Probable source of rocks for millstones and cannon balls of Goa, India

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The Europeans started to come to India at the beginning of the 16th century for trade. The Portuguese were the first group of Europeans to reach the southwestern coast of India in 1498 and establish their colonies. They were also the last group of the Europeans to leave the Indian territory after ruling a part of the country for about 450 years. With their arrival, new technology and warfare tactics were introduced in the region. Associated with their artillery, preparation of gunpowder as a new technology was introduced in Goa. Gigantic sized millstones were used for the production of gunpowder in Casa de Polvora, Panelim, Goa. In 2007, when real estate developers commenced their construction work at Casa de Polvora, the Archaeological Survey of India salvaged the endangered millstones from Panelim. The aim of the present communication is to analyse the samples and to find out whether the stone used was quarried from Dharavi (Uttan; which was a part of Bassein territory of the Portuguese) from where the Portuguese acquired stones on a large scale for the decoration of churches in Goa. To achieve this, archaeological, petrographic, mineralogical and geochemical studies have been carried out on samples of millstones and the quarried site at Dharavi (Uttan). In addition sample was also collected from cannon ball found at Arsenal (Old Goa) to find out whether stone from Dharavi (Uttan) was used. The analytical results suggest that the millstones are made of limestone, the Dharavi (Uttan) stone is more siliceous – and the cannon balls are made from basalt.

Keywords: Cannon balls, gunpowder, millstones, rock source.

IN 2007, when real estate activities were at their peak in Goa, new lands, hills, seashore and river front properties attracted many people and accordingly, projects for residential complexes began to proliferate. Several areas were converted for construction activities and one among them was Casa de Polvora at Panelim or Panvel, a site of gunpowder factory (Figure 1 *a*). Panelim is a small village situated half-way between Panaji and old Goa beyond Ribander in North Goa District at 15°29′58.04″N, 73°53′08.46″E. In Portuguese, Casa de Polvora means 'House of gunpowder', where production of gunpowder was carried out on a large scale during the Portuguese period and was supplied to other areas. Casa de Polvora at Panelim was established in 1630 by Francisco da Gama (grandson of Vasco da Gama), the Viceroy of Goa during 1622–1628 (ref. 1). At the abandoned site of Casa de Polvora, which is situated on the bank of the river Mandovi, construction activities began on a massive scale. Excavations and subsequent salvage archaeology by the Archaeological Survey of India (ASI) revealed the occurrence of 12 huge millstones of varying size from 1.6 to 2.5 m in diameter and weighing 2 to 6 tonnes, which are unique in the Indian subcontinent[2]. The ASI, Goa Circle salvaged the millstones and shifted them to a safer place (Figure 1 *b*).

With the Portuguese arriving in India, the first European contact was established and with their expansion they introduced a new culture over the Indian territory under their control. The city of Goa (Old Goa/Velha Goa) conquered by Albuquerque, is located in the northeastern corner of the island of Tiswadi. This island is bordered in the north and south by Mandovi and Zuari rivers respectively, and is separated from the mainland by the narrow Cumbarjua canal. Old Goa is nestled amidst several lateritic hills on the northeastern half of the island along the banks of the Mandovi. Religious orders first started to arrive in Goa for the evangelization of local people for which churches and convents were built on a large scale. Laterites were exploited on a large scale for the construction of these buildings and basalt was acquired from Bassein (Vasai, Mumbai) to decorate the façades and windows of the churches and secular structures in Goa[3,4]. The Bassein territory included the areas of Thana, Dharavi (Uttan) and the island of Bombay. Bassein, now called Vasai, is located on the northern side of Bassein (Vasai) Creek of Ulhas River.

At the tip of the creek, a fort was built by the Portuguese and Dharavi (Uttan) is situated to the south of this creek (Figure 2). This place requires special mention because of its importance for the present study. From this area, the Portuguese had quarried stones by extracting blocks, each 15–30 ft long. This quarrying was done continuously from AD 1536–1600. The quarried stone was used on a large scale for the decoration of churches in Goa[5–7]. The quarry site at Dharavi (Uttan) forms an important source of basalt. The basalts quarried from Dharavi (Uttan) were, in fact, finally taken to Goa. It reaffirms the importance of Dharavi for the archaeological studies. A section of this quarried hill is locally known as *Ashmastambha*[8] (Figure 3). Since it was believed by historians that the cannon balls and millstones were made of basalt, the possibility that Dharavi

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Figure 1. ***a***, Real estate activity at the Casa de Polvora, Panelim, Goa, India. ***b***, Salvage archaeology at Casa de Polvora.

