

in limestone. The occurrence of talc as a clay mineral in sedimentary rocks is also suggested<sup>17</sup>. Field, petrographic and SEM studies, as well as XRD, IR observations and fluid inclusions studies reveal that the antipathic relations of silica and talc are indicative of the fact that the latter is a product of diagenetic sedimentary environment, being formed by the reaction of magnesite and silica ( $3\text{MgCO}_3 + 4\text{SiO}_2 + \text{H}_2\text{O} + \text{MgSi}_4\text{O}_{10}(\text{OH})_2 + 3\text{CO}_2$ ) at a temperature less than 300°C.

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## Shoreline changes during the last 2000 years on the Saurashtra coast of India: Study based on archaeological evidences

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**Shoreline shift coupled with sea-level change have always remained intriguing aspects due to wider ramifications for the populations living on the coast. Different methods are employed to understand and explain their causes and quantum. In this communication an attempt is made to study shoreline and sea-level changes during the last 2000 years on the basis of archaeological evidence. Archaeological excavations undertaken at Bet Dwarka (western most part of India) revealed an interesting cultural sequence commencing from protohistoric period (3800 yrs BP) to historical period (1600 yrs BP). Excavation was undertaken in six trenches up to the lowest level of archaeological findings. The results from these trenches suggest that the oldest habitation was situated below the present high water line. This is an indication of a lower sea level during that period of settlement. <sup>14</sup>C ages and archaeological data suggest a time bracket for these habitations between 2050 and 1650 yrs BP (calibrated). Analysis of sea level versus ancient settlement suggests that around the Christian era sea level was lower by 2 m than the present. The remains from the excavation also suggest that one of the attractions for early settlers was the availability of marine resources around the island. Data from early historical period and other archaeological sites situated along the Indian coast confirm this finding.**

**Keywords:** Archaeological evidence, Bet Dwarka, Saurashtra coast, shoreline and sea level.

THE fluctuations of sea level played a prominent role in the emergence and decline of cultures during Pleistocene and Holocene periods. Several authors have updated sea-level studies along the west coast of India<sup>1–7</sup>. There are well-defined observational data on Quaternary sea-level oscillations based on geological proxies like coral, limestone, foraminifera and other marine organisms. Focusing on long time-frames involves a high degree of error due to various reasons like paucity of data, methods of measurement, instrumental errors, etc. In comparison, archaeological evidences, when available, provide foolproof manifestation of the event that has taken place in one particular geographical entity. Ancient settlements also preserve each event, whether it be environmental, political, cultural diffusion, etc. that occurred in the course of time.

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These have been used by archaeologists and historians to rebuild the political and cultural history of the region. Though environmental history from archaeological sites has been a part of excavation reports, it has not received enough attention as full-fledged scientific data. However, archaeological sites are the *in situ* records of past events such as change in climate and shorelines in the respective regions. Besides archaeological sites, ancient maps and satellite imagery have been used extensively to understand the changes in past shorelines.

Though the study of the ancient human settlement on the shallow submarine zones and migration via land bridges between continents has been made for over 50 years, only few significant sites have been located to date having connections on the continental shelves<sup>8</sup>. One of the major reasons for the absence of evidence of ancient human settlement is that the continental shelves witnessed dynamic sedimentation and erosion pattern that might have destroyed a site by burial or removal<sup>9</sup>. Many archaeological sites show evidence of maritime activities either from the excavation or from literary references as important port towns during their heyday. In the course of time they got either submerged or land-locked due to siltation, sea-level change and tectonic activity. Such sites provide vital clues with dates to infer the shoreline changes. Systematic archaeological excavation carried out on the island of Bet Dwarka provided useful information on cultural sequence. Additionally it also provided data which can be used to understand the sea-level changes in the area. The present communication, therefore, deals with the sea level changes around Bet Dwarka island in the Gulf of Kachchh during historical period (late Holocene) based on archaeological evidence.

