



Geochemical and mineralogical analysis of stone anchors from west coast of India: provenance study using thin sections, XRF and SEM-EDS

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ABSTRACT

Stone anchors have been recovered along the Indian coast as a part of the maritime archaeological studies at the National Institute of Oceanography (NIO), Goa. Study of stone anchors provides clues to understand the ancient maritime trade contacts of India with other countries. These anchors resemble those found in the Mediterranean Sea, Persian Gulf and Red Sea Coast. Underwater explorations at Bet Dwarka, Dwarka, Goa, Visawada and Somnath have yielded stone anchors of widely varying shapes, sizes and weights ranging between 16 and 410 kg. Sixteen (10 Indo-Arabian, 4 Ringstone and 2 Single hole type) of the total of 269 stone anchors have been studied to determine provenance of rock through petrographic analysis using thin section studies, X-ray Fluorescence (XRF), and Scanning Electron Microscope – Energy Dispersive Spectrometer (SEM-EDS).

Our results suggest that these anchors were made from various rock types, such as granodiorite, dolerite, varieties of basalt, schist, calcareous sandstone, limestone and sandstone. The coastal tract of western India has exposures of all these rock types of igneous and sedimentary rock suites while ultramafic rocks occur inland along the Gujarat and Rajasthan border. It is inferred that these stone anchors have been sourced from rock formations from Gujarat, Goa, Karnataka and Maharashtra regions for use in maritime trading activities of the ancient and medieval periods.

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1. Introduction

Maritime archaeologists are actively involved in mapping the ancient maritime trade routes to understand the evolution of civilisation, trade and cultural relationships among different countries. In order to achieve this, underwater explorations and excavations are conducted to locate shipwrecks, remains of ports, anchorages and anchors. During explorations, artefacts that survive decomposition, such as amphorae, semi-precious artefacts, metal objects, ceramics, stone and iron anchors, glasses, etc. are generally found. The recovery of stone anchors validates the assumption that ships had anchored or sailed in the area in maritime past. Information on shape, size, weight and other characteristics of stone anchors found both underwater and on land will help to relate them to other finds.

Numerous stone anchors of different shapes and types have been reported during onshore and offshore explorations around the world, notably from Arabian Gulf, Egypt, Israel, Greece, India, China, Korea, Japan, Sri Lanka, Black Sea, Mediterranean Sea, South China Sea and Red Sea (Agius, 2005; Athiyaman and Jayakumar,

2004; Frost, 1970, 1985, 1989, 1996; Gaur et al., 2007; Kapitan, 1994; Moll, 1927; Nibbi, 1993; Nouhuys, 1951; Raban, 2000; Tripathi et al., 1998, 2003; Tripathi, 2009; Souter, 1998; Upham, 1983; Wachsmann, 1998).

Since the initiation of maritime archaeological research in 1983 in Indian waters by the National Institute of Oceanography (NIO), Goa, (<http://www.nio.org>) to locate submerged habitational and port sites and shipwrecks and several types of stone anchors have been recovered during both onshore and underwater explorations off Bet Dwarka, Aramda, Dwarka, Miyani, Visawada, Somnath, Mithi Virdi, Vijaydurg, Sindhudurg, Goa, Kannur, Minicoy, Manapad and Chilika Lake (Table 1 & Fig. 1).

In order to ascertain the provenance of stone anchors, it is essential to understand the rock types of stone anchors as well the exposures of rocks along the coastline. The paper discusses results of studies of mineralogy, petrology and geochemical analyses of 16 stone anchors recovered from west coast of India to infer the provenance of rocks.

1.1. Geology of the west coast of India (WCI)

The west coast of India is a near straight coastline of ~2000 km length between 8° and 24° N with exposures of

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Table 1
Various types of stone anchors observed along the Indian coast (North–South).

Find Sites	Composite Anchors	Indo-Arabian Anchors	Ring stone Anchors	Single hole Anchors	Total
West Coast					
Bet Dwarka, Gujarat	13	7	1	–	21
Aramda, Gujarat	2	1	–	–	3
Dwarka, Gujarat	35	63	24	1	123
Miyani, Gujarat	2	6	4	–	12
Visawada, Gujarat	10	2	1	1	14
Somnath, Gujarat	6	2	35	–	43
Mithi Virdi, Gujarat	–	4	–	–	4
Vijaydurg, Maharashtra	1	23	–	–	24
Sindhudurg, Maharashtra	3	5	–	–	8
Baga, Goa	–	1	–	–	1
Sunchi Reef, Goa	–	1	1	–	2
Grandelsland, Goa	–	2	–	–	2
Kannur, Kerala	–	1	–	–	1
Minicoy, Lakshadweep Is.	–	1	–	–	1
East Coast					
Chilika Lake, Orissa	4	–	–	1	5
Manapad, Tamil Nadu	–	–	–	5	5

various rock types ranging from Archaean granites/schists to recent alluvium. Various rock sequences of Indian sub-continent have been well mapped in detail (Krishnan, 1968; Pascoe, 1959; Wadia, 1975). The exposures to the north of the Gulf of Kachchh include recent sedimentary deposits Tertiary to Jurassic rock sequences, mostly sedimentary rocks with fossils (Merh, 1995). Along the northern WCI, (Maharashtra and Gujarat) Deccan Trap basalts, miliolite limestones and fossiliferous limestones of Quaternary age and fossiliferous sedimentary rocks of Tertiary sequence are exposed. In the central WCI, (particularly Goa) laterite cliffs are present with a few locations having metamorphosed sequence of metagreywacke and quartzites (Gokul et al., 1985; Purushothaman et al., 2009) while Deccan Trap basalts line the coast with alkaline complexes at few locations (Deshpande, 1998). The southern WCI (Kerala and Karnataka) has rock suites of granites, schists, granitic and gneissic complexes with localised exposures of Pleistocene sequence (Soman, 2002) (Fig. 4).