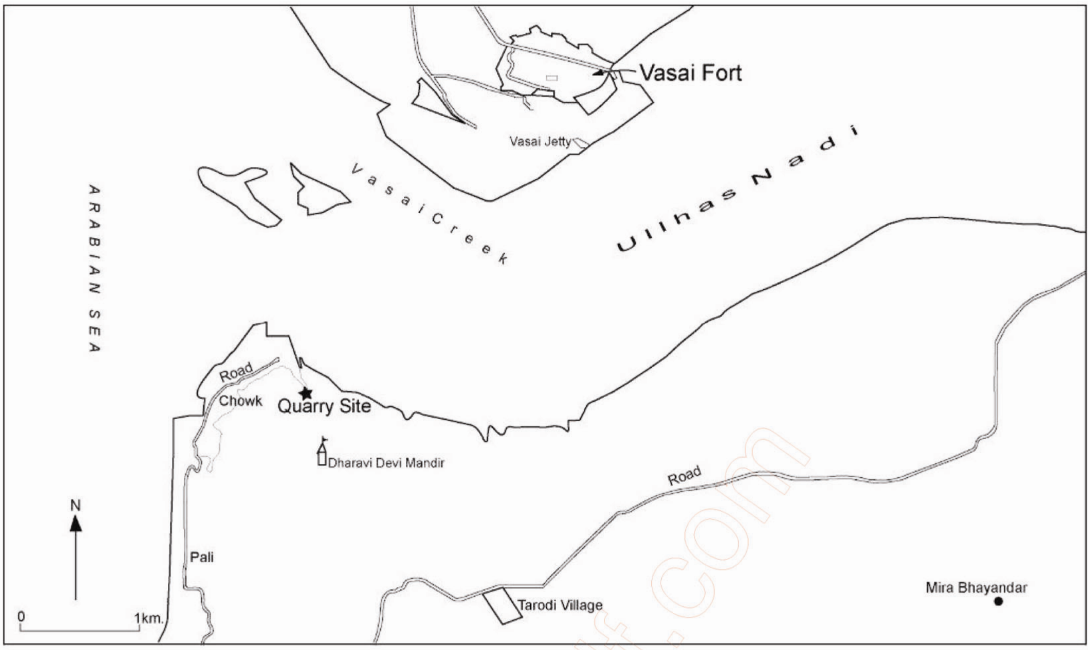

Figure 2. Location of quarry site at Dharavi, District Thane, Maharashtra, India.

Figure 3. Cliff section of quarried site at Dharavi (Uttan).

(Uttan) stone might have been used for this purpose needs to be ascertained.

To verify this hypothesis, total chemical and mineralogical analyses were carried out with three different samples – one from a millstone, another sample from the quarry site and a third sample from the cannon ball. As stated earlier, the Portuguese mainly acquired or quarried basalt from the hills located at Dharavi (Uttan/Dongari) of Bassein (Vasai) apart from other secondary or minor sources. The remains of such quarries in the form of vertical rock cliffs are noticed at Dharavi hills even today. Goa has abundant resource of laterite, but lacks basalt, except for some outcrops in the northeastern part of the state[9]. Hence, to confirm the source of these stones with the available information, a study was carried out to

Table 1. Details of the samples studied

Samples/materials	Village and location	District	State	Latitude/longitude	Other features, if any, like settlement, vegetation, etc.
Quarry site	Dharavi, Dongari, Uttan	Thane	Maharashtra	19°18′19.67″N 72°47′40.41″E	The quarry site is situated on the left side of the road and opposite to a dargah. There are no settlements around the site. It is located on the bank of River Ulhas (south of Vasai Creek)
Cannon ball	Arsenal, Old Goa	North Goa	Goa	15°30′14.03″N 73°54′27.43″E	Abandoned site, on the left bank of River Mandovi
Millstones	Casa de Polvora, Panelim	North Goa	Goa	15°29′58.04″N 73°53'09.89"E	Casa de Polvora is surrounded by settlements and is situated on the left bank of Mandovi River

Figure 4. Cannon balls at Arsenal, Old Goa.

establish whether the millstones and cannon balls were both quarried from Dharavi (Uttan). Efforts were also made to find out the mineralogical make-up of the rocks using the X-ray diffraction techniques.

