2. All these rocks are metamorphosed and show granoblastic texture. Hornblendes constitute more major proportions than plagioclase feldspar. Mineralogical composition suggests medium amphibolite grade metamorphic conditions.
3. Chemistry classifies these rocks as olivine tholeiitic mafic rocks. They contain appreciable amount of hypersthene and olivine in their normative compositions.
4. Trace elements particularly HFSE and REE compositions, suggest that all these rocks are co-genetic and probably derived from olivine tholeiite magma originated from a depleted mantle lherzolite source.
5. These mafic rocks show very close geochemical similarities with mafic rocks reported from the Central Crystallines of Western Himalaya, suggesting large mafic magmatic events during the Proterozoic.
6. These are preliminary results; more detailed work is required for the proper evaluation and establishment of a petrogenetic model for these interesting rocks.

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Analysis of timber and coating material on an iron anchor recovered off Aguada Bay, Goa

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Distinct developments have been observed in the evolution of stone and iron anchors. A wide variety of stone anchors have been reported from Indian waters, preceding the introduction of iron anchors by the Europeans. Recently, an Admiralty Long Shanked iron anchor measuring 3.30 m long with a 4.37 m wooden stock was recovered off Aguada Bay, Goa at a water depth of 11 m. The anchor has been tentatively dated contemporary with the maritime history of Goa and Portugal between the 16th and 17th centuries.

A thin and uniform coat of finely ground material has been noticed on the surface of the anchor and wooden stock, applied for the endurance of the anchor and the stock in tropical waters. The upper portion of the wooden stock was slightly weathered by the wood-

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borers and a deposit of bivalves and growth of barnacles were also noticed on the flukes of the anchor. The anatomical analysis of timber revealed that *Terminalia* spp. and *Phoebe* spp. timber were used for making the stock. Wood, other than teak, such as *Terminalia* and *Phoebe* were also used during the 16th and 17th centuries for anchor stocks because of their weight and endurance.

This study is focused mainly on the anatomical analysis of timber to understand the timber species used in making the wooden stock of the anchor and its probable provenance. In addition, a Scanning Electron Microscope and an Energy Dispersive Spectrum analysis of the thin coat on the iron anchor as well of the wooden stock was done to infer the chemical composition of the fine powdered material applied.

Keywords: Aguada Bay, anatomical analysis, coating material, iron anchor, wooden stock.

TIMBER has played an important role in the shipbuilding industry since ancient times, particularly in the construction of seaworthy boats and ships including stone, lead and iron anchors. For instance, timber was used as flukes for stone anchors, shank for lead stock anchors and also stock for iron anchors. Although lead stock anchor with wooden shank has so far not been recovered from Indian waters, wooden flukes in stone anchors and wooden stock in iron anchors were reported from offshore regions of Maharashtra[1] and Goa[2] in the west coast. Indian literature namely *Yuktikalpataru* vividly mentions about ancient shipbuilding activities, i.e. various parts of the ships, types of ships used for trade, warfare, pleasure trips and kinds of timber used in their construction but hardly any mention is made about the use of timber in stone and iron anchors.

In the *Astadhyayi*, Panini (5th century BC) mentions the use of a large variety of timbers namely amra (*Mangifera indica*), khadira khair (*Acacia catechu*), simsapa/ blackwood (*Dalbergia sissoo*) (*Dalbergia sisoo*), salmali/ silk and cotton tree (*Bombax malabaricum*)[3]. The *Periplus of the Erythraean Sea* (*Periplus Maris Erythraei*) enumerates teak wood, black wood and ebony as the important wood varieties exported from Barygaza to the ports of Apologos (Apologues) and Ommana on the Persian Gulf coast[4]. During the rule of king Nebuchadnezzar (604–562 BC), India is said to have exported timber to Mesopotamia required for shipbuilding and his palace is said to have been built with teak from India[5]. Hourani[6] states that Indian teak is most precious and valuable due to its durability, elasticity, strength, non-yielding ability to cracks, splits and shrinks.

