investigations (March 2013 and April 2014), monasteries and habitation sites with ancient stone constructions, ancient quarries and natural outcropping rocks as well as ancient reservoirs were systematically identified and surveyed (Fig. 3).

The petrological characteristics of building and source rocks were macroscopically described, focusing on their dominant structural and textural features and mineral composition. Samples collected from ancient buildings are fragments detached as results of natural and mechanical degradation (gneiss samples $n = 28$, marble samples $n = 10$). In the case of monuments with several building stages, a visual check was made to identify whether the collected fragments originated from the original building or from an unrestored part. Unsecured pieces were excluded from the analysis. Collected bedrock samples originate from ancient quarry sites and natural rock exposures (gneiss samples $n = 19$, marble samples $n = 4$) (Table S1, supplementary data). All samples were collected with the permission of the Department of Archaeology, Sri Lanka. In all cases only unweathered material with fresh surfaces was sampled and analyzed.

The entire fieldwork was documented with photographs. The locations were recorded using a handheld GPS device (Garmin 60CS). Lithological maps at a scale of 1:100,000 (GSMB, 2009a, 2009b, 2001, 1995) were incorporated to support the fieldwork. A digital elevation model (SRTM 3; 90 m $*$ 90 m pixel size) was used to delineate the topography of the study area.

### 3.2. Laboratory analysis

A portable Analyticon NITON XL3t energy-dispersive X-ray fluorescence spectrometer (p-ED-XRF) equipped with a CCD-camera for visual spot control and a semi-conductor detector was applied to analyze the elemental composition of samples. All samples were homogenized using a WIDIA-steel agate swing mill and kept dry at 55 °C. For analysis we placed ~4 g of the homogenized sample into a plastic cup and sealed it with a mylar foil (0.4 μm). The cups were mounted on the p-ED-XRF and measured for 120 s with different filters to detect specific elements (Table S2, supplementary data). The p-ED-XRF was calibrated using internal reference material (IRM; cf. Supplementary data), calibration was re-checked with the IRM every 12 measurements.

The standard material used for calibration results from 12 representative samples from local gneiss and marble. The chemical composition of these samples was analyzed with a wavelength dispersive XRF at the Institute of Applied Geosciences of the Technische Universität Berlin against an extensive set of certified reference materials (see supplementary data). The twelve representative samples were then used as in-house standard material and measured repeatedly through-

**Table 2**
Major oxide and minor element concentration of gneiss rocks (oxides (mass%) and traces (ppm)) (values displayed are four times larger than their 1σ measurement error).

| | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $K_2O$ | $P_2O_5$ | LOI[a] | SUM[b] | Ba | Zr | Sr | Rb | Zn | Co | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Granitic gneiss: building rocks* | | | | | | | | | | | | | | | | |
| AB.32.Bu | 73.0 | 0.20 | 11.0 | 1.41 | 0.96 | 5.10 | 0.11 | 0.32 | 92.1 | 0.15 | 0.040 | 0.040 | 0.010 | 0.020 | 0.010 | 0.010 |
| AB.34.Bu | 72.9 | 0.19 | 10.8 | 1.37 | 0.95 | 5.12 | 0.10 | 0.30 | 91.7 | 0.15 | 0.002 | 0.037 | 0.009 | 0.009 | 0.010 | 0.013 |
| AB.39.Bu | 81.5 | 0.07 | 9.4 | 1.34 | 0.39 | 4.91 | 0.10 | 0.13 | 97.8 | 0.04 | 0.022 | 0.002 | 0.023 | 0.018 | 0.022 | 0.001 |
| BK.09.Bu | 76.2 | 0.13 | 11.3 | 1.55 | 1.09 | 5.29 | 0.12 | 0.35 | 96.0 | 0.06 | 0.016 | 0.010 | 0.018 | 0.014 | 0.019 | 0.005 |
| C.01.Bu | 75.7 | 0.14 | 11.2 | 1.59 | 1.20 | 5.11 | 0.10 | 0.27 | 95.3 | 0.07 | 0.011 | 0.011 | 0.019 | 0.015 | 0.017 | 0.005 |
| J.02.Bu | 77.6 | 0.14 | 12.3 | 1.62 | 1.19 | 5.03 | 0.15 | 0.30 | 98.3 | 0.06 | 0.012 | 0.011 | 0.016 | 0.016 | 0.017 | 0.005 |
| J.03.Bu | 72.2 | 0.37 | 11.6 | 0.93 | 0.88 | 5.10 | 0.15 | 0.58 | 91.8 | 0.22 | 0.019 | 0.135 | 0.010 | 0.010 | 0.014 | 0.020 |
| MR.01.Bu | 77.2 | 0.10 | 10.0 | 1.85 | 0.72 | 5.43 | 0.11 | 0.32 | 95.7 | 0.05 | 0.021 | < d.l. | 0.027 | 0.015 | 0.010 | 0.003 |
| MR.04.Bu | 71.4 | 0.50 | 11.8 | 5.76 | 3.57 | 0.92 | 0.21 | 0.65 | 94.8 | 0.06 | 0.019 | 0.030 | 0.001 | 0.009 | 0.015 | 0.005 |
| MR.05.Bu | 73.4 | 0.38 | 9.8 | 1.41 | 1.24 | 3.60 | 0.09 | 0.38 | 90.3 | 0.33 | 0.006 | 0.044 | 0.005 | 0.012 | 0.019 | 0.033 |
| VI.03.Bu | 73.4 | 0.29 | 11.7 | 3.11 | 1.39 | 5.35 | 0.09 | 0.32 | 95.7 | 0.07 | 0.038 | 0.009 | 0.013 | 0.016 | 0.011 | 0.006 |
| VI.04.Bu | 73.1 | 0.11 | 12.1 | 0.85 | 1.27 | 4.92 | 0.08 | 0.30 | 92.7 | 0.12 | 0.003 | 0.040 | 0.008 | 0.007 | 0.007 | 0.009 |
| WM.03.Bu | 74.6 | 0.14 | 10.9 | 1.81 | 0.75 | 5.71 | 0.06 | 0.50 | 94.5 | 0.07 | 0.016 | 0.008 | 0.020 | 0.012 | 0.010 | 0.005 |
| WM.04.Bu | 73.9 | 0.21 | 10.4 | 1.82 | 1.34 | 5.28 | 0.07 | 0.45 | 93.5 | 0.10 | 0.019 | 0.019 | 0.013 | 0.010 | 0.014 | 0.009 |
| WM.07.Bu | 76.1 | 0.30 | 10.4 | 1.83 | 1.31 | 5.27 | 0.15 | 0.49 | 95.9 | 0.06 | 0.020 | 0.020 | 0.010 | 0.010 | 0.010 | 0.010 |
| WM.08.Bu | 74.1 | 0.34 | 11.0 | 2.28 | 1.29 | 5.54 | 0.13 | 0.44 | 95.1 | 0.09 | 0.027 | 0.020 | 0.017 | 0.013 | 0.023 | 0.008 |
| WM.09.Bu | 74.9 | 0.20 | 11.7 | 1.70 | 1.25 | 5.71 | 0.15 | 0.47 | 96.1 | 0.07 | 0.015 | 0.015 | 0.021 | 0.009 | 0.009 | 0.006 |
| WM.16.Bu | 76.2 | 0.23 | 11.6 | 1.83 | 1.25 | 5.44 | 0.15 | 0.41 | 97.1 | 0.06 | 0.015 | 0.016 | 0.025 | 0.009 | 0.010 | 0.006 |
| WM.17.Bu | 77.2 | 0.27 | 11.9 | 2.16 | 1.36 | 5.58 | 0.13 | 0.53 | 99.1 | 0.06 | 0.020 | 0.017 | 0.017 | 0.012 | 0.016 | 0.007 |
| WM.18.Bu | 63.9 | 0.30 | 11.3 | 2.52 | 1.60 | 5.36 | 0.11 | 0.30 | 85.4 | 0.09 | 0.036 | 0.010 | 0.014 | 0.007 | < d.l. | 0.006 |
| WM.19.Bu | 76.3 | 0.20 | 11.5 | 1.46 | 0.96 | 5.88 | 0.11 | 0.37 | 96.8 | 0.07 | 0.018 | 0.025 | 0.012 | 0.011 | 0.016 | 0.005 |
| WM.24.Bu | 72.4 | 0.31 | 11.4 | 3.50 | 1.54 | 5.02 | 0.16 | 0.84 | 95.2 | 0.09 | 0.034 | 0.021 | 0.010 | 0.016 | < d.l. | 0.006 |
| WM.25.Bu | 74.7 | 0.16 | 10.8 | 1.59 | 1.11 | 5.13 | 0.14 | 0.47 | 94.1 | 0.08 | 0.012 | 0.009 | 0.019 | 0.023 | 0.011 | 0.006 |
| WM.26.Bu | 72.7 | 0.28 | 11.2 | 2.88 | 1.37 | 5.56 | 0.10 | 0.42 | 94.5 | 0.08 | 0.032 | 0.011 | 0.012 | 0.017 | 0.013 | 0.006 |
| WM.29.Bu | 73.1 | 0.20 | 10.4 | 2.07 | 1.58 | 4.48 | 0.14 | 0.69 | 92.7 | 0.08 | 0.023 | 0.016 | 0.012 | 0.013 | 0.017 | 0.006 |
| WM.33.Bu | 69.6 | 0.20 | 10.2 | 0.57 | 0.52 | 3.86 | 0.07 | 0.34 | 85.4 | 0.16 | 0.004 | 0.132 | 0.006 | 0.010 | 0.011 | 0.014 |
| WM.34.Bu | 77.0 | 0.22 | 10.8 | 0.45 | 0.95 | 5.90 | 0.12 | 0.53 | 96.0 | 0.19 | 0.008 | 0.037 | 0.014 | 0.011 | 0.017 | 0.018 |
| Average | 74.2 | 0.23 | 11.1 | 1.90 | 1.22 | 5.02 | 0.12 | 0.42 | 94.2 | 0.10 | 0.019 | 0.027 | 0.014 | 0.013 | 0.013 | 0.009 |
| SD | 3.2 | 0.10 | 0.7 | 1.04 | 0.56 | 0.97 | 0.03 | 0.15 | 3.3 | 0.06 | 0.010 | 0.033 | 0.006 | 0.004 | 0.006 | 0.006 |
| *Granitic gneiss: source rocks* | | | | | | | | | | | | | | | | |
| AB.03.Be | 73.0 | 0.30 | 12.9 | 3.39 | 1.33 | 5.97 | 0.167 | 0.81 | 97.9 | 0.075 | 0.025 | 0.012 | 0.016 | 0.015 | 0.006 | 0.007 |
| AB.08.Be | 73.3 | 0.23 | 11.7 | 1.91 | 1.06 | 5.65 | 0.160 | 0.17 | 94.2 | 0.085 | 0.029 | 0.009 | 0.014 | 0.012 | 0.005 | 0.007 |
| AB.15.Be | 76.0 | 0.21 | 11.5 | 2.12 | 1.36 | 4.91 | 0.119 | 0.40 | 96.6 | 0.061 | 0.022 | 0.004 | 0.015 | 0.011 | 0.014 | 0.004 |
| AB.20.Be | 71.1 | 0.26 | 11.0 | 2.69 | 1.40 | 5.22 | 0.110 | 0.37 | 92.2 | 0.065 | 0.030 | 0.008 | 0.013 | 0.016 | 0.009 | 0.006 |
| AB.21.Be | 76.2 | 0.20 | 11.9 | 2.54 | 1.11 | 5.68 | 0.140 | 0.33 | 98.1 | 0.076 | 0.036 | 0.005 | 0.013 | 0.016 | 0.014 | 0.007 |
| AB.22.Be | 71.5 | 0.19 | 10.1 | 2.55 | 0.83 | 6.05 | 0.130 | 0.77 | 92.1 | 0.057 | 0.023 | 0.003 | 0.023 | 0.010 | 0.014 | 0.004 |
| BK.03.Be | 72.8 | 0.22 | 11.2 | 2.36 | 1.23 | 5.57 | 0.165 | 0.50 | 94.0 | 0.067 | 0.026 | 0.008 | 0.017 | 0.015 | 0.010 | 0.006 |
| BK.05.Be | 70.7 | 0.18 | 12.5 | 1.75 | 3.34 | 1.11 | 0.156 | 0.74 | 90.5 | 0.052 | 0.014 | 0.051 | 0.002 | 0.010 | 0.008 | 0.004 |
| I.08.Be | 74.1 | 0.24 | 10.9 | 2.61 | 1.14 | 5.45 | 0.078 | 0.38 | 94.9 | 0.081 | 0.030 | 0.003 | 0.023 | 0.012 | 0.007 | 0.006 |
| I.13.Be | 73.4 | 0.18 | 11.4 | 2.16 | 1.15 | 5.26 | 0.098 | 0.39 | 94.0 | 0.069 | 0.022 | 0.007 | 0.017 | 0.012 | 0.007 | 0.005 |
| MR.03.Be | 74.8 | 0.09 | 10.5 | 0.97 | 1.07 | 4.19 | 0.069 | 0.39 | 92.0 | 0.106 | 0.004 | 0.022 | 0.005 | 0.014 | 0.023 | 0.009 |
| V.10.Be | 79.0 | 0.16 | 10.2 | 1.45 | 0.72 | 5.41 | 0.082 | 0.35 | 97.3 | 0.050 | 0.017 | 0.002 | 0.020 | 0.012 | 0.019 | 0.004 |
| V.16.Be | 74.9 | 0.18 | 11.2 | 2.61 | 0.82 | 5.49 | 0.108 | 1.63 | 96.9 | 0.057 | 0.024 | 0.003 | 0.022 | 0.009 | 0.008 | 0.004 |
| V.19.Be | 76.4 | 0.23 | 11.2 | 2.18 | 0.80 | 5.60 | 0.142 | 0.55 | 97.1 | 0.054 | 0.024 | 0.003 | 0.025 | 0.013 | 0.015 | 0.005 |
| V.25.Be | 76.5 | 0.21 | 11.3 | 2.34 | 0.78 | 5.73 | 0.124 | 0.64 | 97.6 | 0.085 | 0.022 | 0.004 | 0.024 | 0.013 | 0.010 | 0.006 |
| WM.13.Be | 70.2 | 0.08 | 11.6 | 0.68 | 2.94 | 1.53 | 0.078 | 1.28 | 88.4 | 0.075 | < d.l. | 0.065 | 0.003 | 0.007 | 0.007 | 0.004 |
| WM.27.Be | 73.9 | 0.18 | 11.2 | 1.69 | 1.29 | 5.14 | 0.144 | 0.58 | 94.1 | 0.064 | 0.014 | 0.015 | 0.020 | 0.009 | 0.012 | 0.005 |
| WM.30.Be | 74.8 | 0.16 | 10.5 | 1.46 | 1.10 | 5.42 | 0.112 | 0.52 | 94.1 | 0.056 | 0.013 | 0.014 | 0.023 | 0.011 | 0.020 | 0.004 |
| Average | 74.03 | 0.19 | 11.3 | 2.08 | 1.30 | 5.00 | 0.121 | 0.60 | 94.4 | 0.069 | 0.021 | 0.013 | 0.016 | 0.012 | 0.012 | 0.005 |
| SD | 2.3 | 0.05 | 0.7 | 0.66 | 0.70 | 1.39 | 0.032 | 0.36 | 2.78 | 0.015 | 0.009 | 0.017 | 0.007 | 0.003 | 0.005 | 0.001 |
| *Migmatitic hornblende gneiss: building rock* | | | | | | | | | | | | | | | | |
| C.02.Bu | 49.2 | 1.25 | 16.4 | 10.5 | 6.77 | 2.58 | 0.455 | 0.32 | 87.5 | 0.075 | 0.018 | 0.043 | 0.012 | 0.015 | < d.l. | 0.013 |
| *Migmatitic hornblende gneiss: source rock* | | | | | | | | | | | | | | | | |
| WM.23.Be | 46.5 | 2.70 | 16.1 | 14.0 | 7.79 | 1.90 | 0.977 | 0.28 | 90.2 | 0.119 | 0.010 | 0.051 | 0.003 | 0.016 | < d.l. | 0.015 |