1.2. Maritime activities of the WCI

The people of the Indus civilisation were the first mariners in India who began the maritime trade along the west coast of India. Contacts of the Indus civilisation with Egypt, Mesopotamia and Persian Gulf countries have been documented since the third millennium BC (Rao, 1991). During the Christian era, maritime trade contacts of India with Roman, Greek and Southeast Asian countries flourished (Mookerji, 1912; Mukerjee, 1956; Warmington, 1974). Recent archaeological finds from the WCI and the *Periplus Maris Erythraei* (60–100 AD) (Casson, 1989) and Ptolemy's Geography (150 AD) (McCrinkle, 1985) provide information on India's maritime trade contacts in regions of the Mediterranean Sea, Persian Gulf and Red Sea (Sidebotham et al., 2001–2002; Tomber, 2008). These evidences show that Arab, Roman and other mariners frequently visited the ports of India during this period. Arabs were great seafarers before the birth of Islam (Sridharan, 1982) and had trade contacts with the west coast of India. During the 8th century AD maritime trade between India and Arab grew. Since then great number of Arab mariners came to India as traders. By the end of the 12th century, with the decline of the Chola kingdom, the Arabs

gained control over the east coast of India. Hourani (1995) suggested that Arab traders used heavy anchors onboard their ships and Indo-Arabian type of stone anchors were an important feature of the Arab ships. Similar types of Indo-Arabian anchors have been reported from Siraf port, Iran on the northern shore of the Persian Gulf (Whitehouse, 1970), east African and Red Sea coast (Chittick, 1980; Raban, 1990), in conjunction with other findings, dated between 8th and 14th centuries. Along with Indo-Arabian type of stone anchors, ringstone anchors have also been found in the Persian Gulf (Vosmer, 1999). Some of the anchors recovered in the waters of west coast of India may also belong to the above period, and some are dated to the later period as Arab traders were active along the Indian coast during this period.

1.3. Types of anchors in the WCI

Studies on stone anchors offer new evidences on the maritime activities of a country; hence Frost (1973) suggested that stone anchors are the potsherds of maritime archaeology. Anchors are mostly found along the ancient trade routes, particularly in sheltered bays, ports and harbour sites and within shipwrecks.

In India, the evolution of stone anchors has been traced during onshore and underwater archaeological explorations. In land excavations at Lothal and Kuntasi (Rao, 1979; Dhavalikar et al., 1996) unearthed the simplest type of stone anchors along with other finds belonging to the Harappan period (2500–1900 BC) but these stone anchors differ in shape and size from the anchors found in maritime archaeological explorations.

Earliest stone anchors had only one hole for tying the rope without flukes and were termed as dead weight anchors due to their weight. These anchors are even used now in country crafts by the mariners in shallow and back waters. Later on stone anchors were sculpted with two or three holes and were termed as composite anchors made of triangular or prismatic shaped stone blocks. In these anchors the apex hole meant for cable whereas wooden flukes were provided in lower holes. Composite anchors continued from the Bronze Age to the Early Historic and Historic period. Subsequently, mariners invented Indo-Arabian stone anchors, which were different in shape and size from composite stone anchors. These anchors were developed when the size and carrying capacity of ships increased and were highly useful in the regions with corals and rocky seabed. The other type of anchors, called ringstone (mushroom type) anchors, came into use simultaneously. In all these anchors wooden flukes were introduced. Even Ludovico di Varthema (AD 1470–1510), the Italian traveller mentions that in Kerala coast anchors made of marble were used, which were eight *palmi* long and two *palmi* every other way (Jones, 1863; Mookerji, 1912). Historically, the stone anchors gave way to lead stock anchors and further to iron anchors. Although the Europeans introduced iron anchors in India during the 16th–17th centuries (Qaisar, 1982), the finding of various types of stone anchors in Indian waters suggests that they were in use as recently as the 20th century.

About 269 stone anchors pertaining to composite, Indo-Arabian, ringstone and single hole types have been observed in Indian waters and their physical characteristics and dimensions are catalogued and documented. Some of the stone anchors have been recovered from Bet Dwarka, Dwarka, Goa, Somnath and Visawada waters (Gaur et al., 2002, 2005; Gaur and Tripathi, 2006; Rao, 1999; Tripathi, 2002; Tripathi et al., 2003; Sundaresh et al., 1999, 2002), whereas anchors of other sites are *in situ*. Total 16 stone anchors of various size and shape and constituting different rock types from Bet Dwarka, Dwarka, Goa, Somnath and Visawada waters in the west coast of India have been selected for the present study (Table 2 & Fig. 2).



Fig. 1. Locations of stone anchor find sites in India.

1.4. Previous petrographic studies of stone anchors

Frost (1993) has stressed on the importance of knowledge of the provenance of the rock anchors through thin section study for identifying their origin and typology. From the available information, it appears that for the first time XRD and thin section analysis of stone anchors of Anatolian coast, Uluburun wreck and the stone anchors displayed at the Bodrum Museum of Underwater Archaeology (BMUA), Bodrum, Turkey, have been carried out to ascertain their provenance (Evrin et al., 2002). Their analysis established that these anchors are made of igneous, sedimentary and metamorphic rocks found around the Mediterranean Sea region. Iyer et al. (2006) analysed composite, ringstone and two holed stone anchors off Dwarka coast in Gujarat, India, using only XRD, and the study showed that composite and two holed anchors are made of limestone and calcareous sandstone respectively, while the ring stone anchor is made of basalt. In addition, only limited research has been carried out in India and abroad to understand the provenance of rock types used for making anchors.

2. Methodology

2.1. Thin section studies

A rock chip was sliced off from each anchor for petrographical and geochemical analysis. One surface of the rock chip was ground to fine smoothness and was mounted on to the glass slide with help of Araldite® (resin & hardner) and then clamped to prevent development of air bubbles. After overnight cooling and curing, the thin sections were prepared using Buehler®'s automated thin section preparation machine. These thin sections were later placed under Leica® DMLP Petrological Microscope attached with the microphotography system for taking photographs of the texture and mineral characteristics of samples.

2.2. XRF studies

Another part of the rock chip was powdered using the agate ball mill for non-contamination. This powder was dried in the