The study area, as mentioned earlier, represents Panelim, Arsenal and Dharavi (Figures 2 and 3). Exploration and extensive documentation were carried out where the cannons were placed. A study was also done of the millstones, cannon balls, as well as workshops of country crackers and ironsmiths. Spot visits showed that a similar method and ingredients were used for the preparation of country crackers, but in smaller proportion compared to gunpowder for cannons. But the process of mixing the ingredients remains the same over time[10]. Thorough documentation which includes collecting information of almost all the cannons in Goa has been carried out. The literature in the Central and University Libraries, Archives of Goa[11] and Fundacao Oriente was studied and resource persons were consulted during the entire period of study. The samples collected for total chemical and mineralogical studies and other related work are given in Table 1. Salvage archaeology was conducted at Gun Powder Factory, Panelim by excavation at the site[10].

The rock samples were crushed and passed through 100 mesh sieve to carry out the chemical and mineralogical analyses. Total chemical analyses were carried out with the samples following $HF/HClO_4$ digestion[12,13]. The elements were analysed by ICP-PS using ICAP Model (Prodigy Teledyne Leeman Labs). Major elements are expressed as oxides of different elements. Ignition loss was determined after heating the soil samples in an electronic furnace at 700°C for 30 min. Bulk density of the stones was determined following wax method[12]. The crushed powdered samples were subjected to X-ray analysis (Philips X’Pert Pro diffractometer with Ni-filter) using Cu-Kα radiation at a scanning speed of 2° (2θ/min) and the X-ray diffractograms were interpreted for identifying various minerals following the standard methods[14].

Table 2 provides the analytical results of the three samples of the study area and data on limestone and basalts. Cannon balls contain large amount of iron. Chemical analysis of the cannon ball sample with MgO (3.74%), SiO_2 (51.68%) and Fe_2O_3 (12.69%) broadly resembles the chemical properties of basalt[15] (Table 2). Occurrence of basalt in the Deccan Province, central and northwest India (Gujarat) has been studied by many geologists. Based on such studies, an attempt is made here to relate these geological observations with the results from our investigations (Table 2)[15–19]. Iron content in basalt appears to be greater in northwestern India (part of Gujarat) than in central Maharashtra. Hence it may be provisionally inferred that the Portuguese probably acquired the raw materials for preparing cannon balls from the northwestern part of India. Their trade relations with these areas further support this connotation[20]. Comparison of basalt from the mainland and coastal areas

Table 2. Total chemical analysis of the samples used for millstones and cannon balls

Materials	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Fe_2O_3 (%)	MnO_2 (%)	CuO (%)	K_2O	Li_2O	TiO_2	Na_2O	Loss on ignition	Bulk density (Mg m^{-3})	Remarks/ reference
Study area Millstones, India	1.24	1.47	62.06	1.69	0.014	0.79	–	–	1.80	–	–	30.62	1.916	Highly calcareous materials dominated by $CaCO_3$ confirmed by violent effervescence with HCl. Also holds more moisture as evidenced by high LOI. No similarity, whatsoever, with the other two materials.
Cannon balls, India	51.68	11.81	9.20	3.74	12.69	0.84	0.04	3.43	1.60	2.49	–	2.57	1.919	Basalt composition
Quarry site, Dharavi, Uttan, India	70.54	6.91	1.59	0.91	3.20	1.06	0.017	4.20	1.70	–	5.29	3.65	2.136	Mainly siliceous material with less alumina and magnesium content.
Other areas														
Limestone in dolomite, Turkey	1.61	0.45	52.72	1.09	0.20	0.01 (MnO)	–	0.11	–	0.02	0.02	43.5	NA	27
Basalt, Kutch, Gujarat, India	43.94	12.84	11.85	6.47	13.55	0.17 (MnO)	–	1.79	–	3.20	3.29	NA	NA	16
Crystalline limestone, Bohemia	3.11	1.05	51.94	0.76	0.35	0.22 (MnO)	–	0.15	–	0.05	0.20	NA	NA	28
Bhir basalt, Central Deccan, India	51.24	12.42	8.88	5.86	14.89	0.18 (MnO)	–	0.94	–	2.10	3.19	2.73	NA	15
Limestone, Karnataka, India	11.5	1.06	44.1	0.46	0.42	NA	NA	0.20	NA	0.04	0.04	NA	NA	29
Basalt, Mahabaleswar, India	49.46	13.17	9.91	5.58	14.92	0.23 (MnO)	NA	0.67	NA	3.32	2.40	NA	NA	18

(*Contd*)