< d.l.–below the detection limit.
[a] mass% 900 °C.
[b] Sum of major oxides and LOI 900 °C.

out the measurements to assure analytical stability.

Only elements with mean values four times larger than their 1σ measurement error were considered for further data analysis. The contents of the trace elements Ba, Zr, Sr, Rb, Zn, Co, V are given in ppm, the contents of the major components $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, $K_2O$, $P_2O_5$ and $TiO_2$ are calculated as oxides and are given in mass%.

The qualitative and semi-quantitative mineralogical compounds were examined by X-Ray powder diffraction (XRD). The powdered samples were analyzed using a RIGAKU Miniflex600 diffractometer at 15 mA/40 kV (Cu kα) from 3° to 80° (2θ) with a goniometer step velocity of 0.02° steps and 0.5° $min^{-1}$. The software X-Pert HighScore Version 1.0b by PHILIPS Analytical B.V. was used for semi-quantitative diffractogram analysis, following the procedure introduced by Schütt et al. (2010) and Schwanghart et al. (2016). Within this software outliers were corrected, the kα2 peaks were eliminated, and a calibration to the quartz100 main peak (d = 3.34 Å) was applied. The Powder Diffraction Files (PDF) of the ICDD (International Centre for Diffraction Data) were used for identifying the peaks. The LOI was analyzed according to Heiri et al. (2001) at 900 °C in a Thermo Scientific M110 Muffle Furnace.

Simple descriptive statistics and graphical representations were applied to investigate differences between the characteristics of the

**Table 3**
Major oxide and minor element concentration of marble rocks (oxides (mass%) and traces (ppm)) (values displayed are four times larger than their 1σ measurement error)

| Code | CaO | MgO | $SiO_2$ | $Fe_2O_3$ | $K_2O$ | $P_2O_5$ | $Al_2O_3$ | LOI[a] | SUM[b] | Ba | Sr |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Building rocks* | | | | | | | | | | | |
| AB.33.Bu | 35.6 | 13.5 | 9.1 | 0.52 | 0.24 | 0.52 | 5.14 | 18.9 | 83.5 | 0.050 | 0.010 |
| AB.35.Bu | 34.4 | 14.4 | 11.9 | 0.50 | 0.07 | 0.46 | 4.97 | 33.7 | 100.4 | 0.040 | 0.010 |
| AB.36.Bu | 32.5 | 14.6 | 10.1 | 0.59 | 0.15 | 0.56 | 4.81 | 33.4 | 96.7 | 0.045 | 0.011 |
| AB.37.Bu | 32.0 | 15.2 | 9.1 | 0.57 | < d.l. | 1.49 | 4.94 | 34.3 | 97.6 | 0.041 | 0.001 |
| AB.38.Bu | 31.1 | 15.3 | 9.0 | 0.55 | 0.15 | 1.30 | 4.80 | 33.3 | 95.5 | 0.094 | 0.023 |
| J.01.Bu | 36.1 | 13.4 | 48.3 | 0.61 | < d.l. | 0.64 | 5.15 | 24.7 | 128.9 | 0.043 | 0.006 |
| V.01.Bu | 48.1 | 16.9 | 8.3 | 0.30 | 0.16 | 0.85 | 6.91 | 30.0 | 111.5 | 0.039 | 0.003 |
| V.08.Bu | 48.2 | 16.1 | 8.8 | 0.29 | 0.15 | 0.69 | 7.23 | 37.9 | 119.4 | 0.039 | 0.002 |
| VI.01.Bu | 32.0 | 17.3 | 12.8 | 0.27 | < d.l. | 0.53 | 4.65 | 30.0 | 97.6 | 0.039 | 0.003 |
| VI.02.Bu | 44.9 | 16.3 | 8.3 | 0.60 | 0.78 | 0.65 | 8.48 | 38.0 | 118.0 | 0.040 | < d.l. |
| Average | 37.5 | 15.3 | 13.6 | 0.48 | 0.24 | 0.77 | 5.71 | 31.4 | 104.9 | 0.047 | 0.007 |
| SD | 6.9 | 1.4 | 12.3 | 0.14 | 0.24 | 0.35 | 1.33 | 5.9 | 13.9 | 0.017 | 0.007 |
| *Bedrocks* | | | | | | | | | | | |
| KN.01.Be | 49.4 | 15.9 | 9.0 | 0.226 | < d.l. | 0.75 | 7.39 | 32.5 | 115.2 | 0.047 | 0.030 |
| MG.04.Be | 42.9 | 17.5 | 6.8 | 0.240 | < d.l. | 0.62 | 6.78 | 54.5 | 129.3 | 0.039 | 0.006 |
| MG.06.Be | 49.8 | 17.5 | 0.2 | 0.167 | < d.l. | 0.77 | 7.57 | 44.6 | 120.6 | 0.043 | 0.044 |
| MG.11.Be | 34.5 | 15.6 | < d.l. | 0.299 | < d.l. | 0.45 | 4.82 | 46.3 | 102.0 | 0.040 | 0.011 |
| Average | 44.2 | 16.6 | 5.3 | 0.233 | < d.l. | 0.63 | 6.64 | 44.5 | 116.8 | 0.042 | 0.023 |
| SD | 7.2 | 1.0 | 4.9 | 0.054 | < d.l. | 0.13 | 1.26 | 9.01 | 11.4 | 0.004 | 0.018 |