History of maritime activities in Gujarat<sup>10</sup> dates back to the 3rd millennium BC. Evidence of the exploitation of marine resources like shells, salt and fish has been recorded from many coastal sites. Bet Dwarka island, situated at the entrance of the Gulf of Kachchh, acted as a transit point for trade and commerce during the later phase of the Indus Civilization between Kachchh and Sind on one side and Saurashtra and mainland Gujarat on the other. Archaeological explorations suggest that the availability of marine resources around this island attracted early settlers. Subsequently, the island became an international trade centre from the early historical period<sup>11</sup>. As onshore explorations in the island since 1983 have revealed the presence of a large number of habitational remains of the historical period in the present-day inter-tidal zone, it was reckoned that evidence of shoreline change and sea-level variation may be ascertained from here. Therefore, to understand the stratigraphy of human habitation, as also the relationship between man and the sea, a few trenches were opened in the coastal area of the Bet Dwarka island for systematic archaeological excavation.

For the excavation, six places were identified on Bet Dwarka, especially in the south-eastern coastal area of

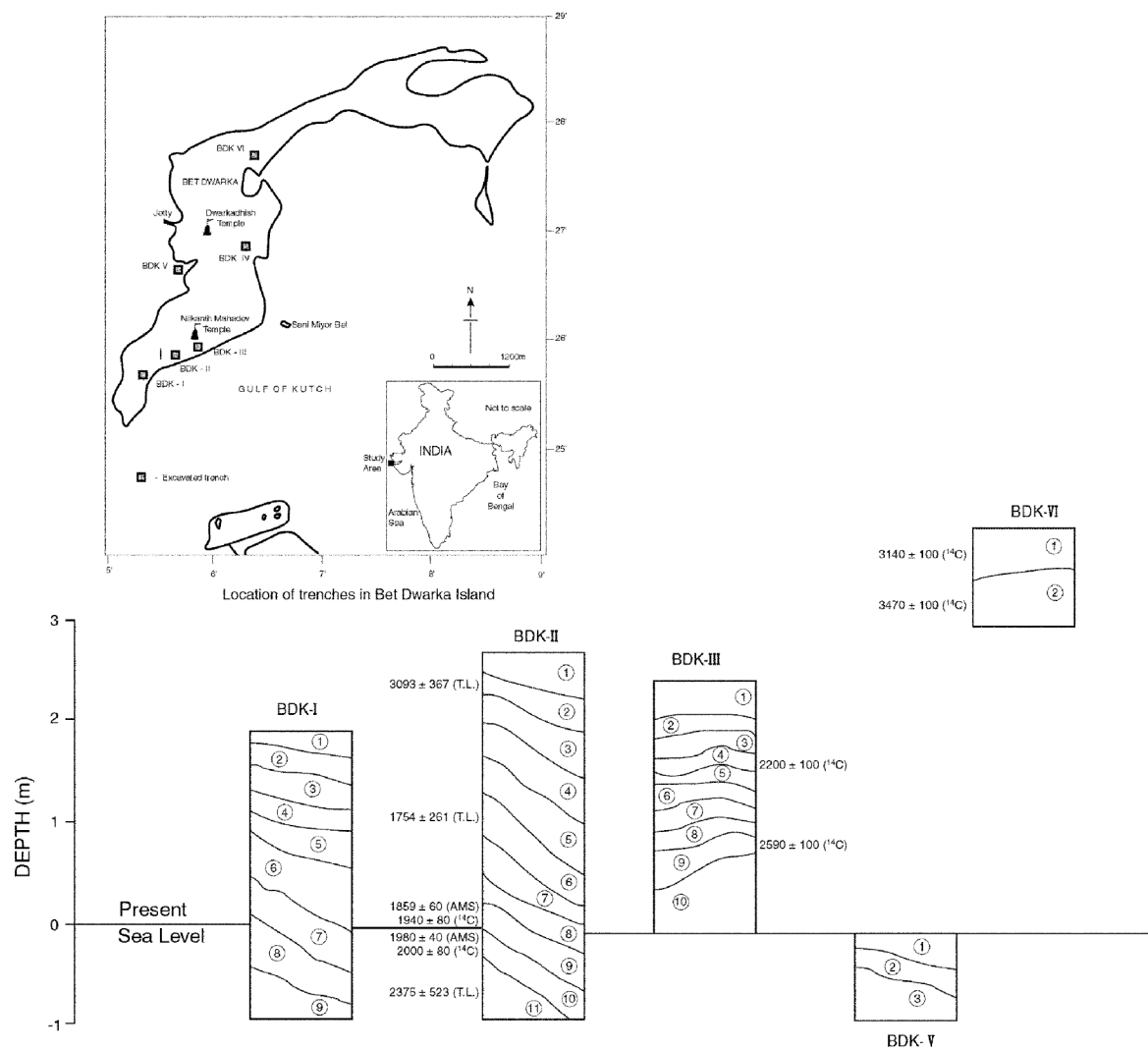
the island and trenches were dug at each location. The excavation was continued up to the base of the occupational remains and even a few centimetres into the virgin soil bed. Layer by layer archaeological artifacts were recorded and samples collected and finally dated by radiocarbon (conventional as well as AMS technique), and TL methods. Subsequently, differences in the level between depth of present high waterline and occupational deposits in three trenches (BDK-I, II and III) were measured. Samples were dated by conventional radiocarbon method at the Birbal Sahni Institute of Palaeobotany (BSIP), Lucknow; two samples from trench BDK-II were analysed by <sup>14</sup>C-AMS method at Beta Analytics, Miami, USA and after radiocarbon at Lab Wellington, New Zealand<sup>12</sup>. Three samples were analysed by thermoluminescence at Physical Research Laboratory (PRL), Ahmedabad (Table 1).