During the Portuguese period, the Aguada Bay of Goa was used as a sheltering and refuelling stop for the ships en-route to Old Goa, as well as Portugal. Portuguese records state that while crossing a sandbar (a somewhat linear landform within or extending into a body of water, typically composed of sand, silt or small pebbles) in the river Mandovi, a number of ships had been wrecked. This sandbar was referred in the Portuguese hydrographic charts as Barra de Agoada. During 1977–82, the sandbar was dredged leading to the recovery of four iron anchors of different types and a number of timber pieces. These anchors are presently housed in the Goa State Museum, Panaji[2]. In 1999, Florenco Marques (owner of a local fishing boat) found an Admiralty Long Shanked iron anchor off the Aguada Bay in the 'satbahu' (14 m water depth) and reported the same to NIO, Goa. Another anchor of similar type, but without the wooden stock had earlier been found from a shipwreck site at Sunchi Reef[7]. The present study reports recovery of a prototype of Admiralty Long Shanked iron anchor with a wooden stock from 11 m water depth (15°26′568″N and 73°46′950″E) in the vicinity of the Aguada Bay lighthouse in January 2008 (Figure 1). This paper deals with an anatomical analysis of the wooden stock to identify the species of the timber and its probable provenance. In addition, Scanning Electron Microscope (SEM) and Energy Dispersive Spectrum (EDS) analysis of fine-powdered layer applied on the anchor surface has been carried out to understand its elemental composition, purpose of its application and to tentatively date the anchor in relation with the maritime history of Goa. Further, we also report on the uses of timber, other than teak, in the shipbuilding industry.

The anchor recovered from the Aguada Bay (Figure 2) is intact, with a length of 3.30 m and flukes measuring 1.35 m. The diameter of the shank varies from 45 to 47 cm. A 2.5 cm thick and 55 cm diameter iron ring has been provided for tying the cable. The length of the wooden stock is 4.37 m and is made of two timbers joined together with nine nails (pins) (Figure 3). The thickness of each timber varies from 20 to 30 cm. Incidentally the length of the stock is much longer than the anchor. A well-preserved uniform thin layer of protective coating has been observed on the surface of the flukes, shank and nails of the wooden stock. The upper stock is covered with huge deposits of shell colony (bivalves) (Figure 4) in addition to the deterioration by the wood-borers at a few places. Oysters were also noticed on the flukes of the anchor. However, the lower timber, buried in sediment, is hard and has not decomposed like the upper timber. Nine iron nails were used to join the upper and lower timber of the stock keeping the shank at the centre of the stock. Nails are placed at a varied distance and remained intact with the coating layer. No iron bands or strips have been used for further fastening of the wooden stock, as found in the anchors of late 18th and early 19th centuries[8,9].

In order to identify the timber species, its quality, state and suitability of making a stock, samples were collected from both the pieces of the stock. The material used for anatomical study consisted of small un-carbonized and partly deteriorated wood pieces. Small blocks were made