< d.l.-below the detection limit.
[a] mass% 900 °C.
[b] Sum of major oxides and LOI 900 °C.

samples originating from constructions and the bedrock in the vicinity of the investigated monuments. p-ED-XRF data (Table 2 and 3) are scaled following Aitchison Geometry to an Aitchison composition scale, in order to honor the characteristics of a compositional dataset, i.e. scaling, perturbation, and permutation invariance as well as subcompositional coherence (van de Boogaart and Tolosana-Delgado, 2013). Computational analyses of the compositional data were conducted using the *compositions*-package (van den Boogaart et al., 2014) in R (R Core Team, 2015).

## 4. Results

### 4.1. Stone architecture and outcropping rocks

In the ancient city of Anuradhapura 478 ancient building and non-building structures (e.g. channels, ramparts, wavebreakers of tanks, etc.) constructed under the utilization of stone blocks were mapped. There are 456 ancient constructions with gneiss as construction material, while marble is found in 22 constructions (Fig. 4). Gneiss was predominantly utilized in the foundations, walls, pillars, and staircases of the ancient buildings, as well as for constructions of ramparts, wavebreakers, channels, ponds, and bridges (Fig. 3a,d). Marble was rarely used in the ancient built environment and predominantly occurs in highly sacred Buddhist constructions such as Buddha image houses, stupas, Bodhi tree shrine (*Bodhigara* in Sinhala), Buddha statues and footprints of Buddha (Fig. 3b,c).

The central part of the city is situated in an area characterized by charnockitic gneisses in the subsurface. In contrast stone architectural features of the ancient buildings in this area are mostly constructed of granitic gneiss, which is exposed along the line of rock outcrop (Fig. 2b). The Western monasteries in the ancient city of Anuradhapura are located in the migmatitic hornblende gneiss zone; architectural features in this area are predominantly constructed using migmatitic hornblende gneiss (Fig. 3d, e).

### 4.2. Petrographic and chemical characteristics of the rocks

#### 4.2.1. Petrographic and chemical characteristics of gneissic rocks

Gneissic rocks utilized as a construction material in ancient Anuradhapura are characterized by fine- to medium-grained rocks; small patches with coarse-grained quartz and feldspar are found locally. The gneissic rocks are made up of quartz, K-feldspar, and plagioclase. Mafic minerals such as biotite and hornblende occur with minor amounts and are highly variable. The textural features of the rocks originating from ancient quarries are similar to those of the rocks found in buildings and other constructions. Granitic gneiss samples are mainly composed of $SiO_2$ averaging 74.2 mass% in samples from building rocks (SD = 3.2, n = 47) and 74.0 mass% in samples from bedrock (SD = 2.3, n = 27). Contents of $Al_2O_3$ average 11.1 mass% in building rock samples (SD = 0.7, n = 47) and 11.3 mass% in bedrock samples (SD = 0.7, n = 27). Potassium has the character of a minor component reaching average $K_2O$ contents of 5.02 mass% in building rock samples (SD = 0.97, n = 47) and 5.0 mass% in bedrock samples (SD = 1.39, n = 27). The average $Fe_2O_3$ contents total 1.9 mass% in the building rock samples (SD = 1.04, n = 47) and 2.08 mass% in the bedrock samples (SD = 0.66, n = 27). The mean residual of the remaining major oxides sums up to < 2 mass% for each analyzed sample category. The mean values for the LOI at 900°C are 0.42 mass% in building rock samples (SD = 0.15, n = 47) and 0.6 mass% in bedrock samples (SD = 0.36, n = 27)). Barium, zircon, strontium, rubidium, zinc, cobalt and vanadium were detected in traces in all the gneissic rock samples analyzed.

Migmatitic hornblend gneiss samples (n = 2) can be clearly differentiated from granitic gneiss samples ($\alpha < 0.05$) by lower $SiO_2$ and $K_2O$ contents and higher contents of $TiO_2$, $Al_2O_3$, $Fe_2O_3$, and CaO.

For the granitic gneiss samples the sum of detected oxides and the LOI totals in average 94.1 mass% (SD = 3.3, n = 47) for the building rock samples and 94.6 mass% for the bedrock samples (SD = 2.78, n = 27; Table 2).