The trenches were numbered as follows: BDK-I, II, III, IV, V and VI. The findings and total archaeological deposits of each trench (Figure 1) are described below to understand the nature of habitation on the one hand and difference between present-day high waterline and the oldest deposit in each trench on the other.

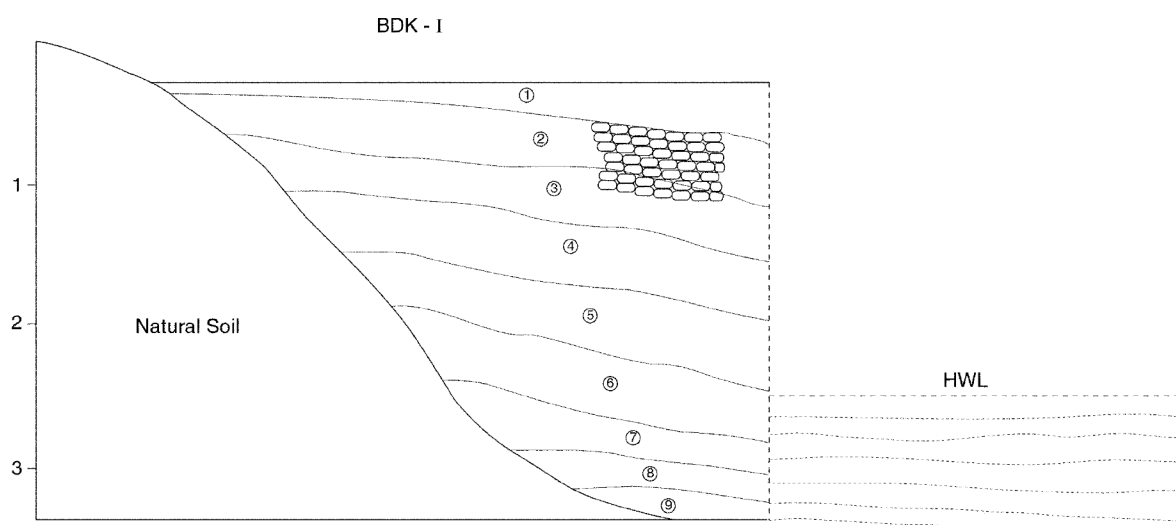
Trench BDK-1 measuring 5 m × 5 m was laid in the southwestern coast of the island. A total deposit of 2.75 m was excavated and nine layers were identified (Figure 2). Initial habitation took place on the foot of a hill extending towards the sea. During the later phase, the habitation was extended towards the land (Figure 3). Due to its geographic situation, it is possible that the major part of the early habitation was eroded by the sea. The present location is a high cliff section with archaeological remains facing seawards. From layer 6, two copper coins of Kushana period (1st–2nd century AD) were recovered and there is no habitational break-up from lower strata. The lowest habitation of this trench was traced 65 cm below the present-day high waterline.