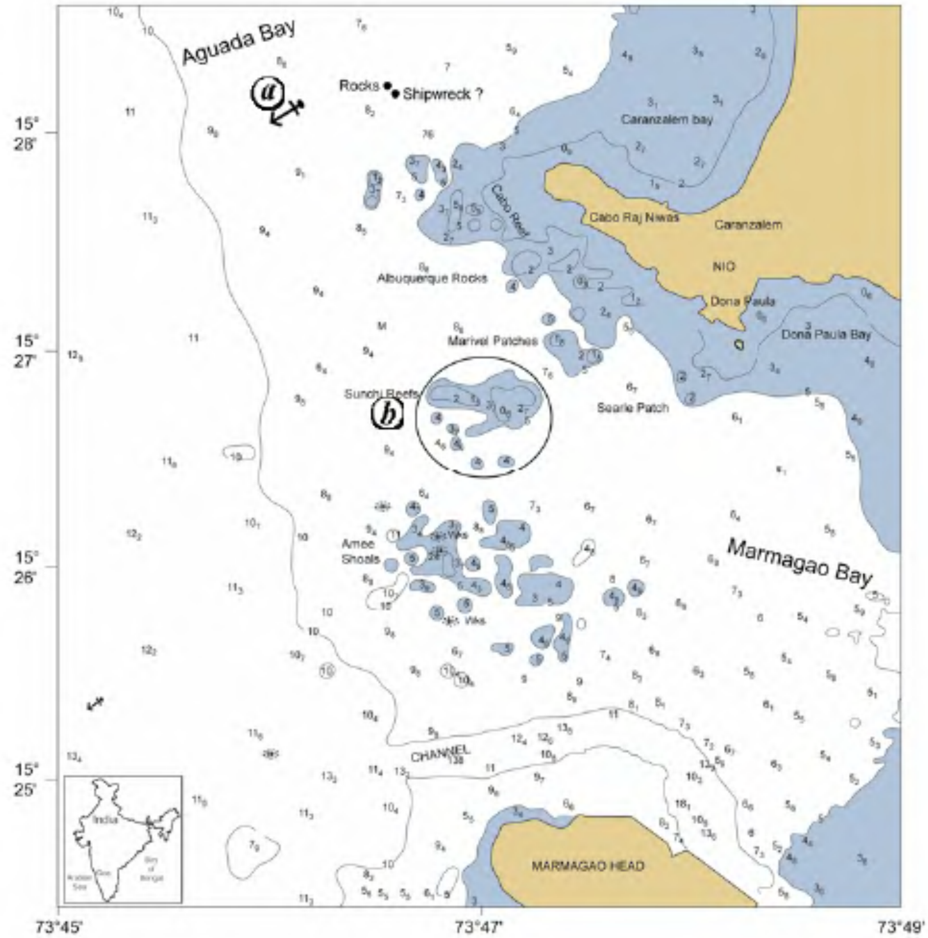

Figure 1. Location map showing (*a*) iron anchor recovery site off Aguada Bay and (*b*) shipwreck site at Sunchi Reef, offshore Goa.

Figure 2. Recovered iron anchor with wooden stock.

from these samples and boiled in water and 20 μm sections (cross, tangential and radial) were cut using Reichert sliding microtome. The sections were stained in haematoxylin, safranin and mounted with DPX mountant. Sections were studied under a Leitz Laborlux microscope connected to a Quantimet 500 MC Image Analysis system for anatomical characterization and identification also for capturing the photomicrographs. Part of the wood was then converted into chips and macerated for observing individual elements[10]. The samples were observed with and without hand lens (10×) to study the wood[11]. Specific gravity was determined using the formulae: mass of the sample at test/oven dry weight of the sample.

Further, to determine the elemental composition of the coating material, SEM and EDS studies were carried out at spots on these flaky coating specimens. The specimens were cleaned in an ultrasonic bath to remove the loose material deposited from the water column. Then these flakes were placed on a carbon conductive tape stuck on a nylon stub. To minimize the effect of depositional material, the specimen peeled from the anchor was mounted on the stub in such a way that the lower surface of the specimen to be analysed faced upwards. Afterwards the specimens were sputter coated with about 20 nm thick gold coating using a gold sputter coater. Coated specimen images were then analysed using SEM (model JOEL JSM 5800 LV) with an Oxford EDS attachment.

Analysis of timber was carried out for identification of wood material including the combination of physical features, gross structure and anatomical characters as per IAWA[12] list of microscopic features for hardwood identification.

The upper timber of the stock is dark in colour. Its outer side is soggy, soft and peels off easily, while the inner side is non-soggy, hard, heavy (sp. gr. 0.875, oven-dry) shallowly interlocked, grained and even textured. Anatomical study showed that growth rings are distinct. Wood is diffuse porous and vessels are found in radial multiples of 2–3 (44%), singles (28%) and clusters (28%). Solitary vessels are oval in outline, infrequently filled with yellowish deposits. Vessels are large, with tangential diameter in the range of 141–213 μm: av = 181 μm. Vessel frequency varied from 4 to 5 mm^{-2} and their element length was found in the range of 271–410 μm: av = 330 μm) with simple perforations. Intervessel pits are alternate, round to angular in shape and medium to large in size i.e. 7–11 μm, av = 9 μm and vestured. The vessel ray pits are similar to intervessel pits. Fibres are filled with dark coloured deposits, septate, thin to thick walled. Their length ranged from 837–1311 μm (average 1098 μm). Fibres from the surface area of the sample showed soft rot cavities. Axial parenchyma is paratracheal, aliform, aliform confluent, joining 2–4 vessels forming zigzag pattern; also diffuse, consisting of four cells per strand without crystals but full of dark deposits. Rays are predominantly uni-seriate, 8–12 mm^{-1}, homocellular to weakly heterocellular composed of procumbent with one row of upright/square marginal cells. Some rays are partly bi-seriate. Ray height varied from 203–473 μm, with dark coloured deposits (Figure 5). Prismatic crystals were observed in procumbent, upright and square cells.