#### 4.2.2. Petrographic and chemical characteristics of marble

The marbles used as construction material are predominantly composed of carbonates and have minor diopside, phlogophite, muscovite, and olivine contents. The size of the minerals varies from fine to very coarse. Marble bedrock samples show an average LOI (900 °C) of 44.5 mass% in bedrock samples (SD = 9.01, n = 4) and of 31.4 mass% in building rock samples (SD = 5.9, n = 10; Table 3). With a significant linear correlation to the LOI (900°C) ($\alpha < 0.05$), the CaO contents average 44.2 mass% in bedrock samples (SD = 7.2, n = 4) and 37.5 mass% in building rock samples (SD = 6.9, n = 10). MgO and

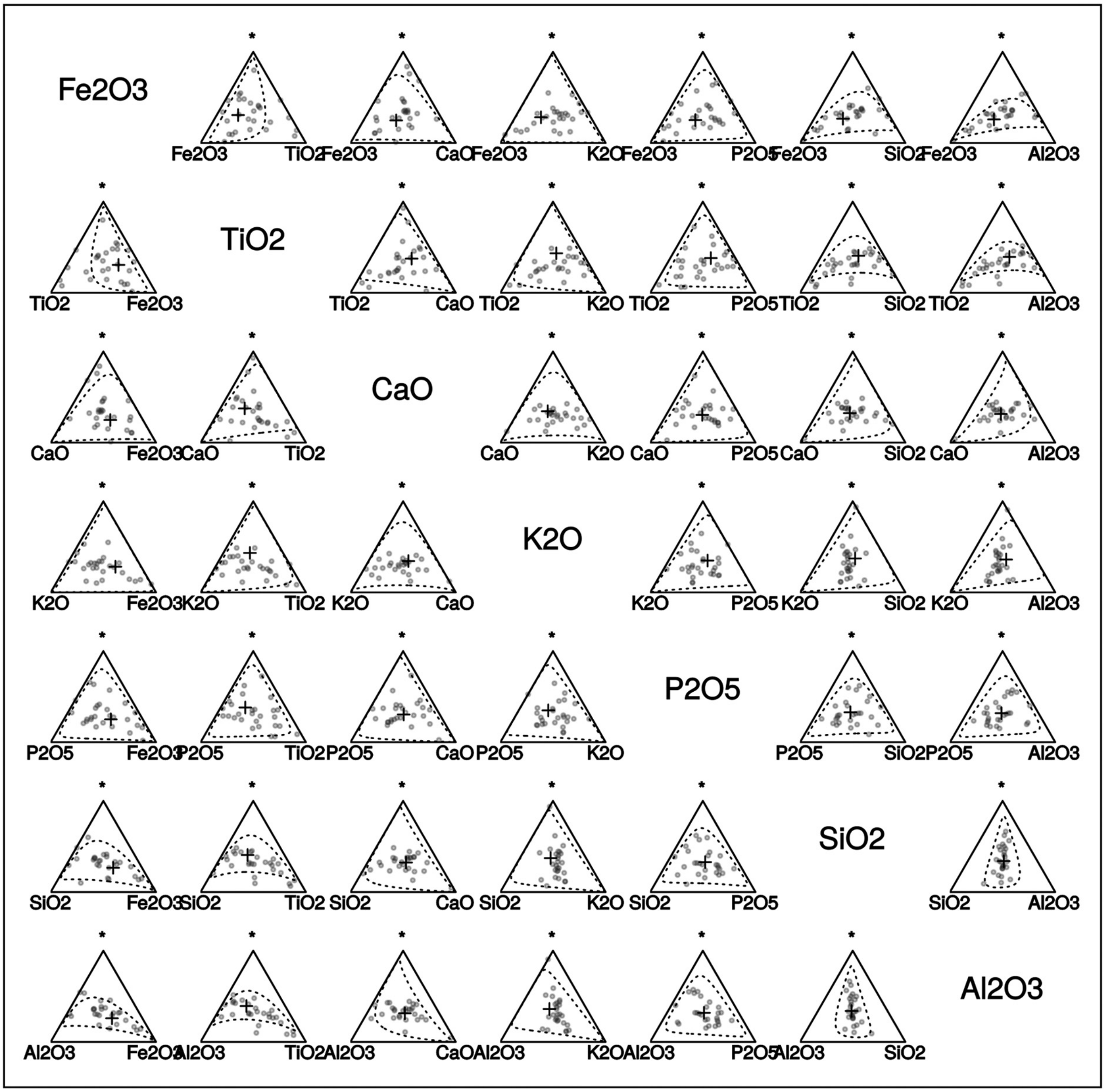


**Fig. 5.** Matrix plot of ternary diagrams of oxides in gneiss rocks. (n = 47). The third component equals the geometric mean of the remaining components. Cross (+) shows the mean of the characteristics of the source rock samples, dashed ellipse shows 95% confidence region of the source rocks; grey dots indicate the characteristics of the different building rock samples.

$SiO_2$ occur with mean values in the two-digit range (Table 3). The mean content of $Al_2O_3$ is 5.7 mass% in building rocks (SD = 1.3, n = 10) and 6.6 mass% in bedrocks (SD = 1.2, n = 4). Barium and strontium occur all over in traces. In the marble samples the mean sum of the major oxides and LOI (900°C) totals 104.9 mass% for the samples originating from building rocks (SD = 13.9, n = 10) and 117.0 mass% for bedrock samples (SD = 11.4, n = 4).

#### *4.2.3. Comparison of petrographic and chemical characteristics of bedrock and construction material*

The comparison of presented datasets describing the character of the samples originating from construction rocks and the bedrock sample shows that the chemical character of samples of the same lithology (gneiss and marble) does not differ significantly between the two sample groups ($\alpha > 0.05$). Their similarities are also clearly displayed in the matrix plot of ternary diagrams of gneiss oxides (Fig. 5) and marble oxides (Fig. 6). Data appear in most combinations as undifferentiated point clouds and do not allow a differentiation of provenance based on the chemical characteristics of the rocks. Trace elements were not considered in this analysis due to measurement uncertainty.

### *4.3. Mineralogical composition of rocks*

XRD analyses reveal that the granitic gneiss consists mainly of quartz with minor constituents of feldspar such as orthoclase, microcline, plagioclase and anorthite (Table 4). Hornblende, biotite and muscovite are other minor constituents encountered in some samples. Accessory minerals such as dispoide and enstatite are occasionally found. These observations apply to all building rock and bedrock samples. Migmatitic hornblende gneiss (C.02.Bu and WM.23.Be) is characterized by feldspar as the major mineral with minor quartz contents (Table 4).

Dolomite and calcites are the major rock-forming minerals in all marble samples (Table 5) while quartz and silicates are encountered as minor mineralogical components. In general, marble samples originating from buildings have a similar mineralogical composition to those from the two marble exposures investigated.