Table 2. (*Contd*)

Materials		SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Fe_2O_3 (%)	MnO_2 (%)	CuO (%)	K_2O	Li_2O	TiO_2	Na_2O	Loss on ignition	Bulk density (Mg m^{-3})	Remarks/ reference
Columnar basalt of Deccan Trap near Chincholi, Beed district, Maharashtra		48.69	13.98	12.67	4.76	2.08	0.19 (MnO)	–	0.29	–	2.89	3.80	–	–	19
Limestone of Saurashtra, Gujarat (average of 10 samples)	Average	7.04	–	66.02	6.80	5.59	0.30	–	–	–	–	–			24
Major oxides concentration (wt.%) in limestone and grey shale of the Dalmiapuram Formation	Coral–algal limestone (sample no. K14)	2.20	0.57	53.70	0.33	0.68	0.02 (MnO)	–		0.16	–	0.04	0.03	42.12	30
	Bedded limestone (sample no. KI14)	15.74	2.76	42.91	0.84	1.38	0.04 (MnO)	–	0.26	–	0.08	0.03	35.74		
	Grey shale (sample no. GS1)	46.12	13.27	13.05	1.67	4.95	0.04 (MnO)	–	5.34	–	0.63	0.43	13.73		
The lithology, geochemistry, and metamorphic gradation of the crystalline basement	Geochemistry of carbonate-bearing rocks (sample no. 1/928)	3.11	1.05	51.94	0.76	0.35 (FeO_{tot})	0.22 (MnO)	–	0.15	–	0.05	0.20	–	–	28
of the Cheb (Eger) Tertiary Basin, Saxothuringian Unit (average of 12 samples)	Average	13.99	1.08	41.50	0.6	0.34			0.23		0.04	0.04			31

(*Contd*)

Table 2. (*Contd*)

Materials		SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Fe_2O_3 (%)	MnO_2 (%)	CuO (%)	K_2O	Li_2O	TiO_2	Na_2O	Loss on ignition	Bulk density (Mg m^{-3})	Remarks/ reference
Chemical properties of marble/limestone in Rajasthan	Marble area	0.01–3.18	–	26–33	21–25	0.73–1.01	–	–	–	–	–	–	–	40–47	32
	Jhiri, Alwar														
	Tripura Sundari, Banswara	≤ 23.4	–	32	23–24	0.02–0.84	–	–	–	–	–	–	–	42–44	
	Mandaldeh, Chittaurgarh	18.52	–	35.92	3.01	2.93	–	–		–	–	–	–	33.18	
	Sandwa, Churu	≤ 6.4	–	31–37	13–22.6	0.12–0.26	–	–		–	–	–	–	45–46	
	Dungarpur	10.75	–	48.18	2.04	1.13	–	–	–	–	–	–	–	35.55	
	Bhainslana, Jaipur	1–3	–	48–54	2–4	1.5–3	–	–	–	–	–	–	–	35–45	
	Phalodi, Jodhpur	8.70	–	39.03	9.36	0.48	–	–	–	–	–	–	–	42.83	
	Makrana, Nagaur	0.33–1.20	–	50–56	0.8–1.8	0.10–0.28	–	–	–	–	–	–	–	34.8–43.2	
	Rajnagar	0.01–7.6	–	30–33	16–25	0.12–0.95	–	–	–	–	–	–	–	36–44	
	Sirohi	8.52	–	51.49	0.90	0.54	–	–	–	–	–	–	–	39.36	
	Keshariyaji, Udaipur	31.51	–	18.56	21.29	5.33	–	–	–	–	–	–	–	21.82	
	Babarmal, Udaipur	14.35	–	20.79	2.21	0.28	–	–	–	–	–	–		24.00	