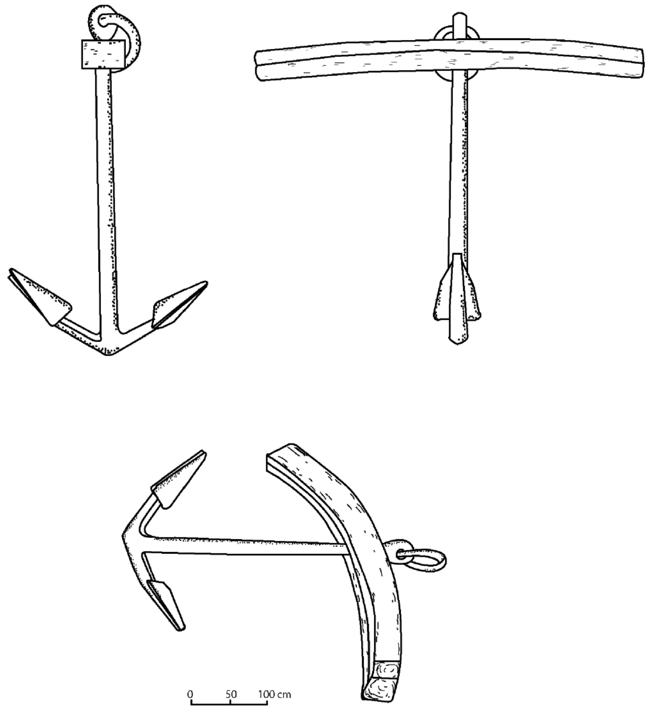

Figure 3. Figure showing the schematic drawing of the anchor.

Figure 4. Figure showing the nail head and deposition of bivalves on the wooden stock.

The card key features of upper timber as per IAWA 1989 are as follows: 1, 5, 13, 22, 23, 26, 27, 29, 30, 42, 46, 52, 56, 60, 65, 69, 72, 79, 83, 92, 96, 106, 115, 137, 138, 189, 192, 195. The diagnosis of the timber has been carried out based on the characters mentioned above and the sample has been identified as *Terminalia* spp. belonging to Combretaceae.

The general feature of the lower wood is dark brownish in colour with the outer side soggy, soft and peeling off easily while the inner side non-soggy, hard and heavy (sp. gr. 0.88, oven-dry), deeply interlocked, grained and even textured. The anatomical study showed the growth rings are distinct to indistinct. Wood is diffuse porous and vessels are in radial multiples of 2–3 rarely up to 4 or more and occur mostly as clusters. Solitary vessels are oval to angular in shape and its tangential diameter varied between 62 and 104 μm (av = 88 μm) with thin walled tyloses. Vessel frequency varied from 13 to 20 mm^{-2} and average length varied from 214 to 612 μm (av = 430 μm) with simple perforations. Intervessel pits are alternate, polygonal and large, 10–14 μm (av = 12 μm) in size, non-vestured. The vessel ray pits have highly reduced border to simple pits, horizontal, 11–21 μm (av = 15 μm) in size. Fibres are with simple to minutely bordered pits, septate, thin to thick walled. Fibre length varied in the range 1097–1675 μm (av = 1446 μm). Axial parenchyma is vasicentric consisting of 3–4 cells per strand. Crystals are not observed. Rays are 1–3 seriate, predominantly 2–3 seriate, 33–56 μm (av = 41 μm) wide, 6–8 mm^{-1} heterocellular and composed of procumbent and one row of