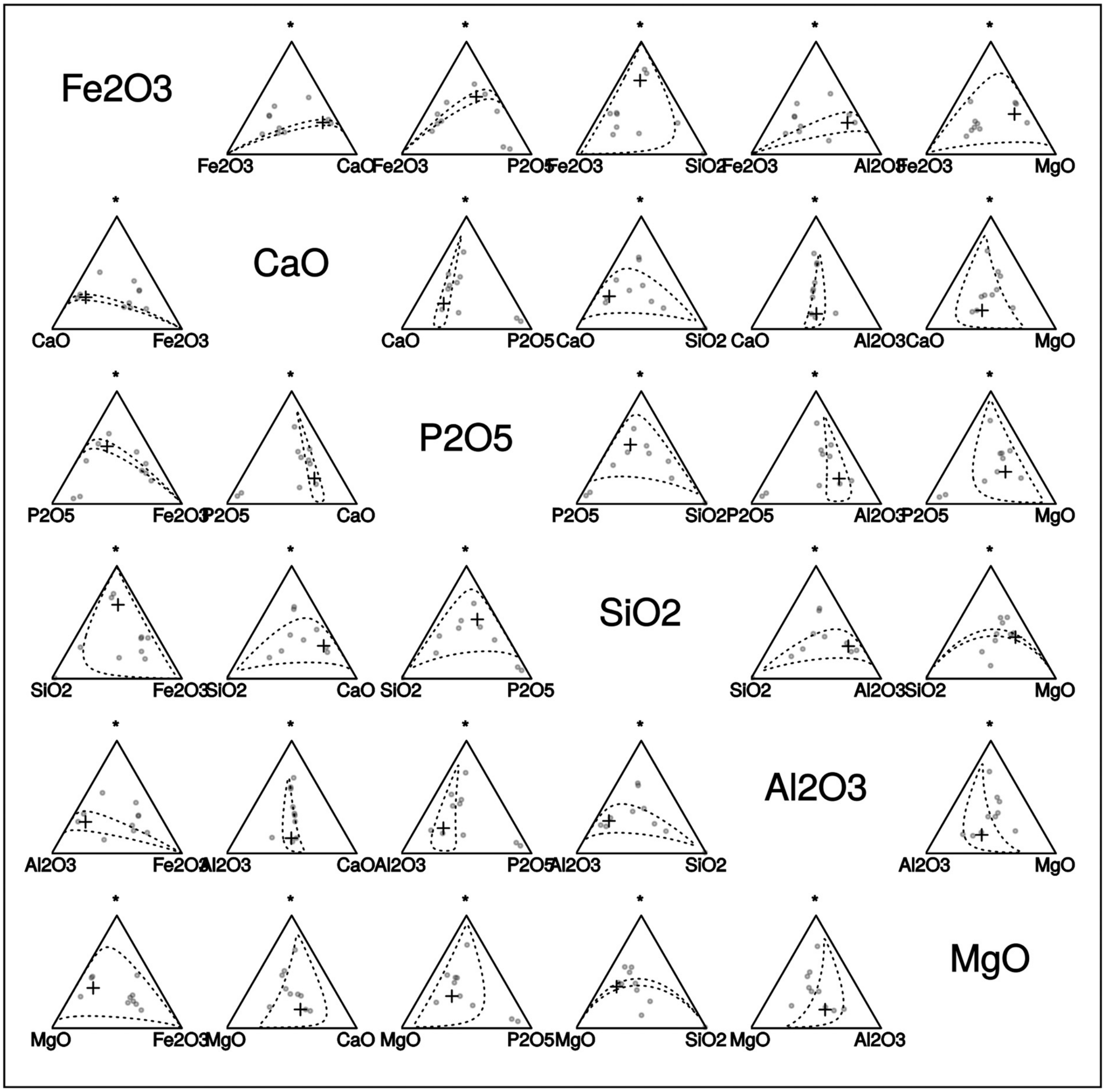


**Fig. 6.** Matrix plot of ternary diagrams of analyzed oxides from marble rocks (n = 14). The third component equals the geometric mean of the remaining components. Cross (+) shows the mean of the characteristics of the source rock samples, dashed ellipse shows 95% confidence region of the source rocks; grey dots indicate the characteristics of the different building rock samples.

## 5. Discussion

### 5.1. Geochemical and mineralogical composition and petrography

The comparison of the rock chemistry of the samples investigated in this study with data from other regions in Sri Lanka (Table 6) shows that the chemical composition of the granitic gneiss originating from the surroundings of Anuradhapura is largely similar to that of the granitic gneiss analyzed by Pohl and Emmermann (1991). The $Al_2O_3$ and $Fe_2O_3$ contents of the migmatitic gneisses are comparable to one another. Contents of $SiO_2$ vary up to 10% between the two studies compared, corresponding to the high variability of free silica occurring in granitic bedrock (Katupotha, 2014). In consequence, the chemical character of the major building rocks does not provide a distinct reference to its provenance. Furthermore, the chemical analysis of the marble samples of building rocks and bedrock also does not allow a distinct provenance assignment.

XRD analysis shows that building and bedrock samples of gneiss rocks have quartz as the major rock-forming mineral (Table 4). The results of the present study are comparable to previous studies by (Ratnayake and Pitawala, 2009). Orthoclase, icrocline, plagioclase and anorthite are found as minor minerals in the gneiss samples. In contrast to granitic gneiss, migmatitic hornblend gneiss is rich in feldspars. The calcite contents of some marble samples are particularly high, compared to marble found in other areas of the country (Madugalla et al., 2013).

The gneiss rocks belonging to the Wanni Complex of Sri Lanka and originating from the area around Anuradhapura are characterized by well-developed joints along the foliation plains (Cooray, 1994). Historical examples of gneissic rock constructions provide evidence that these materials were primarily used in basal structures, pillars or for the construction of walls (Bugini and Folli, 2008; Dunkley, 1936; Hellström, 1991). In Anuradhapura gneissic rocks were also preferentially utilized for the construction of structures such as pillars, stairs, balustrades and foundations (Brown, 2013; Katupotha, 2014; Ratnayake and Pitawala, 2009).

Ductile and brittle structures in rocks represent favorable conditions for rock harvesting (Ritchie, 1999; Smith and Bruhn, 1984); bedrock