Trench BDK-II measuring 2.5 m × 5 m was opened on the eastern side of BDK-I on a high terraced mound. A total deposit of 3.35 m was traced with 11 layers (Figure 4). The initial habitation was on an area having gradient extending towards the sea and gradually habitation extended landward also. The major portion of the early habitation is eroded and a high cliff section exposing archaeological remains can be observed. There are two <sup>14</sup>C-AMS (Table 2), two conventional radiocarbon (Table 3) and three thermoluminescence (Table 4) dates, suggesting that the oldest habitation was 2375 ± 523 yrs BP and the youngest 1754 ± 261 yrs BP. A potsherd with graffiti mark (*Brahmi* letter 'A') datable to 3rd century AD was recovered from layer 4. The lowest habitation of this trench was traced up to 75 cm below the present-day high waterline. It is pertinent to note that Rajendran *et al.*<sup>12</sup> found traced liquefied material in layer 9, a resultant of the past earthquake which they date to 1st–2nd century AD.

Trench BDK-III measuring 2.5 m × 5 m was opened at the eastern side of BDK-II near the present water pump-



**Figure 1.** Bet Dwarka: Location of sites and depth of trenches.



**Figure 2.** Bet Dwarka: Section of trench BDK-I with reference to HWL (high waterline).

**Table 1.** TL dates from Bet Dwarka sample collected during excavation in season 2001 December. Dates have been supplied by A. K. Singhvi, PRL

Sample no.	$Q$ (min)	$I$ (min)	ED (Gy) $Q + I$	Total dose $D$ (uGy/a)	Age (yrs)
BDK-II (L-2)*	$0.90 \pm 0.13$	$2.59 \pm 0.04$	$8.54 \pm 0.41$	$2761 \pm 300$	$3093 \pm 367$
BDK-II (L-6)	$1.27 \pm 0.14$	$1.26 \pm 0.1$	$6.17 \pm 0.58$	$3517 \pm 407$	$1754 \pm 261$
BDK-II (L-11)	$1.23 \pm 0.1$	$1.87 \pm 0.16$	$7.56 \pm 0.63$	$3183 \pm 649$	$2375 \pm 523$

\*Not corresponding with cultural deposit, may be due to mixing of upper layer as it appears that some pottery of earlier period is deposited.

**Table 2.** Cultural associations and their possible dates from BDK excavations

Site	Total deposit (m)	Layers	Cultural deposit	Possible time bracket (yrs BP)
BDK-I	2.65	9	Historical period	2100–1800
BDK-II	3.45	11	Historical period	2100–1700
BDK-III	2.35	10	Early historic	2600–2100
BDK-IV	0.75	2	From surface medieval pottery	800–600
BDK-V	0.9	3	Historical period	2000–1800
BDK-VI	0.95	2	Protohistoric period	3800–3500

**Figure 3.** Bet Dwarka: Excavated section of BDK-I with archaeological remains.

house. A total deposit of 2.75 m with ten layers was unearthed (Figure 5). The initial habitation is on even soil bed, concentrated in the coastal area. There are three  $^{14}\text{C}$  dates from this trench. The oldest deposit is dated to 6th century BC. It is older than the earlier habitation of the above two trenches. The lowest deposit is just a few centimetres above the present-day high waterline.