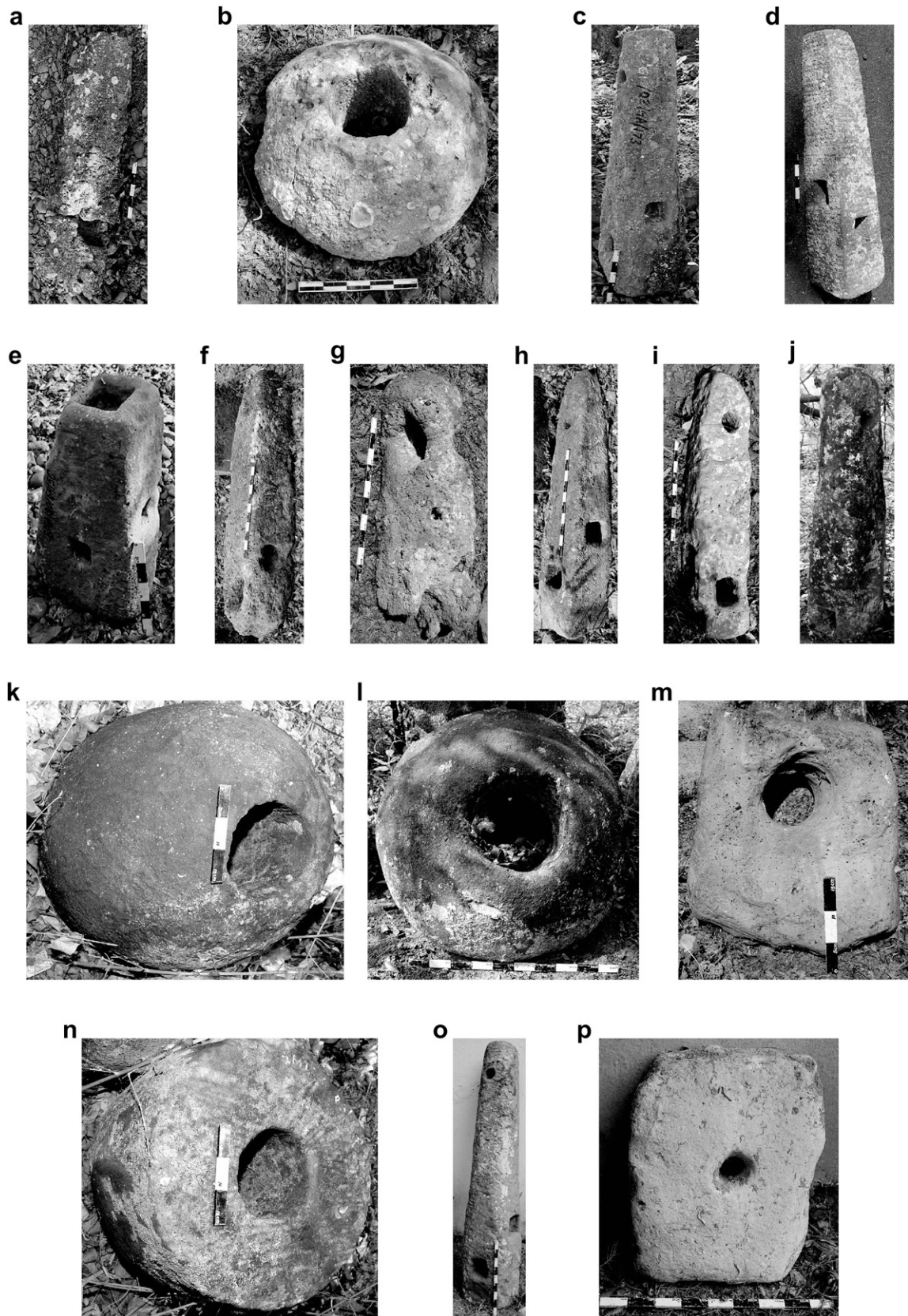


Fig. 2. Stone anchors of west coast of India (a to p) included in the present study.