**Table 4**
Mineralogical composition of gneiss rock samples.

| | Qz | Or | Mc | Pl | An | Hbl | Bt | Ms | Di | En | Car | Pal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Granitic gneiss: building rocks* | | | | | | | | | | | | |
| AB.32.Bu | + + + | + + | + + | | + + | | | | + | + | | |
| AB.34.Bu | + + + | + + | + + | + + | + + | | | | | + | + | + |
| AB.39.Bu | + + + | + + | + + | + + | + + | | | | + | + | + | |
| BK.09.Bu | + + + | + + | | | + + | | | + + | + + | + + | + + | |
| C.01.Bu | + + + | + + | + + | + + | + + | | | | + | + | | |
| J.02.Bu | + + + | + + | + + | + + | + + | | | | + | + | | |
| J.03.Bu | + + + | + + | + + | + + | + + | | | | + | + | | |
| MR.01.Bu | + + + | + + | + + | | + + | | | | + | | + | |
| MR.04.Bu | + + + | | | | + + | | | | + | | + | |
| MR.05.Bu | + + + | + + | + + | | + + | | | | | + | + | |
| VI.03.Bu | + + + | + + | + + | | + + | | | | + | | + | |
| VI.04.Bu | + + + | + + | + + | + + | + + | | | | + | + | | + |
| WM.03.Bu | + + + | + + | + + | | + + | | | | | + | + | |
| WM.04.Bu | + + + | + + | + + | | + + | | | | + | | | |
| WM.08.Bu | + + + | + + | + + | | + + | | | | + + | + + | | |
| WM.09.Bu | + + + | + + | + + | | + + | | | | + | | + | |
| WM.16.Bu | + + + | + + | + + | | + + | | + + | | + + | + + | | |
| WM.17.Bu | + + + | + + | + + | | + + | | | | + | | | |
| WM.18.Bu | + + | + + | + + + | | + + | | + + | | + + | + + | | |
| WM.19.Bu | + + + | + + | + + | | + + | | | | | + | | |
| WM.23.Be | + + | | | + + | | + + | + + | + + | + + | + + | | |
| WM.24.Bu | + + + | + + | + + | | + + | | + + | | + + | | | |
| WM.25.Bu | + + + | + + | + + | | + + | | + + | | + + | + + | | |
| WM.26.Bu | + + + | + + | + + | | + + | | | | + | | + | + |
| WM.29.Bu | + + + | + + | + + | | + + | | | | + | + | + | + |
| WM.33.Bu | + + + | + + | | + + | + + | | | | + | + | + | |
| WM.34.Bu | + + + | + + | | + + | + + | | | | + | + | + | |
| *Granitic gneiss: source rocks* | | | | | | | | | | | | |
| AB.03.Be | + + + | + + | + + | | + + | | | | + | + | | |
| AB.08.Be | + + + | + + | + + | | + + | | | | + | + | + | + |
| AB.15.Be | + + + | + + | + + | + + | + + | | | | + | + | | |
| AB.20.Be | + + + | + + | + + | + + | + + | + + | | | | + + | | |
| AB.21.Be | + + + | + + | + + | + + | | | | | + | | + | + |
| AB.22.Be | + + + | + + | + + | | + + | | | | + | + | | |
| BK.03.Be | + + + | + + | | | + + | | | | + | + | + | |
| BK.05.Be | + + + | | | | + + | | | | | | + | |
| I.03.Be | + + + | + + | | | + + | + + | + + | | + + | | + + | |
| I.08.Be | + + + | + + | + + | | + + | | | | + | + | | |
| I.13.Be | + + + | + + | + + | + + | + + | | + + | | | + + | | |
| MR.03.Be | + + + | + + | + + | | + + | | | | | + | | |
| V.10.Be | + + + | + + | + + | | + + | | | | | + | | |
| V.16.Be | + + + | | + + | | + + | | + + | | | | | |
| V.19.Be | + + + | + + | + + | | + + | | + + | | | + + | | |
| V.25.Be | + + + | + + | + + | | + + | | + + | | | | | |
| WM.27.Be | + + + | + + | + + | | + + | | | | + | | + | + |
| WM.30.Be | + + + | + + | | | + + | | | + + | + + | | + + | |
| *Migmatitic hornblende gneiss: building rocks* | | | | | | | | | | | | |
| C.02.Bu | + + | + + | | + + + | + + + | + + | + + | | | + + | | |
| *Migmatitic hornblende gneiss: source rocks* | | | | | | | | | | | | |
| WM.23.Be | + + | | | + + + | | + + | + + | + + | + + | + + | | |

+ + + major components, + + minor components, + trace, + + +/+ + max. contents per sample. Qz = quartz, Or = orthoclase, Mc = microcline, Pl = plagioclase, An = anorthite, Hbl = hornblende, Bt = biotite, Ma = muscovite, Di = dispoide, En = enstatite, Car = carnotite, Pal = palygorskite.

outcrops with bedded layers, natural foliations or mechanical weathering fractures were preferably used for quarrying in ancient cultures (Dworakowska, 1975; Heldal, 2009; Kelany et al., 2009; Schierhold, 2009). Levers were used to widen these natural cracks and joints in the bedrock (Heldal, 2009), a technique frequently used in the surroundings of Anuradhapura (Wagalawatta et al., 2016).

### 5.2. Local versus imported construction material

The spatial juxtaposition of quarrying sites for gneissic building rock exploitation and gneissic construction material of monumental buildings clearly indicates that ancient architects preferred to use bedrock from local sources as a construction material for non-decorative purposes. This observation can be clearly verified by focusing on the western monasteries of ancient Anuradhapura, which are located in the migmatic hornblende gneiss zone and where migmatic hornblende gneiss is the prevailing construction material. In contrast, the majority of constructions in the ancient center of the city are built of granitic gneiss, which crops out along the central rock outcrop line from where it was systematically mined (Wagalawatta et al., 2015). This observation emphasizes the attraction of utilizing local bedrock resources as construction materials in order to minimize the effort of transport. In the wider surroundings of Anuradhapura, locations with outcropping bedrocks are scarce. In addition to other natural resources, Chisholm (2007, 114) mentions the availability of rocks as building materials as an important locational factor influencing the establishment of settlements. The presented results document that this also holds true for the development of Anuradhapura.

In addition, the ancient citizens of Anuradhapura used marble for prominent construction purposes, a bedrock that occurs rarely in the

**Table 5**
Mineralogical composition of marble rock samples.

| | Dol | Cal | An | Qz | Ma | Bt |
|---|---|---|---|---|---|---|
| *Building rocks* | | | | | | |
| AB.33.Bu. | + + + | + + + | | | + + | |
| AB.35.Bu. | + + + | + + + | | + + | + + | + + |
| AB.36.Bu. | + + + | + + + | | | + + | |
| AB.37.Bu. | + + + | + + + | | | | |
| AB.38.Bu. | + + + | + + + | | | + + | |
| J.01.Bu. | + + + | + + + | | + + | | |
| V.01.Bu. | + + + | + + + | | + + | | |
| V.08.Bu. | + + + | + + + | | + + | | |
| VI.01.Bu. | + + + | + + + | | | | |
| VI.02.Bu. | + + + | + + + | | + + | | |
| *Bedrocks* | | | | | | |
| KN.01.Be. | | + + + | | | | |
| MG.04.Be. | | + + + | + + | | | |
| MG.06.Be. | + + + | + + + | | | + + | |
| MG.11.Be. | + + + | + + + | | | | |

+ + + major components, + + minor components, + + +/+ + max. contents per sample, Dol = dolomite, Cal = calcite, An = anorthite, Qz = quartz, Ma = muscovite, Bt = biotite.