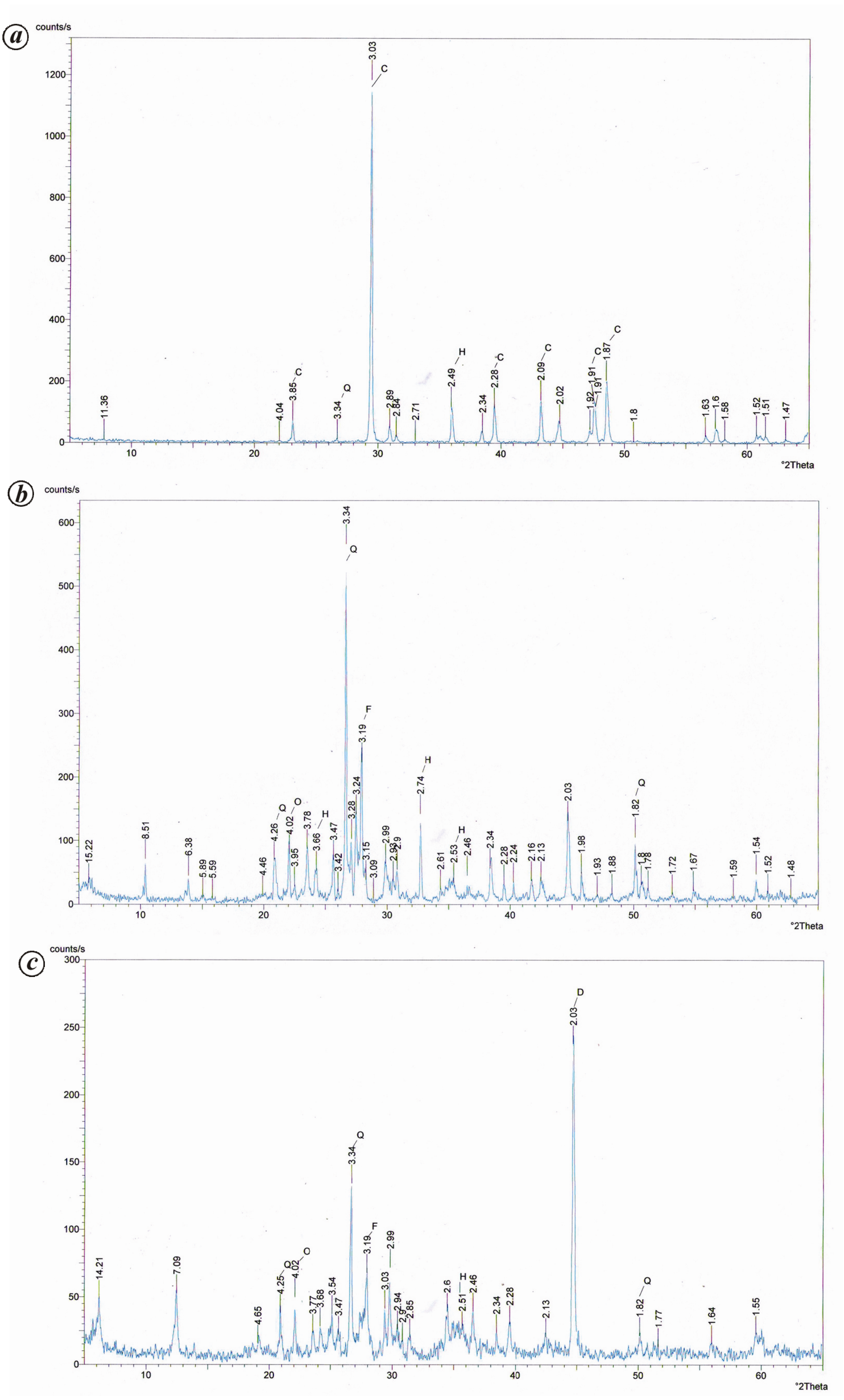

Figure 5. Representative X-ray diffractograph of (***a***) powdered millstone (Goa) sample, (***b***) powdered Dharavi (Uttan) sample and (***c***) powdered cannon ball sample (C, Calcite; F, Feldspars; H, Hamatite; Q, Quartz; O, Opal CT).

indicates that the Portuguese, who had partial cultural contact with the mainland of Maharashtra and central India, did not obtain the stone for the cannon balls from these areas as they were far away from their colonies and not connected by sea. On the other hand, Portuguese settlements at Daman and Diu in Gujarat which survived till 1961, suggest that these stones were perhaps acquired from the nearby areas of Gujarat. It has been indicated that compact stone is required for making cannon balls. It appears that the Dharavi materials which are more siliceous (70.54%) and less compact were not used for making cannon balls (Figure 4). High bulk density (1.9–2.1) of these samples further supports our connotation (Table 2).