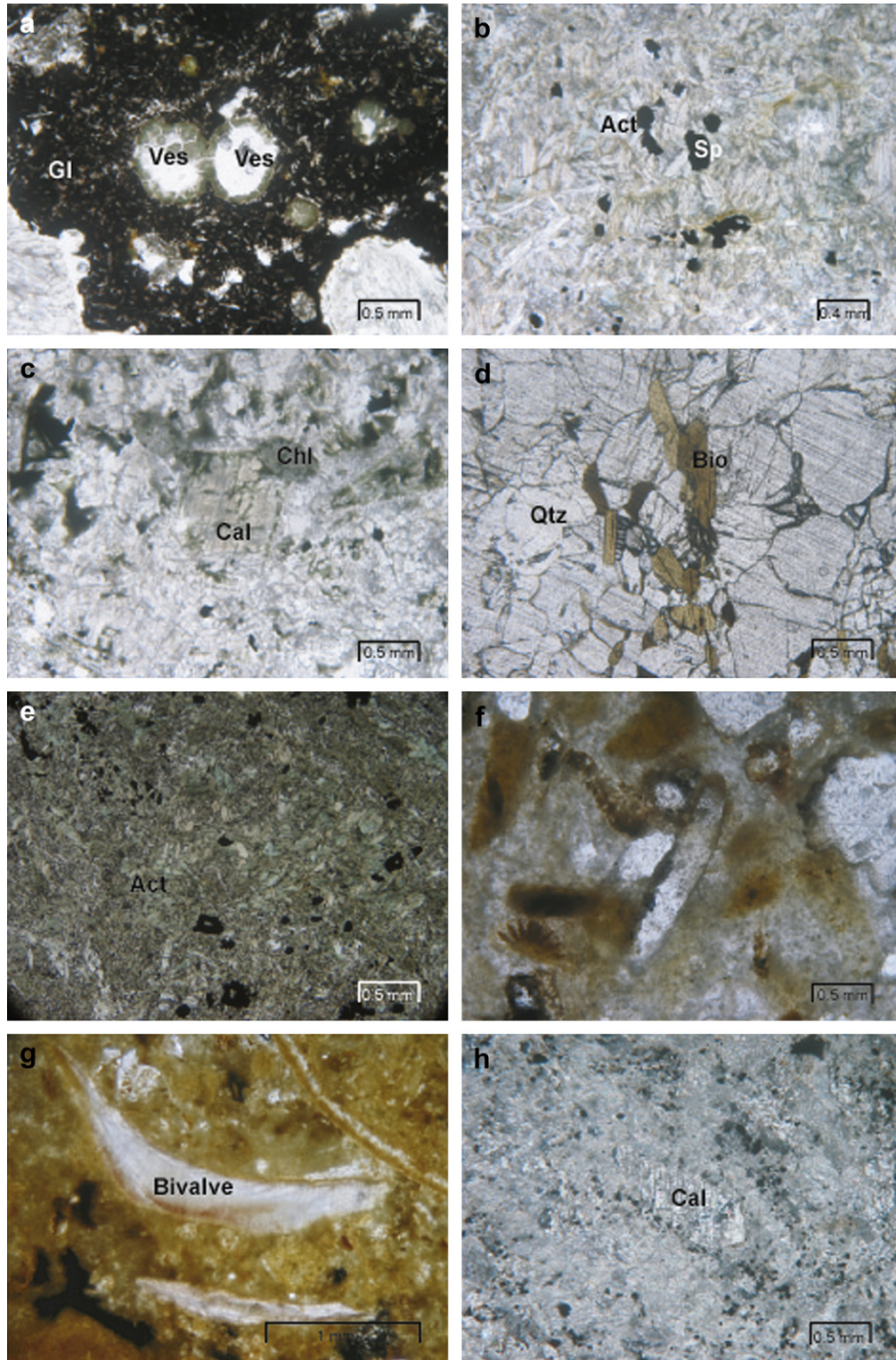


Fig. 3. a. Microphotographs corresponding to the respective stone anchors shown in the Fig. 2 (a to p). a. Vesicular basalt, Vesicles lined by chlorophaeite in a glassy groundmass. Groundmass contains small acicular plagioclase. PPL (Ves = vesicle; Gl = Glass). b. Actinolite schist, Dull green coloured fibrous crystals of actinolite are seen. Black coloured spinels are seen within the rock. PPL (Act = actinolite; Sp = spinel). c. Calcite and chlorite in a rock with black coloured spinels. Pyroxenes show alteration. PPL (Chl = chlorite; Cal = calcite). d. Schistose texture with bands of flaky, pleochroic biotite alternating with bands of quartz and plagioclase. PPL (Bio = biotite; Qtz = quartz). e. Actinolite schist with opaque spinels. Actinolite is fibrous & dull green coloured mineral. PPL (Act = actinolite). f. Rock is composed of carbonate mud with a few fossils. Elongated tube like feature is ~ 1.4 mm long, PPL g. Fossiliferous limestone, bivalve shell of ~ 2 mm size surrounded by fine carbonate mud, PPL (Bivalve). h. Totally altered serpentinite crystals with magnesite ($MgCO_3$). At the centre of the image pseudomorph of calcite after olivine. PPL. (Cal = calcite). i. Fossiliferous limestone with a fossil of sponge (size 1.5 mm long) in the carbonate mud, PPL j. Basalt, Plagioclase and olivine are present. Black coloured spinels are occasionally observed strewn in the rock. Altered basalt with plagioclase altered to sericite, PPL. (Ol = olivine; Sp = spinel; plag = plagioclase). k. Granodiorite - volcanic rock with plagioclase laths in a glassy groundmass. BXN. (Plag = plagioclase). l. Basalt with typical porphyritic texture. Plagioclase lath is seen in the basaltic groundmass of plagioclase, olivine and spinels, BXN. (Plag = plagioclase). m. Sandstone with fine grains of quartz (0.04–0.06 mm) and feldspars are seen in a carbonate cement. PPL. n. Basalt with plagioclase and olivine as main mineral phases. BXN. (Ol = olivine; Plag = plagioclase). o. Dolerite with Olivine and Plagioclase altered. PPL. (Ol = olivine; Plag = plagioclase). p. Calcareous sandstone with high SiO_2 and 12% Cao, area is ~ 4 × 5 mm, PPL. Rock consists of fine-grained quartz and rarely feldspars in calcareous cement. PPL: Plane Polarised Light BXN: Between Crossed Nicols.

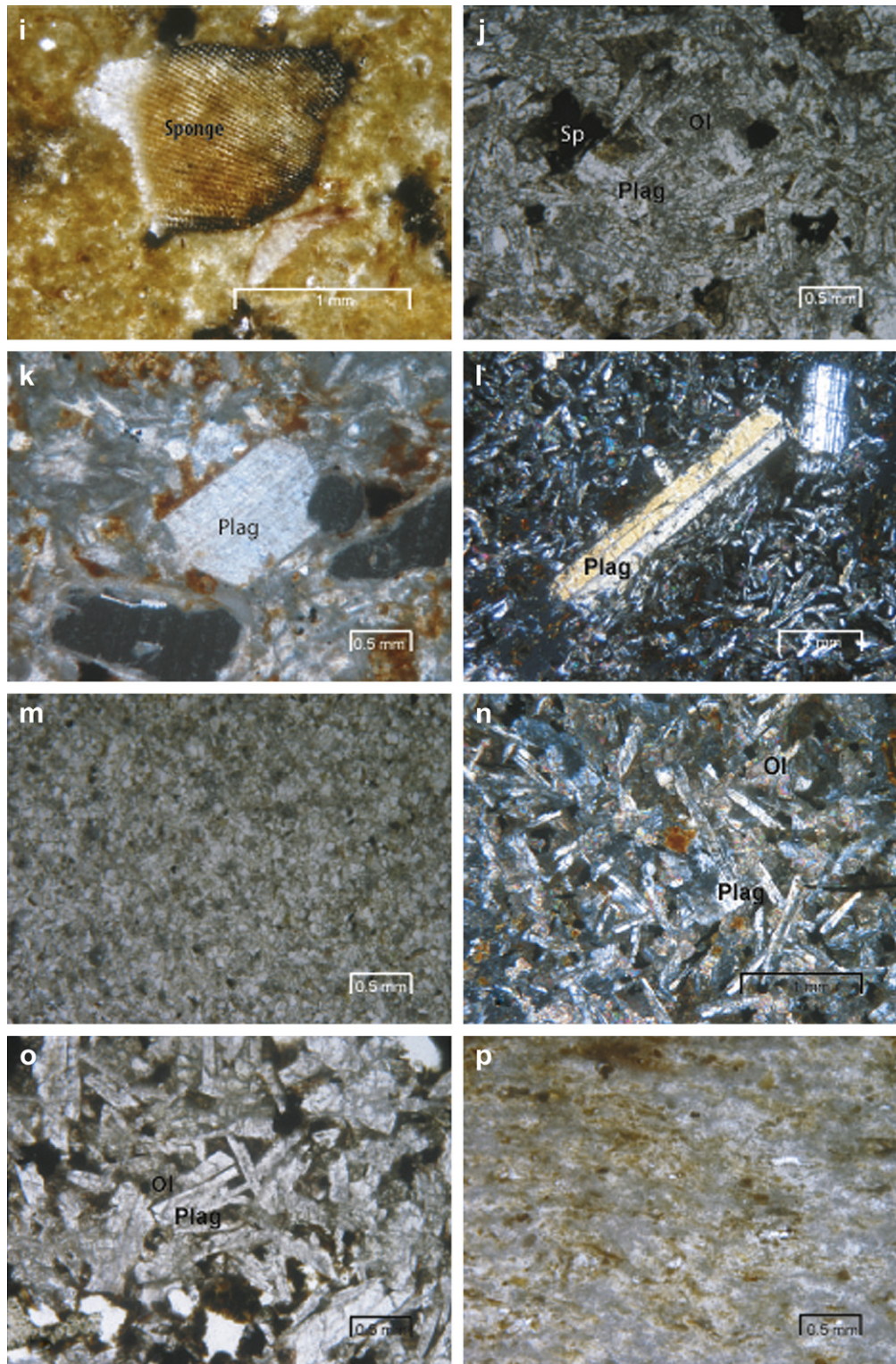


Fig. 3. (continued).

