

Deterioration of Tropical Stone Culture; Sri Lankan Experiences

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Abstract

Sri Lanka is one of the tropical countries in the world with a rich ancient stone culture. Existence of stone monuments and sculptures which are presently naked, express an evolution of amazing ancient stone industry. Research investigations done during the last 7 years infer the use of advance quarrying techniques in ancient stone industry. It further reveals that almost all the stone monuments and sculptures are made up of Gneisses and Marble of Proterozoic metamorphic rocks. Advance technological understanding of stone materials in selecting, quarrying and carving is specifically observed. Most of the stone heritage of the country is under threat of deterioration. Those in the World Heritage Sites of Anuradhapura, Polonnaruwa, Sigiriya and Kandy show highly specific deterioration patterns caused by tropical climatic variations and distinctive local geology. The identified deterioration patterns are dominated by discoloration, flaking, fragmentation, splitting, salt crystallization and dissolution. Biological weathering mainly by lichen growths seems to be a silent agent and it removes surface mineral fragments that range from 2 to 47 mg with a mean of 23 mg/year by weight. Presently conservation activities based on research investigations are carried out. A monitoring and management plan where a scientific approach is included has been proposed.

Key words: tropical country, ancient stone culture, metamorphic rocks, deterioration, biological weathering

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Citation: Jayasingha, Pathmakumara, (2013), Deterioration of Tropical Stone Culture; Sri Lankan Experiences, The Journal of Archaeology and Heritage Studies, 1(2)

Introduction

Sri Lanka is a tropical country where most historic legends and stories are companionable with its archaeological evidences (Abeyratne 1991). The written history of over 2500 years describes an evolution of a great culture in the country (Geiger, 1958). Establishment of the Kingdom of Anuradhapura that lasted for a period of 1384 years and the next Kingdom of Polonnaruwa that existed for a period of 186 years had flourished in developing various technological and industrial advances (De Silva 1981, Deraniyagala 1998, Coomaraswami,

1986). The stone industry is one such example and the commonness of stone carvings, monumental stone sculptures and stoneware buildings give evidence for the extensive uses of stones in the past (Jayasingha, 2009).

The fashion of carvings in ancient stone works distributed all around the country expresses the evolutionary change in techniques of the industry and significant influence of domination of the Sinhalese Buddhist culture (Jayasingha, 2010). Itemized pieces of ancient stone works in specific purposes further indicate the

technological enhancement. The in-situ carvings and sculptures on bed rocks are thought to be the master pieces of ancient stone culture (Senevirathne and Polk, 1992). Caring of them was done by the application of surface coatings such as plasters and paints. The collapse of the kingdoms due to invasions caused total destruction or abandoning of these. Hence they have been exposed and presently naked to the natural environment.

The Research Laboratory of Central Cultural Fund (CCF), Sri Lanka started a study on ancient stone culture of the country in 2005. The study mainly focuses on technology of quarrying and carving, deterioration and present state with a final aim of establishing conservation measures and monitoring plans. This paper briefly discusses the important findings of the last 7 years with special emphasis on deterioration.

Study area

The study was carried out in the archaeological sites which are under control of the CCF. World heritage sites such as Anuradhapura (A), Polonnaruwa (P), Sigiriya (S) and Kandy (K) and archaeological sites such as Thissamaharamaya (T) and Rambaviharaya (R) were also included (Fig. 1).

Physiography

As a tropical island located at the southern tip of the Indian continent, Sri Lanka experiences year round high rainfall and high temperature. Average annual rainfall and temperature are 2500 mm and 27 °C respectively. The annual rainfall is resulted by two dominant monsoonal rains; northeast and southwest monsoons and further by inter-monsoonal rains. The country can be divided into three main climatic zones such as; wet zone, intermediate zone and dry zone (Fig. 1). Kandy is the only study site found in wet zone of the country.