For trench BDK-IV, there were no archaeological finds below 10 cm from the surface.

The small trench BDK-V measuring  $1 \times 1 \text{ m}^2$  was opened in the inter-tidal zone near Khuda-Dost-Dargah during low tide. A deposit of 65 cm was found with three layers (Figure 6). The archaeological material indicates a possible date of the site as the beginning of the Christian Era. The site is submerged during high tide.

Trench BDK-VI measuring  $2.5 \text{ m} \times 2.5 \text{ m}$  was opened in a presently cultivated land in the northeastern coast of the island. A deposit of 95 cm was excavated with two

layers. Archaeological findings and two  $^{14}\text{C}$  dates of the worked shells suggest a date for the oldest habitation to 16th century BC, which is situated about 4 m above the present high waterline.

Excavations at Bet Dwarka island have yielded a rich antiquity concerning the exploitation of marine resources by ancient man. The habitation was spread in a vast area (more than 2 km) along the southeastern coast and major parts of the ancient settlement have been destroyed by the sea, as a large number of ancient pottery can be collected from the inter-tidal zone of this area. The oldest habitation in three trenches, namely BDK-I, II and V is traced 1 m below the present high waterline, which is a clear indication of the lower sea level during these settlements.

The glacio-eustatic sea level reached its present state (or close to it)<sup>7,13,14</sup> around 6000 yrs BP. However, minor sea-level fluctuations have played a significant role in the evolution and decline of many habitation sites situated along the coasts. It is believed that after 6000 yrs BP, the sea-level fluctuated between 2 and 6 m above the present at various places<sup>15</sup>. A recent study<sup>16</sup> in northern Europe suggests three phases of rapid regression during the last 3000 years; they are 2600, 1500 and 950 yrs BP. A sea-level curve for North Konkan proposed by Ghate<sup>17</sup>, suggests a lower sea level around the beginning of the Christian Era, which corresponds well with evidence from Bet Dwarka.

Radiocarbon dates from Bet Dwarka island suggest that the oldest habitation dates back to  $3470 \pm 80$  yrs BP (BDK-VI, layer 2), i.e. to a late phase of Harappan Civilization, a habitation which lasted up to  $3140 \pm 100$  yrs BP (layer 1). Settlement was concentrated on the northeastern (BDK-I) part of the island, about 3 m above the present high waterline. The archaeological material is similar to that found at Rangpur and many other late Harappan sites of Saurashtra<sup>18</sup>.

**Table 3.**  $^{14}\text{C}$  dates from Bet Dwarka island samples collected during excavation in December 2001

Site	NIO sample nos	Depth (cm)	Layer	Lab number BSIP	$^{14}\text{C}$ date (yrs BP)	Calibrated date
BDK-II	BDK-II/shell/2001/21	240	8	1998	$1940 \pm 80$	1990–1820
BDK-II	BDK-II/shell/2001/22	275	10	1996	$2000 \pm 80$	2040–1870
BDK-III	BDK-III/charcoal/2001/23	70	4	2005	$2200 \pm 100$	2340–2060
BDK-III	BDK-III/charcoal/2001/24	225	9	2009	$2590 \pm 100$	2780–2500
BDK-VI	BDK-VI/shell/2001/26	20	1	2000	$3140 \pm 100$	3470–3260
BDK-VI	BDK-VI/shell/2001/27	50	2	1993	$3470 \pm 80$	3830–3640