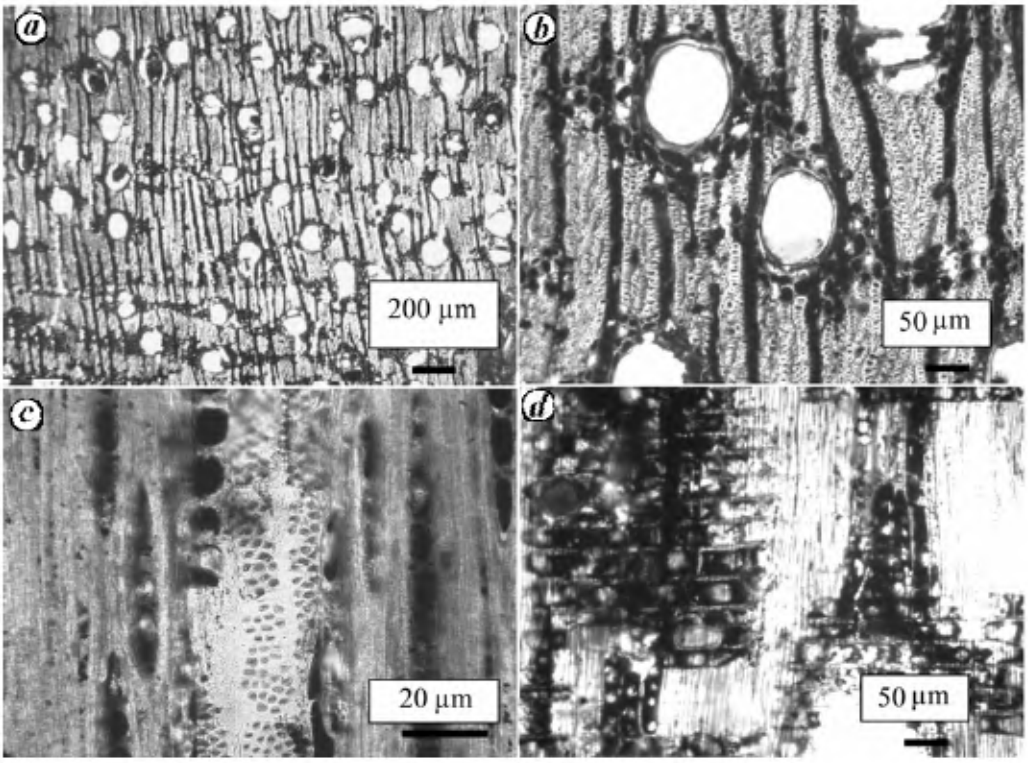

Figure 5. Anatomical analysis of timber of upper wooden stock (*Terminalia* spp.). ***a*** and ***b***, CS showing diffuse porous wood with aliform and aliform confluent parenchyma. Parenchyma contains dark coloured deposits. ***c***, TLS showing uniseriate rays with dark coloured deposits and intervessel pits. ***d***, RLS showing weakly heterocellular rays with dark coloured deposits.