Geological background

The country is a part of the Precambrian craton and hence eighty percent of the land mass is composed of Proterozoic high grade metamorphic rocks (Cooray, 1994). The rest is covered with Jurassic sandstones, Miocene limestones and Quaternary sediments. The high grade rocks are categorized into four complexes according to the chronological and structural differences; 1. Highland Complex, 2. Vijayan Complex, 3. Wannai Complex, 4. Kadugannawa Complex (Fig. 1). All the study sites are situated in metamorphic terrains (Jayasingha, 2010).

Materials and Methods

Lithological, mineralogical and structural features (joints, fractures, cracks etc) of the monuments, carvings and surrounding areas were studied and mapped. Quarrying techniques such as characteristics of drill holes, length, width, diameter, depth, distance between two drill holes, number of holes per meter, relationship with rock structures etc were studied and recorded.

Damages of the monuments and carvings were identified and categorized while the classification of weathering features and forms introduced by Fitzner and Henrichs (1995) was referred. Some weathering products collected were analyzed by XRD technique to identify the secondary formations.

Different types of biological agents responsible for biological weathering were studied. Dried lichens attached to the monumental surfaces were collected and the weight of any attached minerals was determined by loss on ignition method.

Results and discussions

Site specific geology

World heritage site of Anuradhapura belongs to Wannai complex while that of

Polonnaruwa, Sigiriya and Kandy are located in Highland complex (Fig.1). Anuradhapura sacred city which is a flat terrain is characterized by charnockitic biotite gneiss, granitic gneiss and hornblende biotite gneiss, all of which trend north-south.

Rocks that cover Polonnaruwa World Heritage Site consist of a complex of rocks called Polonnaruwa-Mahiyangana Gneiss which includes migmatized and charnockitized black and white layered ortho gneiss, charnockitic biotite gneiss and garnet biotite gneiss. A small band of marble runs within those rocks and all of them are trending north-south direction. Sigiriya fortress located on an isolated hill is a geologically significant place where three different rock units are piled up. The cap rock is garnet gneiss while the middle rock is biotite hornblende migmatitic gneiss. The root or base rock of Sigiriya inselberge is garnet hornblende biotite gneiss and adjacent rocks are granitic gneiss and impure marble. Gadaladeniya; the study site of Kandy world heritage site is covered with biotite hornblende migmatitic gneiss which trends north-south.

Thissamaharamaya and Rambaviharaya archaeological sites are situated in Vijayan complex. The high grade rocks that cover Thissamaharamaya are granitic gneiss, hornblende biotite gneiss and hornblende biotite migmatitic gneiss. The dominant rocks in Rambaviharaya site are charnockitic gneiss, charnockitic biotite gneiss, biotite gneiss and marble.

Ancient quarries and quarrying techniques

Extensive use of stone materials for various purposes in the fields of construction, decorations, irrigation and hydrology, sanitary and entertainment was noted. Hence advance technological understanding of stone materials in selecting, quarrying and carving is

remarkably evidenced. Almost all the studied stone monuments, sculptures, carvings and building components are made up of varieties of gneiss of Proterozoic high grade metamorphic rocks (Fig. 2a, 2b and 2c). Marble, impure marble and dolomitic marble were used for special purposes such as carving of Buddha statues (Ex; Samadhi statue in Anuradhapura) and decorative stones used in palaces and monasteries (Fig. 3a and 3b).

Petrological and mineralogical similarities between ancient stone quarries and local geology help in identification of geological provenance of stones used in ancient stone works (Harrel, 1992; Campbell and Folk, 1991). It is clearly indicated that most of the stones used in all the studied archaeological sites have been quarried from the adjacent rock exposures (Jayasingha, 2009; 2010), hence ancient quarries are common in most of the study sites. In special occasions, when the required resources were unavailable, interested rock types were quarried and transported from the nearest place where it was available (Jayasingha, 2009). Further it is well noted that the difficulties in transportation and handling of rock slabs were overcome by the establishment of onsite rock quarries or/and quarries at the nearest place to the construction site. Those local rock quarries are of smaller scale in comparison to those of present day and being part of the monument/building in some cases is an identified significant feature of the quarried exposures (Jayasingha, 2011).