oven at 110 °C overnight to remove the moisture. Later the same powder was heated to ~1050 °C for ~3 h to determine the loss on ignition. This sintered sample was then powdered to fineness again using agate mortar and pestle. This powder was then mixed with flux A-1000® (for sedimentary rocks) and A-12® (for igneous rocks) by Merck® which is the combination of lithium meta-borate and tetra-borate in the proportion of 1:5 (1 sample to 5

flux). This flux and sample is mixed thoroughly and then fused in the platinum crucible in conductive furnace at ~1100 °C in a step-by-step increment to make a glass bead. This fused glass bead was then analysed using wavelength dispersive (WD) X-Ray Fluorescence (XRF) spectrometer, AXIOS® of PANalytical for the major elemental oxide concentration with an accuracy of ±2–4% for standard rocks.

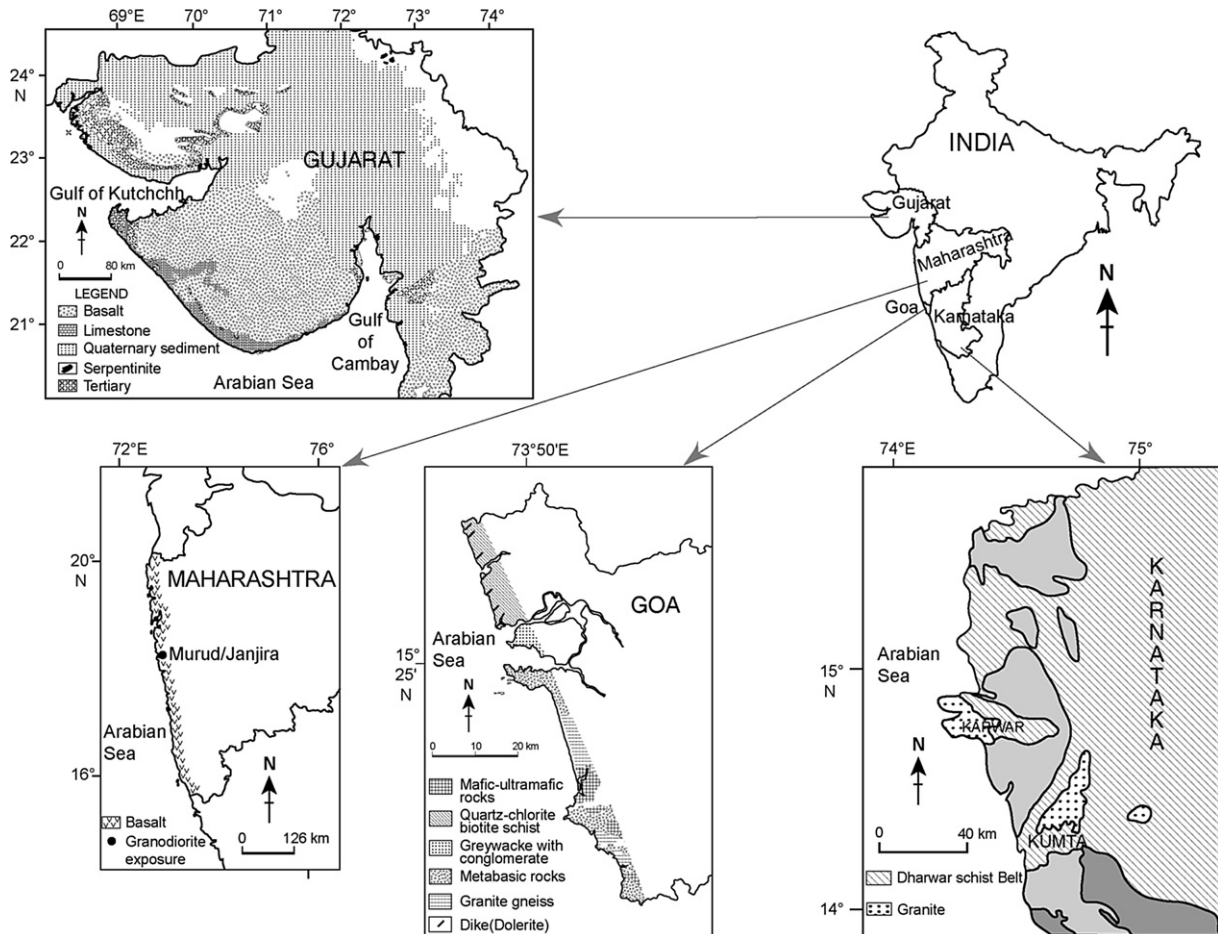


Fig. 4. Map showing the exposure of rocks along Goa (after Purushothaman et al., 2009) and dikes (after Widdowson et al., 2000); Gujarat (after Merh, 1995); Maharashtra and Karnataka (after Radhakrishna and Vaidyanadhan, 1994) coastal tract.

2.3. SEM-EDS studies

In order to confirm the thin section observations, additional analysis, such as SEM-EDS, were undertaken on a few representative samples. These rock chunks used for XRF studies are used for scanning electron microscope (SEM) studies. The fresh specimens (size 3–5 mm) obtained from chunk were placed on a nylon stub with a carbon conductive tape. The specimen was mounted on the stub in such a way that the surface to be studied by XRF faced upwards. The specimen was then sputter coated with about 20 nm thick gold coating using a gold sputter coater. The coated specimen was analysed by SEM (model JEOL JSM 5800 LV) with an Oxford EDS attachment.

3. Results and discussion

This section includes the physical, mineralogical and chemical description of anchors for ready reference.

3.1. Stone anchors off Goa

Sample 1: A fragile and broken Indo-Arabian stone anchor was found on an underwater lateritic outcrop and recovered from 5 m deep off Sunchi Reef, Goa (Table 2 & Fig. 2a). This 114 cm long anchor weighs about 100 kg and has only one abraded lower square hole while its other lower square hole and apex hole are absent.