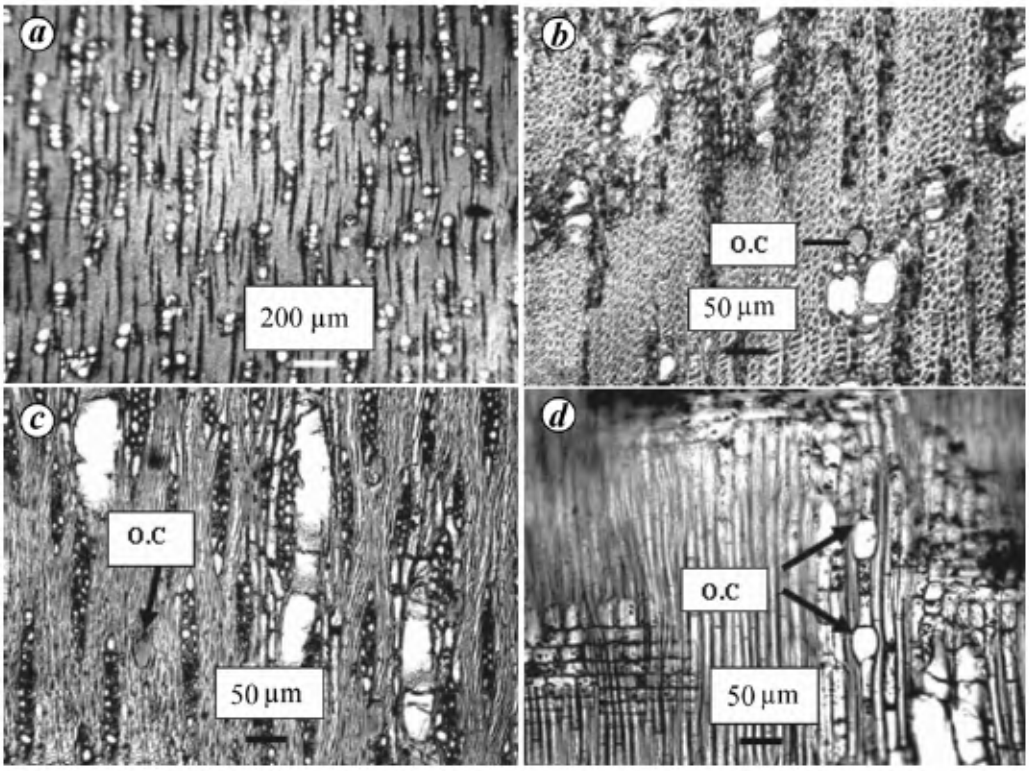

Figure 6. Anatomical analysis of timber of lower wooden stock (*Phoebe* spp.). ***a*** and ***b***, CS showing diffuse porous wood with indistinct to distinct growth rings. ***c***, TLS showing multiseriate heterocellular rays and vessel members with intervessel pits and axial parenchyma with oil cells. ***d***, TLS showing prominent oil cells in axial parenchyma and rays with procumbent and upright cells.

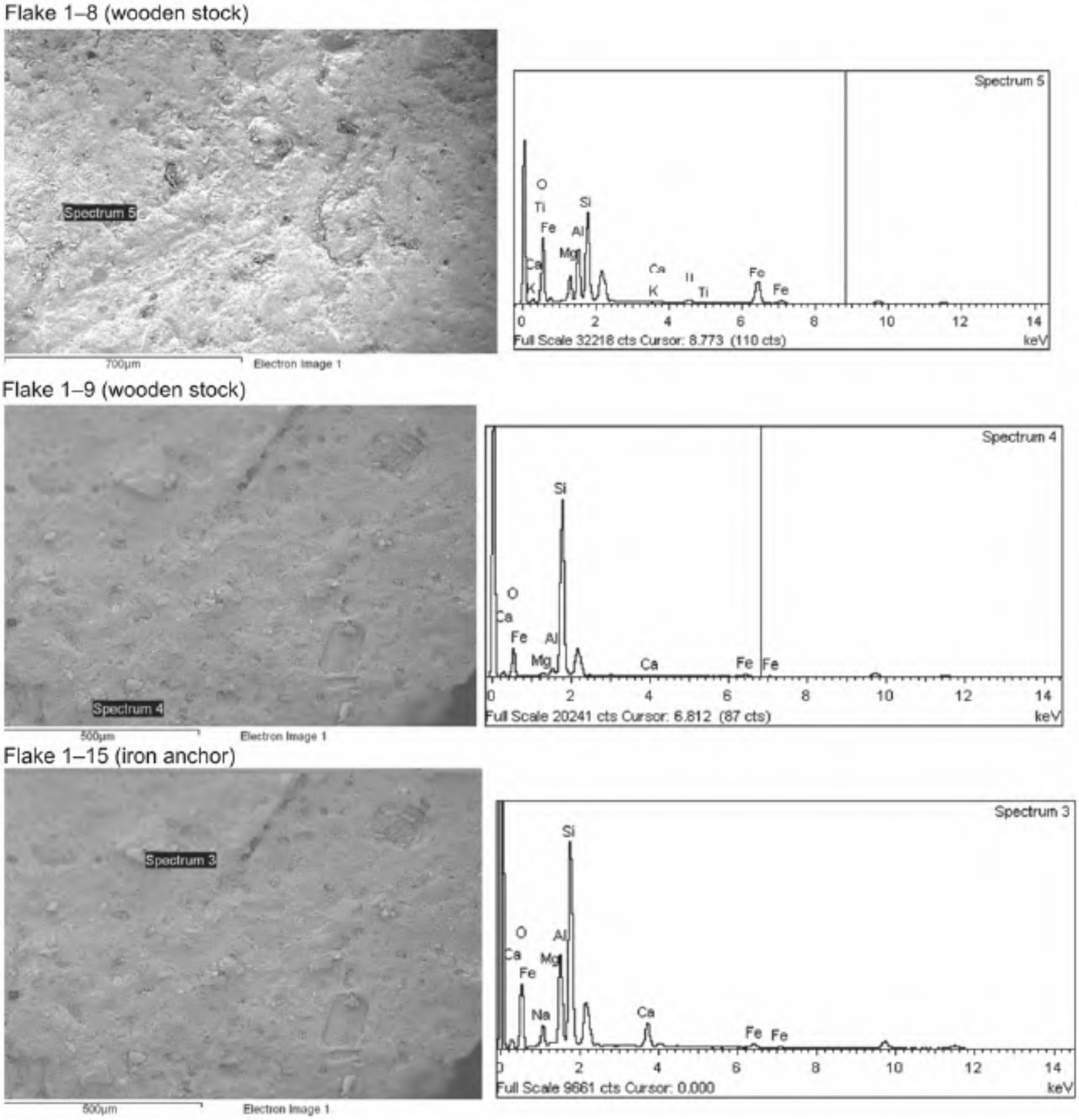

Figure 7. SEM-EDS analysis of representative spots of the coating material from the wooden stock and anchor shank.