Ancient stone quarrying in Sri Lanka was a unique task during the time when the explosives were not discovered in historic time. Drill holes with different shapes and spaces found on quarried stone slabs and bed rocks at quarry sites substantiate the ancient quarrying technique for the raw splitting. Two techniques of wedging that are distinctive to Anuradhapura (377BC-

1017AD) and Polonnaruwa periods (1017-1215 AD) were identified (Jayasingha, 2009). It is noted that oval shaped drill holes which were unique to the Anuradhapura period had been transformed into the rectangular shaped drill holes. These are significantly found in the sites developed during and after the Polonnaruwa period (Fig. 4a and 4b). It is evidenced by the same shape of drill hole noted in places of Yapahuwa, Dambulla and Kandy area. The change of the characteristics of drill holes indicates the differences in wedging techniques applied in the two periods and the continuation of its use which gives further evidences for its advancement and appropriateness in rock quarrying.

The knowledge of ancient people about the rock structures and lithology is well understood by considering the selection criteria for splitting. In most situations tracking the drill holes on Gneisses where well developed gneissic features are found had followed the natural weak planes such as foliation and joints (Fig. 5a and 5b). On rocks of Granitic Gneiss, Charnochitic Gneiss and Migmatitic Gneiss of which the joints and fractures are free or intensity is low, free tracking were observed. The structural characteristics of rocks had been rarely considered in in-situ carvings (Fig. 6). Chiseling and polishing with hard sands (garnet sand?) were carried out according to the purpose and the requirement of displaying.

Deterioration of stone heritage

The study reveals that the ancient stone heritage of the country is under the threat of deterioration and suffered by physical, chemical and biological weathering. Physical weathering is the most dominant type in the studied sites of dry and intermediate zones where Diurnal Temperatures (DT) are high (Avg DT = 7°C at Anuradhapura). Hence Anuradhapura, Polonnaruwa, Sigiriya,

Rambaviharaya and Thissamaharamaya commonly show thermally induced weathering features. Chemical weathering which is frequent in wet zone, also plays a significant role in dry zone weathering though the rates are low. The identified deterioration patterns are dominated by discoloration, coloration, flaking and fragmentation, splitting, salt crystallization and dissolution.

Discoloration is the most commonly observed deterioration feature in Polonnaruwa and Anuradhapura World Heritage Sites. Almost all the gneissic features developed by foliation and mineral lineation of statues of Galviharaya as well as that of a King or a sage, some stone components of Jethawanaya monastery, moonstones and guard stones are completely bleached (Fig. 6). It has been caused by the long term exposure of the statues and monuments to the sun light subsequent to the elimination of plaster or paint layers coated on them (Lee et al., 2006). It is well recognized that comparatively, discoloration in dry zone is high in strength than the wet zone.

Coloration is the other noted common weathering feature in the studied archaeological sites of the country. Weathering of mafic minerals such as biotite, hornblende, garnet, magnetite and ilmenite which contain iron and manganese cause the coloration by staining due to formation of their oxides (González et al., 2004). The coloration is wider spread in monuments and statues made up of gneiss in Sri Lanka. The coloration has been caused not only by chemical weathering of mafic minerals but also the stains of dissolved chemicals in flood water collected from various materials such as bricks, soil etc and decay of organic materials left behind by the biological agents (Rathnayake and Pitawala, 2009; Jayasingha et al., 2009b, Griffin et al., 1991). Floodwater stains are commonly found on lower levels of stone

columns, foundation stones, guard stones, moonstones and step stones providing evidence for the impact of stagnation of water during the rainy seasons. The famous moonstone at Bisomaligawa in Anuradhapura has been affected since a long time by floodwater stains (Fig. 7).