It is made of amygdaloidal basalt (Table 3 & Fig. 3a) with porphyritic texture of plagioclase and olivine within the

cryptocrystalline groundmass. The amygdules within the basalt have presence of secondary mineralisation of calcite, which shows twinkling optical characters of two sets of cleavages. This anchor could have been sourced from Amygdaloidal basalts of Deccan Trap age capping the Jurassic limestones in Kachchh, Gujarat (Merh, 1995).

Sample 2: A ringstone (mushroom type) anchor (Table 2 & Fig. 2b) weighing 76.6 kg was found lying on laterite boulders at 5 m water depth off Sunchi Reef with overgrowths of oysters and shells. Chisel marks are visible on its surface.

The anchor is composed of green coloured pleochroic actinolite laths arranged in parallel fashion along with dark black coloured spinels, which gave the schistosity to the rock (Table 3 & Fig. 3b). The anchor is made of actinolite schist. This stone anchor is plausibly derived from actinolite schists found in northeastern Gujarat bordering Rajasthan and reported as Rakhabdev Ultramafic suite of metamorphosed serpentinites (Bhu et al., 2006; Merh, 1995).

Sample 3: Indo-Arabian stone anchor recovered from 7 m water depth off Grande Island, Goa (Table 2 & Fig. 2c). Deep and distinct chisel marks can be seen on the surface of the anchor. The upper side of the anchor is round instead of square and it tapers upwards after the upper square hole. The anchor weighs 113 kg and contrary to its size, the dimensions of holes are small.

This anchor, with three well preserved holes, is made of granodiorite. The granodiorite, a hypidiomorphic holo-crystalline rock, is composed of quartz and altered feldspars (Table 3 & Fig. 3c) and rich in alkali metals with Na_2O and K_2O together constituting ~7% with high SiO_2 content (~70%). Alkali-rich igneous rocks are reported from Murud-Janjira, along the Maharashtra coast (Desai

Table 2
Details of stone anchors included in the study along with rock types and probable provenance.

Sample No	Location	Anchor type	Length (cm)	Lower hole (cm)	Upper hole (cm)	Maximum thickness (cm)	Weight (Kilograms)	Rock type	Probable Provenance
1	Sunchi Reef, Goa	Indo-Arabian	114	15 × 13, –	–	24	100	Amygdaloidal basalt	Gujarat
2	Sunchi Reef, Goa	Ringstone	56	–	16	21	76.6	Actinolite schist	Gujarat
3	Grande Island, Goa	Indo-Arabian	107	10 × 7, 10 × 7	5	25	113	Granodiorite	Gujarat/Maharashtra
4	Grande Island, Goa	Indo-Arabian	112	11 × 9, 11 × 8	–	23	130	Quartz-biotite schist	Karnataka
5	Baga, Goa	Indo-Arabian	53	6 × 5, 5 × 4.5	–	17	51	Actinolite schist	Gujarat
6	Bet Dwarka, Gujarat	Indo-Arabian	172	17 × 16, 16 × 15	15	35	410*	Limestone	Gujarat
7	Bet Dwarka, Gujarat	Indo-Arabian	82	15 × 15, –	11	22	90*	Limestone	Gujarat
8	Dwarka, Gujarat	Indo-Arabian	146	12 × 11, 12 × 10	6	27	215*	Serpentinite	Gujarat
9	Dwarka, Gujarat	Indo-Arabian	115	12 × 12, 12 × 12	10	25	144*	Limestone	Gujarat
10	Dwarka, Gujarat	Indo-Arabian	130	11 × 10, 11 × 10	8	28	196*	Vesicular Basalt	Gujarat
11	Dwarka, Gujarat	Ringstone	49	–	18	–	109*	Granodiorite	Gujarat/Maharashtra
12	Dwarka, Gujarat	Ringstone	66	–	23	19	245*	Plagioclase Phyrlic Basalt	Gujarat
13	Dwarka, Gujarat	Single hole	35	–	12	8	16*	Sandstone	Gujarat
14	Somnath, Gujarat	Ringstone	46	–	16	40	118*	Basalt	Gujarat
15	Visawada, Gujarat	Indo-Arabian	166	15 × 12, 13 × 13	7	35/22	325*	Dolerite	Goa
16	Visawada, Gujarat	Single hole	45	–	5	10	35*	Calcareous sandstone	Gujarat

Note: * estimated weight: Basalt and Dike: 2900 Kgs/M³, Sandstone and Limestone: 2400 Kgs/M³.

and Bodas, 1984) and Phenai Mata hill in Gujarat (Merh, 1995) which might be the source for the anchor.

Sample 4: This stone anchor (Table 2 & Fig. 2d) was recovered from 4 m water depth off Grande Island in the vicinity of the above anchor (Sample 3) and weighs about 130 kg. The anchor has two lower holes without its apical hole and has been neatly trimmed with visible parallel chisel marks showing no wear and tear perhaps due to less usage. The anchor tapers upward although it is square in section and some portion of the apex side is chafed.

This anchor is made of quartz-biotite schist with quartz and biotite as main mineral phases along with minor amount of feldspars (Table 3 & Fig. 3d). The schistosity of the rock is due to the flaky brown coloured pleochroic biotite mica layer alternating with quartz and feldspars. Accessory minerals like tourmaline, rutile and zircon are observed within the rock. Rocks consisting of Quartz-biotite schist were reported near Karwar in northern Karnataka coast (Radhakrishna and Vaidyanadhan, 1994).

Sample 5: A broken Indo-Arabian stone anchor made of actinolite schist (Table 2 & Fig. 2e) of 53 cm length and 51 kg weight was recovered from 6 m water depth off Baga, Goa. It is unique in its shape with a rectangular cut on the apex. The surface of the anchor is smooth indicating its wear and tear due to continuous use.

This anchor rock is mostly composed of actinolite and is much richer in spinels. This observation is seen in the high Fe₂O₃ content

of the rock (~13%) as well high TiO₂ content (2.73%) (Table 3 & Fig. 3e). It also has loss on ignition (LOI) (~1.5%) due to actinolite dehydration. The composition is similar to the rocks reported from the Rakhadev Ultramafic suite of metamorphosed serpentinites (Bhu et al., 2006; Merh, 1995).

3.2. Stone anchors off Bet Dwarka

Sample 6: The heaviest Indo-Arabian stone anchor was retrieved from the inter-tidal zone on the southern side of Bet Dwarka jetty. The anchor weighs about 410 kg (Table 2 & Fig. 2f). This anchor with smooth surface has an upper circular and two lower square holes which indicate its wide usage. The anchor is comprised of fossiliferous limestone (Table 3 & Fig. 3f) with presence of bivalves, sponge, gastropods, etc.