upright/square marginal cells having coloured deposits. Inclusions are not observed. Ray height varied between 213 and 453 µm (av = 323 µm) or 20 cells high. Crystals of variable types were observed in procumbent or upright cells. Oil cells were observed predominantly in axial parenchyma (95 µm in length and of 57 µm in width in RLS; Figure 6).

The card key features of the lower timber as per IAWA, 1989 are: 1(v), 2, 5, 12(v), 13, 22, 27, 32, 41, 47, 53, 56, 61, 65, 69, 72, 79, 92, 97, 106, 115, 125, 152, 189, 192, 195. Diagnosis of the timber has been carried out based on the characters mentioned here and the sample has been identified as *Phoebe* spp. belonging to Lauraceae.

Note: In view of the fragile nature of the wood, card key features from 164 to 188 and 196 onwards have not been taken into consideration for both the timber samples.

From the coating layer on the anchor, several thin flakes of clean areas have been collected from different spots on wooden stock and anchor shank for SEM and EDS elemental studies (Figure 7) and the results of representative flakes have been presented in Table 1.

The results indicate that silicon oxide (SiO_2) is predominant and its content varies ~61–93% in the coat on

Table 1. Weight per cent of elemental oxides of thin coating material from the wooden stock and iron anchor

Elemental oxides	Flake 1–8	Flake 1–9	Flake 1–14	Flake 1–15	Flake 1–16	Flake 1–17
	Coating layer on wooden stock			Coating layer on nail heads and iron shank		
Na_2O	6.21	–	6.05	–	0.44	–
MgO	0.71	0.97	0.43	10.34	6.58	0.72
Al_2O_3	21.74	2.31	21.76	21.66	28.05	1.68
SiO_2	61.46	92.87	61.37	43.45	46.99	85.28
K_2O	–	–	–	0.22	2.94	0.29
CaO	7.22	0.52	5.74	0.59	0.27	0.33
TiO	–	–	–	2.07	0.81	–
MnO	–	–	–	–	0.36	–
FeO	2.65	3.32	4.65	21.67	13.55	11.69

wooden stock, whereas it ranges from 43 to 85% in the coat on anchor shank. Higher SiO_2 content has been observed at the expense of decreased alumina (Al_2O_3) in samples from wooden stock and anchor shank (Table 1: Flake 1–9 and Flake 1–17). FeO content in the coat from wooden stock is low and ranges from 2 to 5% when compared to 11 to 22% in the coat of anchor shank. Na_2O is high (6%) in the coat on the stock when compared to negligible (<0.5%) content in the anchor shank coat. Interestingly, MgO content shows a reverse trend with its low contents (<1%) in the coat on wooden stock compared to higher values (up to 10%) in the coat of anchor shank. Similarly, FeO is less (2.65–4.65%) in the coat on wooden stock whereas it is high (11.69–21.67%) in the coat from anchor shank. K_2O and TiO were absent in the wooden stock coat and conspicuously present in the anchor shank coat with a varied concentration of 0.2–2.94% and 0.81–2.07% respectively.

The finding of the anchor with wooden stock off the Aguada Bay further confirms the use of good quality timber in the shipbuilding industry during the maritime history of Goa and Portugal. The Indian Ocean region is of tropical nature; hence the effect and attack of woodborers are comparatively more than the other seas. Probably, the application of a coat of finely ground material on the surface of the anchor as well as on the wooden stock was made perhaps to protect them from the marine environment.

It is difficult to identify the individual mineral grains in the coating layer under microscope, as it constitutes very fine powder. Coating layer on the anchor is made of fine powdered material presumably derived from either beach or river sorted sands. Beach sand is moved by near shore wave generated currents. Highly variable wind and wave regime in the coast which accrete and erode beaches determine the fate and final composition of beach sands. Beach sand composition depends mainly on regional geology, more particularly bedrock mineral assemblages in the hinterland and mostly contains mineral sands, biogenic sands and mixtures of these.