Flaking and fragmentation due to various reasons have caused unrecoverable damages to the stone works of the country and in most cases loss of material is significantly observed. Small scale flaking has been caused by cracks in individual minerals, grain boundaries and joints as well as fractures of rocks. Cracks have been developed due to expansion of natural fractures in quartz, cleavages of feldspar, mica and hornblende in gneisses and calcite and dolomite in marble by hydrolyses and oxidation processes in wet climates. Thermally induced cracks in any mineral are commonly resulted in dry climates (Kranze, 1983; Smith, 2009). As a result, most of the edges of the statues and monuments have been fragmented and rounded. The famous guard stone and moonstones in Anuradhapura are worn out by flaking and fragmentation (Fig. 8a and 8b). It is also dominant in most of the marble carvings, statues and monuments in Rambaviharaya and Thissamaharamaya sites. The Samadhi statue in Anuradhapura and standing Buddha statues in Rambaviharaya have been severely fragmented. Loss of original shape devalues the stone heritage of the country.

Two kind of splitting can be identified; structure related cracks and nonrelated cracks and they are most commonly found in the dry zone monuments and statues. The physical weathering in Samadhi Statue at Galviharaya is dominated by thermal cracks (Fig. 9a) which are not correlated with its own structural pattern of the bed rock. At the same time the structurally controlled cracks have been appeared in many places of the statue (Fig. 9b). Thermal expansion has caused

severe splitting of the bed rocks in the places like Sigiriya (Jayasingha, 2005). The chemical weathering and structures of the rocks further augment the widening of cracks. Brutal splitting create blocking in small boulders and sudden detachment causes rock falling that can even damage the tangible heritage as well as tourists (Fig. 10).

Salt crystallizations are commonly found in the sites which are located in wet zone. One of the best examples is the Gadaladeniya Ancient Royal Temple in Kandy which was constructed using blocks of biotite hornblende migmatitic gneiss on the same exposed bed rock. The XRD analysis revealed that those salts are mainly gypsum formed by deterioration of the applied cement during the past conservation works (Fig.11). Salt crystallization enhances the flaking and fragmentation of the rock blocks further.

Acidity of the water can cause mineral dissolution in monuments (Camuffo, 1992; Thornbush and Viles, 2007). Though acid rains or polluted air has not been recorded in dry zone so far, dissolution features can be observed in some monuments. It was commonly recorded in marble rocks which are composed of carbonate minerals such as calcite and dolomite. The stepping stones in Sigiriya, the moonstones in Rambaviharaya and Thissamaharamaya, the guard stones in Anuradhapura which have been severely affected are the best examples. In addition, feldspar and mafic minerals in stone objects made up of gneissic rocks show interested dissolution features (micro and macro cavities) that are the nucleus to be developed into cracks in most cases. The study reveals that the stone objects located in temporary water logging and continuously wet places are the leading examples of dissolution features dominant in Sri Lankan heritage sites.

Biological deterioration is also significantly observed in the studied

heritage sites. Among the biological agents, plants play a major role and many such types of plants have been recorded. Among the higher plants *Ficus* spp grow very easily, rapidly and competitively (Fig. 12). Their root action expands the already developed cracks and joints, and finally causes detachments. In addition, lower plants such as mosses, liverworts, ferns, algae and lichens are well grown. Yet lichen is the silent agent that causes damages in micro level. Lichen growths are common in most of the studied sites specially on the rock pillars facing the direction of monsoon winds (northeast and southwest) and rainy season causes their thallus to be expanded (Jayasingha et al., 2009b). Though the long dry periods in dry zone control their growth, it is clearly noted that those dried lichen thalluses are crumbled and peeled off from the rock surface (Fig. 13) detaching the loosened mineral fragment. It is found that loss of surface mineral fragments range from 2 to 47 mg with a mean of 23 mg/year by weight (Table 2).