Sample 7: Partly broken Indo-Arabian stone anchor (Table 2 & Fig. 2g) was found lying on the rocky seabed off Bet Dwarka. Its upper circular hole and one lower hole are present, whereas other lower hole is absent. The surface of the anchor is rough and porous with blunt (jagged) edges. It weighs about 90 kg.

Both the Indo-Arabian stone anchors from Bet Dwarka (Table 3, Samples 6 & 7 & Fig. 2f and g) are made of fossiliferous limestone and have high CaO content (41 & 47%) and high loss on ignition (~35–40%) showing the calcareous nature. Such fossiliferous limestones belonging to Jurassic formations are vastly exposed along the Gujarat coast (Merh, 1995).

Table 3
showing the percentage of major elemental oxide contents in stone anchors of west coast of India.

Sample No	Location	Anchor type	Rock type	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO ₂	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	LOI ^a
1	Sunchi Reef	Indo-Arabian	Amygdaloidal Basalt	54.1	2.34	13.19	12.44	0.23	4.44	6.84	2.57	2.25	0.27	98.67	1.29
2	Sunchi Reef	Ringstone	Actinolite schist	45.89	0.28	5.89	12.50	0.14	23.77	4.83	0.18	0.02	0.017	93.517	6.47
3	Grande Island	Indo-Arabian	Granodiorite	69.90	0.64	11.49	5.47	0.15	0.55	2.10	3.04	3.65	0.08	97.07	2.92
4	Grande Island	Indo-Arabian	Quartz-biotite schist	69.14	0.41	15.28	3.98	0.03	0.94	4.87	3.50	1.26	0.10	99.51	0.048
5	Baga	Indo-Arabian	Actinolite schist	46.30	2.73	11.87	12.96	0.18	3.92	10.06	2.2	0.93	0.33	91.48	1.5
6	Bet Dwarka	Indo-Arabian	Limestone	6.69	0.04	1.35	1.40	0.06	0.93	47.68	0.50	0.14	0.09	58.88	41.12
7	Bet Dwarka	Indo-Arabian	Limestone	18.53	0.06	1.50	0.75	0.03	0.67	41.81	0.19	0.16	0.18	63.88	36.13
8	Dwarka	Indo-Arabian	Serpentinite	27.08	0.04	0.62	17.51	0.25	28.41	0.66	0.11	0.02	0.015	74.715	25.27
9	Dwarka	Indo-Arabian	Limestone	6.21	0.05	1.37	1.88	0.10	0.62	48.62	0.10	0.04	0.15	59.14	40.86
10	Dwarka	Indo-Arabian	Vesicular Basalt	51.68	1.08	13.52	10.86	0.16	5.40	11.02	2.30	0.62	0.14	96.78	3.2
11	Dwarka	Ringstone	Granodiorite	67.74	0.59	13.85	5.97	0.09	0.42	0.37	3.37	5.03	0.073	97.503	2.5
12	Dwarka	Ringstone	Plagioclase Phyrlic Basalt	48.24	2.50	14.30	14.23	0.22	6.21	9.87	2.47	0.54	0.27	98.85	1.52
13	Dwarka	Single hole	Sandstone	60.89	0.42	7.13	3.34	0.11	2.14	11.29	1.44	1.10	0.13	87.99	12.02
14	Somnath	Ringstone	Basalt	55.02	2.21	15.31	8.50	0.11	2.50	5.44	3.76	3.87	0.46	97.18	2.8
15	Visawada	Indo-Arabian	Dolerite	49.54	1.31	12.55	13.41	0.19	5.41	10.75	2.33	1.04	0.12	96.65	3.35
16	Visawada	Single hole	calcareous sandstone	72.15	0.27	3.06	0.67	0.01	0.50	11.93	0.43	0.29	0.13	89.44	10.56

^a LOI – Loss on Ignition at ~1050 °C for 3 h.

3.3. Stone anchors off Dwarka

Sample 8: The Indo-Arabian stone anchor was recovered during underwater explorations for relocating the submerged cliff off Dwarka. Its edges are sharp with the presence of upper and two lower square holes and weighed 215 kg.

The anchor is made of serpentinite (Table 2 & Fig. 2h). The serpentinite rock exhibits olivine phenocrysts, which are completely altered to magnesite (MgCO_3) and/or Calcite (cal) due to hydration (LOI – 25%) and groundmass altered to serpentine (Table 3 & Fig. 3h). A further analysis of phenocrysts in serpentinite rock (Sample 8 & Fig. 3h) using SEM-EDS confirms the presence of magnesite (MgCO_3) and chromium-rich ($\text{Cr}_2\text{O}_3 \sim 2.5\%$) iron oxide globules. Similar types of serpentinites have been reported from Rakhabdev Ultramafic suite, northeast Gujarat composed of the metamorphosed serpentinites from the Lunavada, Gujarat (Merh, 1995).

Sample 9: The Indo-Arabian anchor has upper and two lower square holes and weighing 144 kg. Its surface is rough with blunt edges and chisel marks visible on its surface (Table 2 & Fig. 2i). The upper hole indicates that it was not used extensively.

The anchor is made of limestone, which has remarkably high loss on ignition ($\sim 41\%$) and high CaO content (48%) (Fig. 3i). This anchor is compositionally similar to the ones recovered from Bet Dwarka (Samples 6 & 7). This limestone is probably sourced from Jurassic formations in the Gujarat coast.

Sample 10: The Indo-Arabian anchor has upper as well as two lower square holes. Chisel marks are distinct on its surface and marine growth is present. Its upper portion is round and weighs 196 kg (Table 2 & Fig. 2j). Presence of chisel marks indicates lesser use although little weathering is noticed on its surface.

The anchor is made of vesicular basalt. This vesicular basalt has plagioclase and ortho-pyroxenes as mineral phases (Table 3 & Fig. 3j). The rock must have been sourced from the coast of Gujarat as similar vesicular basalts are reported from Saurashtra (Merh, 1995).

Sample 11: The ringstone anchor (Table 2 & Fig. 2k), is found on the rocky seabed and weighed 109 kg. The surface of the anchor is smooth with fine edges and chisel marks are distinct inside the hole. The bottom of the anchor is flat and gradually tapers upwards with an axial hole.