SEM and EDS analyses of the thin flakes (Figure 7) show that the composition of this layer is nearly homogenous, indicating the use of well-sorted sands for protective coating on the anchor. The composition of coating material is more analogous to beach sands than river sands. River sands are generally more variable and divergent in composition than the beach sands due to high energy waves swashing the beach front.

Most beach sands, however, are composed of grains of the mineral quartz due to its higher relative density. In addition to the predominant quartz, beach and river sands contain other lithics such as feldspar, mica, hornblende, ilmenite, magnetite, garnet and also a variety of trace minerals such as iron/titanium oxides, zircon, monazite and calcite. Substantial TiO_2 (0.81–2.07%) found in the iron anchor coat may be due to the presence of garnet as garnet is commonly present in lithics derived from the hinterland. Titanium may be present in a trivalent state in garnet along with Fe and Al.

Based on the variations in the contents of oxides of Na, Mg, K, Ca, Ti and Fe in the coats of wooden stock and anchor, it appears that source material from two different beach sands have been used for these coatings.

It is generally believed that coating materials were not applied on iron anchors and wooden stocks. Conversely, a uniform layer would not have existed on the surface of the anchor as well as on either sides of the wooden stock. This type of anchor would not be ground or rolled on the seabed like the stone or lead stock anchors. When anchored, either one fluke or one side of the stock would remain above the seabed. If the coats were a deposit from water column, it would not have been present on the buried portion of the anchor. This fact is also corroborated in the compositional differences in the coats from wooden stock and the anchor.

It could be possible that such type of coats, constituting well-sorted sands from beaches, were applied on the anchors to maximize its endurance in tropical waters, where the nutrient-rich water support faster growth of wood borers which, in turn, could deteriorate the stocks. It is known from the records as well as local mariners that a mixture of lime and other ingredients is applied on the ships, coir, etc. to protect them from woodborers. Another effective deterrent against woodborers is cashew nut oil, which is also popular among mariners.

In an earlier study[13], it was observed that wooden stock of iron anchor were made of teak (*Tectona grandis*) and benteak (*Lagerstroemia* sp.) indicating a preference for tropical timbers in maritime trade. The present study indicates that iron anchor with wooden stock is made of *Terminalia* spp. and *Phoebe* spp. ranging from 250 and 70 respectively; the former having a distribution in the Tropics of the world and the latter in Indo-Malayan region, Pacific Islands, Tropical America and the West Indies[14,15]. Limited studies made on wood anatomy of these two genera[16–19] indicated that identification of timber at species level was difficult. In view of this, it is not possible to comment on which species has been used for making wooden stock of the anchor.

Furthermore, the distribution of these two genera across many countries makes it difficult to pinpoint the exact provenance of the timber. The earlier sea routes, including the timber trade route used by Portuguese, may throw some light on the source of timber used for these purposes. The heavy weight and quality of these two timbers might be the criteria for their selection as wooden stock for the anchor. It is interesting to note that *Terminalia* and preservative-treated *Phoebe* woods were known for their use in shipbuilding, oars, shafts, masts and hatch covers[17,20]. The mariners might have outsourced the raw material from any en-route countries in their voyages. *Phoebe* has not been tested for durability studies under marine conditions, whereas limited studies have been made on a few species of *Terminalia* at selected localities. As both timbers are heavy, the shipbuilders may have used them as wooden stocks of iron anchors.

The anatomical study shows that not only teak but also other timbers such as *Terminalia* and *Phoebe* spp. were used for shipbuilding by the Portuguese for their better endurance in tropical marine conditions. Moreover, Europeans used timbers from India and other countries for the construction of big sea-going vessels and also for stock of the iron anchors. This is the first report from Indian waters about recovery of timber of non-Indian and non-teak type wooden stock. The absence of iron strips, which were common among the anchors made in the 18th–19th centuries, probably indicate that this stock belongs to 16th–17th centuries. This kind of coating material on anchor and stock has not been previously reported. It is presumably applied to have better endurance and protection in the tropical waters. SEM–EDS results revealed that the composition of finely ground material applied on stock and shank are from two different sources of beach sands.

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