Most commonly observed lichen type is the crustose which does the pioneering work in monument deterioration. The common species of crustose are *Xanthoparmelia* spp, *Xanthoria* spp and *Lecanora* spp. Some squamulose type lichens were also recorded. In addition, *Usnea* spp is the only species of fruticose type noted in the study sites (Fig. 14).

Conservation and management

Presently the Central Cultural Fund is conducting a monitoring program covering all the study sites. Understanding of the deterioration process is carried out by intensive laboratory analysis after thorough field investigations. Long term monitoring program which includes recording of climatic factors, material identification, problem identification and accessing post conservation effects as well as mitigation has been proposed. Developing country

specific techniques for conservation and mitigation measures are the high concerns of the proposed program.

Conclusions

The studies of past 7 years done on the world heritage and archaeological sites that are managed by CCF reveal an advance ancient stone culture of Sri Lanka. All most all the studied stone monuments, carvings and statues were made of high grade Proterozoic metamorphic rocks which are the dominant rock type of the country. Advance technological understanding of stone materials in material selection, quarrying, splitting, carving and polishing is specifically observed. Technological evolution in quarrying (wedging) is noted with regard to the period of Anuradhapura and Polonnaruwa. It is observed that most of the stone works of the study sites are under the threat of deterioration. Specific deterioration patterns caused by tropical climatic variations and distinctive local geology were also noted and observed deterioration patterns can be categorized as discoloration, flaking, fragmentation, splitting, salt crystallization and dissolution. Biological weathering mainly by lichen growths, though invisible, seems to be a silent agent of decaying the rock sculptures. Further it is found that lichen can remove the surface mineral fragments ranging from 2 to 47 mg with a mean of 23 mg/year by weight. Presently conservation activities based on research investigations are carried out. A monitoring and management plan where a scientific approach is included has been proposed.

Acknowledgments

Author wishes to thank Prof. Gamini Adikari, Director General of CCF for his immense help given in later part of the study and for the comments in proposing the management plan. All the members

of the CCF that helped me in various ways is specially thanked for his valuable comments in shaping up the manuscript. Mr.W. Bohingamuwa, PhD candidate of Oxford University, UK

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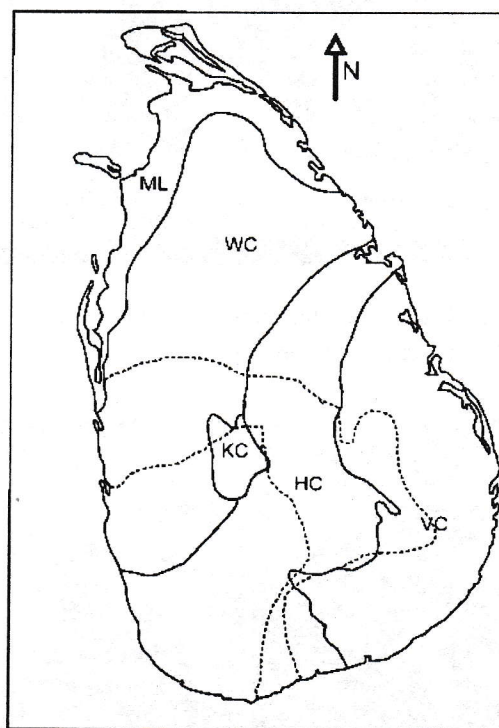


Figure 1: Generalized map of Sri Lanka which shows 1. General Geology; HC: Highland Complex. VC: Vijayan Complex. WC: Wanni Complex. KC: Kadugannawa Complex. ML: Miocene Limestone 2. Climatic zones (dotted lines); WZ- wet zone, IZ- intermediate zone and DR- dry zone



Figure 2: L). Grinding stone (Rambaviharaya) M). Standing budhdha statue (Galviharaya- Polonnaruwa) R). Lion figure (Anuradhapura)