The anchor is made of granodiorite with plagioclase and ortho-pyroxenes as its main minerals (Table 3 & Fig. 3k). This anchor is made of granodiorite with comparable composition of Indo-Arabian anchor recovered off Grande Island (Table 3; Sample 3) in Goa waters. Therefore, it is believed that the source rock must have been either from the Murud-Janjira, Maharashtra (Desai and Bodas, 1984) or from Phenai Mata hills in Gujarat (Merh, 1995). Another possible source for this rock might be from the alkali intrusions with granodioritic composition as reported in the Aravalli Group of rocks exposed near the northeastern part of Gujarat (Mamatani et al., 2002; Saha et al., 2008).

Sample 12: The ringstone anchor (Table 2 & Fig. 2l) recovered from 7 m water depth, has a flat bottom, smooth surface, fine edges and chisel marks visible on its surface. The anchor weighed 245 kg with bigger diameter than the other ring stone anchors.

It is made of plagioclase phyric basalt (Table 3 & Fig. 3l) with larger plagioclase phenocrysts and also shows alteration to clay mineral assemblages. The other mineral present is clino-pyroxene with inclusions of opaque iron oxides. The stone anchor comprising of plagioclase porphyritic basalt and clino-pyroxene, is probably sourced from Gujarat (Merh, 1995).

Sample 13: The trapezoidal shaped single hole anchor is of only 16 kg weight (Table 2 & Fig. 2m) with a smaller circular hole. The rope hole is eroded, due to which it has widened. Lower portion of the anchor is uneven. The anchor has smooth surface and sharp edges.

This anchor is made of fine-grained sandstone (Table 3 & Fig. 3m) with grains of quartz, feldspars and clay pellets of fine grain sediment. This anchor stone may have been mined from the Jurassic sedimentary sequences of the Kachchh (Merh, 1995).

3.4. Stone anchor off Somnath

Sample 14: The ringstone anchor (Table 2 & Fig. 2n) has a thick layer of marine growth. It was lying tilted and partially exposed on the seabed. It has a flat bottom and tapers upwards. Chisel marks are visible at the bottom and inside the hole of the anchor. It is perfectly spherical in shape and has a smooth surface with blunt edges.

It is made of basalt and weighs 118 kg. The laths of plagioclase (Table 3 & Fig. 3n) are seen with the naked eye in this greenish rock. This basalt has high total alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) of $\sim 8\%$ and this type of basalt is reported in Deccan Traps formations in the coastal regions of southern Gujarat and Maharashtra.

3.5. Stone anchors off Visawada

Sample 15: The underwater exploration off Visawada, in 6 m water depth, yielded one each of Indo-Arabian and single hole stone anchors. The Indo-Arabian anchor (Table 2 & Fig. 2o), weighing 325 kg, was partially buried in a channel.

It is made of dolerite composed of plagioclase as predominant mineral and olivine as a minor mineral phase, which is altered to chlorite (Table 3 & Fig. 3o). This anchor might have been derived from either of the dolerite dikes that have been reported along the Goa (Widdowson et al., 2000) as well as Gujarat coast (Merh, 1995).

Sample 16: The trapezoidal stone anchor with small circular single hole at the centre (Table 2 & Fig. 2p), was found lying on rocky sea bottom. The anchor has uneven edges and weighs 35 kg.

It is made of calcareous sandstone. Its chemical composition shows high SiO_2 ($\sim 72\%$) and CaO ($\sim 12\%$) as the main constituents (Table 3 & Fig. 3p). This single hole trapezoidal stone anchor might be quarried from Tertiary formations exposed in the northwestern Kachchh, Gujarat (Merh, 1995).

Recovery of numerous stone anchors along the Indian coast signifies the maritime traffic in the region during historical and medieval periods. These stone anchors have been reported from anchorage points, ports and trade centres of India. Earlier stone anchors were studied only with macro and microscopic observations however mineralogical and geochemical analysis in the present study provides additional information on the provenance of rocks.

Though the Indo-Arabian, ringstone and single hole anchors of Dwarka, Bet Dwarka, Goa, Somnath and Visawada look more or less similar in appearance, the rocks they are made of are different in composition (Table 3). As shown in Table 2, among sixteen anchors ten stone anchors are made of igneous rocks while the remaining six are of sedimentary rock.

It has been observed that some of the Indo-Arabian anchors from Dwarka, Goa and Visawada (Sample 1, 3, 8, 10 & 15) are made of igneous rocks such as basalt, granodiorite, serpentinite and dolerite while others (Sample 4, 5, 6, 7 & 9), recovered from Goa, Bet Dwarka and Dwarka waters are made of quartz-biotite schist, actinolite schist and limestone. Nevertheless, the ringstone and single hole stone anchors (Sample 2, 11, 12, 13, 14 & 16) of Goa, Dwarka, Somnath and Visawada are made of schist, granodiorite, basalt, sandstone and calcareous sandstone.

Evidently igneous rocks, being dense and heavy were preferred for making the Indo-Arabian stone anchors on account of their better holding capacity, easier handling, less storage space and

better endurance while ringstone anchors are made of both igneous and sedimentary rocks.

Sedimentary rocks such as sandstone, schist and calcareous sandstone were used for making of the ringstone and single hole anchors (Sample 2, 11–14 & 16) possibly due to their softness for easy carving out (Table 3). The study shows that fourteen anchors (Sample 1, 3, 4, 6–16) out of sixteen are made of the rocks which are available in the coastal region of Goa, Gujarat, Karnataka and Maharashtra (Fig. 4). However, the provenance of samples 2 and 5 has been sourced from the area far away from the coastline. Two anchors (Sample 2 & 5) are made of actinolite schist found only in the Rakhabdev, landward region in northeast Gujarat, emphasises that mariners were selective about the rock type for making anchor.

4. Conclusions

This study brought to light that different types of rocks, such as granodiorite, dolerite and variety of basalts, schist, calcareous sandstone, limestones and sandstone have been used for making Indo-Arabian, ring and single hole type anchors, collected from the Indian waters. As the Indian sub-continent has variety of exposures from Precambrian granitic rocks to Cretaceous Deccan Trap basalt sequences, a varied choice of rocks was available for using the local stone as stone anchor.

Moreover, along the northern west coast of India, the Cretaceous rocks like miliolite and fossiliferous limestone are exposed on the coast, while Deccan Trap basalts are present a few miles from the coast. The mariners sourced these rocks for making anchors and used for maritime trade.

Our results confirm that the rocks for these stone anchors are sourced from Indian sub-continent mainly from Gujarat, Maharashtra, Goa and Karnataka states in the west coast of India.

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