Powdered samples were subjected to X-ray diffraction (XRD) analysis (Figure 5). Chemical analysis indicates the presence of dominating properties of limestone. This is identified using the standard peaks at 3.85, 3.03, 2.28, 2.09, 1.91 and 1.87 Å from the X-ray diffractometers (Figure 5 *a*). In routine analysis of sand fractions these peaks are not identified[21,22] since the samples are pretreated with chemicals thus destroying $CaCO_3$. Figure 5 *a* and *b* is similar so far as quartz, Fe-bearing minerals (hematite), opal-CT and feldspars contents are concerned. Figure 5 representing cannon ball samples contains a sharp peak at 2.03 Å, which may be due to diopside ($CaMgSi_2O_6$)[23]. Interestingly, this peak is identified in other samples, but in lower proportions. Diopside is a combination of Ca, Mg and SiO_2 and XRD supports the chemical data presented in Table 2.

Limestone is found in Gujarat and Rajasthan in western India[24]. Analytical results and geology of millstone samples match with the composition of limestone. Due to proximity and high quality of limestone, it appears that the Portuguese might have procured it from Gujarat to make these huge millstones. The calcium content of the millstones and limestone from Gujarat is more or less similar, but other radicals like MgO, MnO, SiO_2 and Fe_2O_3 show dissimilarity with the Gujarat samples (Table 2). Therefore, there may be some other sources which could be away from India. We present the indirect evidences of such inference below.

It appears that these stones were brought either from Belgium or Portugal as identical millstones are available at Fabrica de Polvora, Barcarena, Portugal. It is interesting that four millstones of *Fabrica de Polvora*, Barcarena, Portugal which were brought from Belgium are similar in shape, size and material composition to those found in Goa[25]. However, chemical analysis of the limestone samples of Portugal and Belgium is required to confirm the actual source of the millstones of Panelim, Goa. But it is noted that limestone was generally used from the early days of the Barcarena factory when Leonardo Turriano (1618–19), the chief engineer of the Portuguese Kingdom, responsible for the layout and construction of the first gunpowder production mill house in Barcarena, inaugurated the revolutionary system of millstone (a single millstone used for crushing gunpowder elements and powered by watermill). This happened in spite of the fact that there was a structure for black powder production at a place nearby the streamlet of Barcarena, which dates back to the 14th and 15th century (during the age of discoveries). In earlier days pestle device was used for the production of black powder and as a remnant of this system, a great mortar of limestone is displayed in the museum[26]. In 1725, the King of Portugal appointed António Cremer, of Dutch origin, who made technical improvement in the factory using imported limestone for millstone and plate[25]. In 1729, he made improvements in the gunpowder production and imported four new millstones (machines) from the province of Namur, Belgium. The novelty of this machine was that two grinding millstones made of limestone rolled vertically over the plate which was made of limestone. This system functioned until the hydroelectric-power station was established in 1925 (refs 25 and 26).

Based on the above discussion, a provisional inference may be drawn that millstones of Goa might have been brought by the Portuguese from Belgium or Portugal. This finds support from the similarities (in size, shape and material) of the limestone we studied with the millstones of Fabrica de Polvora, Barcarena. The gunpowder site in Panelim, Goa was established during the time of Francisco da Gama for the production of enormous quantity of gunpowder. Thus the tentative date of these millstones is likely to be during the first quarter of the 17th century (Figure 6). These imported millstones were used to crush the ingredients of gunpowder.

The present study focuses on tracing the source materials of the millstones and cannon balls with the inferences from archaeological, geological, chemical and mineralogical analysis. The study shows that the millstones are made of limestone. Though CaO content nearly matches

Figure 6. Millstones at Fabrica de Polvora at Barcarena, Portugal (courtesy: N. Taher, ASI Bhopal).

Figure 7. Logical end of vanished site by salvage archaeology.

with the values of limestone content in Gujarat, other elements do not match with those of the millstone samples. This implies that such variety of limestone for making millstones is not available in western India. It suggests that the raw material for millstones must have been procured from areas away from India. Based on the study, it is inferred that the Portuguese might have brought the raw material or finished product as millstones from outside India, as Portuguese records show that they acquired similar millstones for Fabrica de Polvora at Barcarena, Portugal. However, further studies in the form of collecting more samples from Namur, Belgium are required to prove the provenance of millstones of Panelim, Goa. The cannon balls are made of heavy, compact rock like basalt indicating that basalt rock must have been preferred for making cannon balls from such pockets wherein the rock was fresh, with high iron and MgO content and which was readily available to them. The analytical results of basalts present nearby at Bassein (Dharavi, Uttan) do not match with the composition of the cannon balls. It can therefore be stated that although stones from Dharavi (Uttan) was quarried for decoration of churches of Goa by the Portuguese on a larger scale, the same was not suitable for cannon balls due to their fragile nature (Figure 7).

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