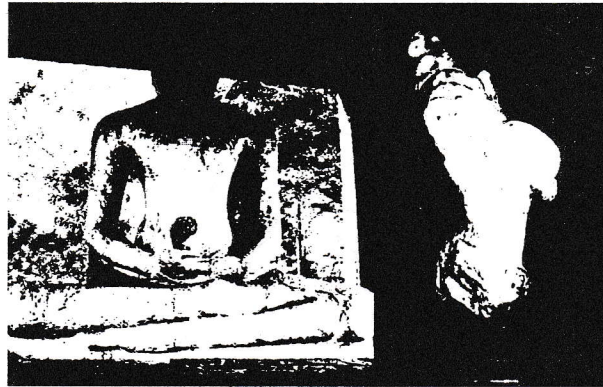


Figure 3: L). Samadhi Statue (Anuradhapura) R). broken hand of a statue (Anuradhapura)

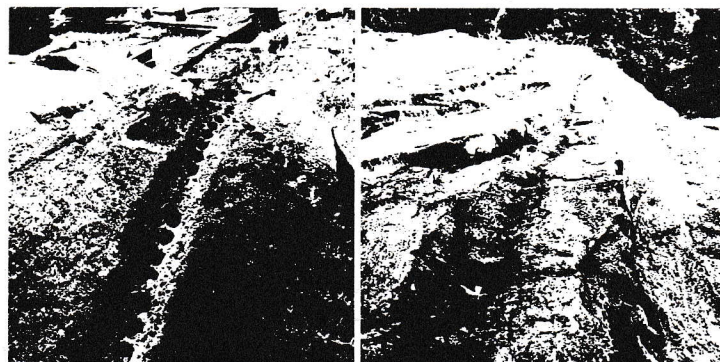


Figure 4: L). Oval shape drill holes (Anuradhapura) R) Rectangular shape drill holes (Polonnaruwa)



Figure 5. a) Orientation of joints in rocks (Anuradhapura) b) Splitting directions



Figure 6: Statue of King or Sage carved on an exposed rock boulder (Polonnaruwa)

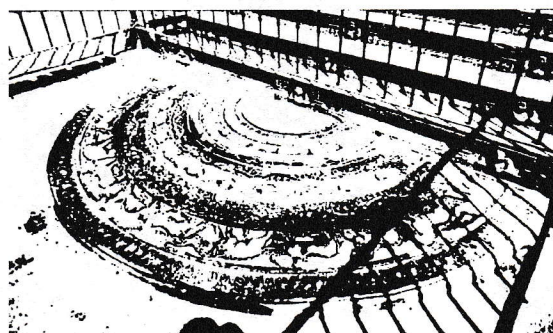


Figure 7: Stained famous moonstone at Bisomaligawa (Anuradhapura)



Figure 8. L) Cracks on crystals R) Loss of materials due to fragmentation (Anuradhapura)



Figure 9. L) thermal cracks R) Splitting in Samadhi statute in Polonnaruwa



Figure 10. Blocking by splitting (Sigiriya)

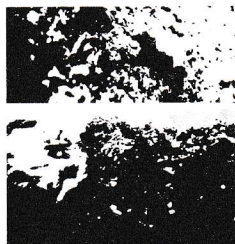


Figure 13. Detached mineral fragments on dried lichen thalluse

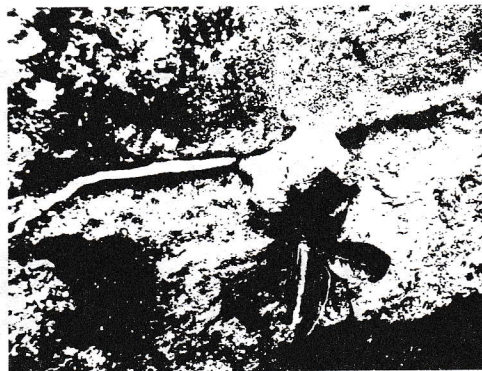


Figure 12. Growth of *Ficus* sps.



Figure 11. Impacts of salt crystallization (Gadaladeniya temple – Kandy)



Figure 14. *Usnea* sps on Sigiriya rock