**Table 6**
Chemistry of granitic gneiss, migmatitic gneiss and marble from different locations in Sri Lanka in comparison to those measured in the environs of Anuradhapura. (Granitic gneiss of the Highland Complex (Pohl and Emmermann, 1991). Migmatitic gneiss of the Wanni Complex (Pram and Pohl, 1994). Marble from Senapura (Pitawala et al., 2003)) (major oxides and LOI are given in mass%).

| | Granitic gneiss | | Migmatitic gneiss | | Marble | |
|---|---|---|---|---|---|---|
| | Pohl and Emmermann (1991) (n = 14) | Anu.* (n = 47) | Pram and Pohl (1994) (n = 14) | Anu.* (n = 2) | Pitawala et al. (2003) | Anu.* (n = 14) |
| $SiO_2$ | 71.04 | 74.17 | 60.59 | 47.85 | 11.29 | 12.91 |
| $TiO_2$ | 0.51 | 0.21 | 1.17 | 1.98 | – | – |
| $Al_2O_3$ | 12.09 | 11.13 | 17.53 | 16.25 | 0.07 | 5.94 |
| $Fe_2O_3$ | 0.09 | 1.97 | 10.03 | 12.25 | 0.62 | 0.45 |
| FeO | 2.96 | – | – | – | – | – |
| MnO | 0.07 | – | 0.24 | – | – | – |
| MgO | 0.53 | – | 2.95 | - | 4.11 | 15.45 |
| CaO | 2.14 | 1.25 | 1.94 | 7.28 | 48.47 | 38.98 |
| $Na_2O$ | 2.42 | – | 2.35 | – | 0.06 | – |
| $K_2O$ | 5.05 | 5.00 | 3.06 | 2.24 | – | 0.14 |
| $H_2O+$ | 0.24 | – | – | – | – | – |
| $P_2O_5$ | 0.13 | 0.12 | 0.06 | 0.72 | 0.08 | 0.73 |
| $CO_2$ | 0.28 | – | – | – | – | – |
| LOI | – | 0.49 | – | 0.30 | 34.5 | 33.73 |
| Total | 97.05 | 94.31 | 99.93 | 88.95 | 99.2 | 109.17 |

*Anu. equals Anuradhapura.

central lowlands of Sri Lanka. Marble was used for ornamentation and decoration, especially of sacred buildings and monuments. In this case the necessity of long transportation distances was accepted (De Jayawardena, 2015; Jayasinghe, 2013; Katupotha, 2014). In the immediate vicinity of Anuradhapura there are no outcrops of high-quality marble, consequently marble had to be mined and imported from more distant places. The nearly exclusive use of marble for ornamentation and decoration documents its high sacred value, which renders its quarrying profitable despite the transportation costs. In ancient India the utilization of marble for the construction of Buddhist sacred monuments and the decoration of sacred constructions was a common practice (Rea, 1989; Sen, 1999). The import of exotic or outstanding building materials from distant locations for selected architectural features, ornamentation and decoration is also well documented for other ancient civilizations such as Ancient Egyptian and Roman cities (Degryse et al., 2008; Klemm and Klemm, 2001). The specific use of individual types of construction rocks for particular construction purposes even in the same building has been known even since the Bronze Age. For example, Bronze Age settlers in Cyprus transported a particular rock type over a long distance for the construction of monumental buildings (Philokyprou, 2011). Pillars in the Roman theater in Catania/Sicily were constructed with material that was imported from eastern Turkey and the island of Elba, while for the general construction volcanic rocks quarried in the vicinity of the city were used (Corsaro et al., 2000).

Bandaranayake (1974) states that marble became a popular building material in the ancient Sinhalese built environment after the 6th century CE. Chronologically, this increased application of marble for decoration purposes coincides with the time when Anuradhapura extended its power to exploit natural resources from far distant locations, e.g. iron from Seruvila (on the east coast of Sri Lanka) (Seneviratne, 1995), contemporary a sophisticated network of tank-cascade systems was implemented across the country (Seneviratna, 1994; Dahdouh-Guebas et al., 2005). Above, it is known, that the city had foreign trade relations reaching into the Mediterranean region (Coningham, 2006, 1999; Deraniyagala, 2004) (Table 1). According to Gringmuth-Dallmer (2011) and Knitter et al. (2014), these enumerated archaeological evidence can be understood as a marker for a central place holding central functions in terms of trade, culture and political power. Thus it is hypnotized that in Anuradhapura the utilization of marble, as a special and valuable building material, emerged with the subsequent development of the capital as a place of centralized political and religious power.

## 6. Conclusions

This investigation analyzes the petrographic, chemical and mineralogical character of building stones of the built environment of ancient Anuradhapura and bedrock from its environs. By in-cooperating survey data on the construction material utilized in building and non-building structures in the ancient city of Anuradhapura, this study clearly shows, that rocks characterising the local lithology of the study area are utilized as main construction material. The majority of the building stones that were used in ancient constructions are granitic and migmatitic gneisses. They dominate first of all the ordinary constructions and inner cores of buildings reflecting their availability and accessibility within or close to the settlement area. Remarkable is, that the majority of ancient complexes is situated in an area with charnockitic gneiss in the subsurface, while the constructions in this area are composed predominantly of granitic gneiss originating from a rock outcrop line situated c. 800 m west of the Citadel. The outcrops along the N-S striking rock outcrop line provided sufficient and suitable construction rocks for the erection of monuments and were probably a strong locational factor for the site selection of ancient Anuradhapura. This is clearly documented by the close spatial relation between monuments and the quarrying sites along the rock outcrop line.

The western monasteries are constructed under the utilization of migmatitic hornblende gneiss, which characterizes the local geology. With the subsequent development of the administrative, religious and social functions of the city, increasingly prestigious constructions were erected. The presented data clearly demonstrates that regionally scarce rocks, namely marble were brought from distant quarrying sites for decoration and ornamentation purposes of these prestigious buildings. Anyhow, the chemical character of the analyzed rock samples does not support a geochemical distinction of the provenance of specific construction material, as a clear marker for fingerprinting of source areas is lacking.

## Acknowledgements

We thank the reviewer for their constructive comments on the first draft of the paper, which helped to improve the paper. We would like to thank the German Academic Exchange Service (DAAD) for financial support. We address special thanks to the Department of Archaeology of Sri Lanka, especially to Mr. S.A.T.G. Priyantha (Assistant Director of Excavation). The assistance during our fieldwork from Mr. L. Jayapala (Anuradhapura) was most helpful and is acknowledged. Frank Kutz, Jacob Hardt, and Julia Meister (Institute of Geographical Sciences, Freie Universität Berlin) helped significantly during the sample preparation and analyses. We thank Katharine Thomas for English proof reading.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2017.03.060.

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