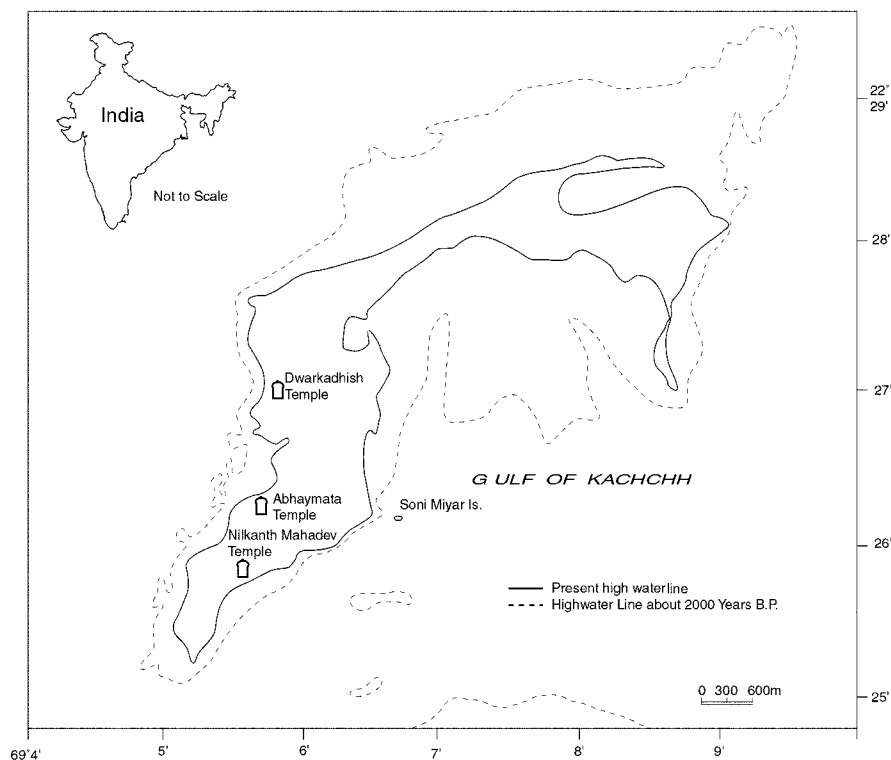
**Figure 4.** Bet Dwarka: Excavated section of BDK-II with archaeological remains.**Figure 5.** Bet Dwarka: Excavated section of BDK-III with archaeological remains.**Figure 6.** Bet Dwarka: Excavated section of BDK-V with archaeological remains.

After a long hiatus, the island was inhabited during the early historical period and remains were noticed at BDK-I, II and III. The oldest  $^{14}\text{C}$  dates coming from BDK-III, are  $2590 \pm 100$  yrs BP (layer 9) and  $2200 \pm 100$  yrs BP (layer 4). The material from this trench corresponds to those with early historical sites of Saurashtra<sup>19</sup> and Deccan<sup>20</sup>. The lowest habitation of BDK-III is situated almost at the present high waterline.  $^{14}\text{C}$  dates of BDK-II are  $2000 \pm 80$  yrs BP (layer 10) and  $1940 \pm 80$  yrs BP (layer 8);  $^{14}\text{C}$ -AMS dates from the same trench are  $1980 \pm 40$  yrs BP (layer 10) and  $1859 \pm 60$  yrs BP (layer 9). Two luminescence dates from this trench are  $2375 \pm 523$  yrs BP (layer 11), and  $1754 \pm 261$  yrs BP (layer 6). The absolute dates are in agreement with the cultural deposits and were verified by the discovery of coins and pottery. It is of major importance that the early habitation of three sites, namely BDK-I, II and V is situated about 1 m below the present high waterline.

It is evident from the above that the lowest habitation in BDK-I and II lies below the present high waterline by

**Table 4.** AMS age data for organic samples from a trench at Bet Dwarka<sup>12</sup>

Sample ID	Trench no.	Material dated	<sup>13</sup> C/ <sup>12</sup> C ratio	<sup>14</sup> C Age (yrs BP)	Calendar age (2 sigma range)	Calendar year (2 sigma range)
BDK-2-L	BDK-II	Charcoal	-24.6‰	1859 ± 60	1925–1620	AD 25 – AD 328
BDK-2-T	BDK-II	Charcoal	-25.8‰	1980 ± 40	2000–1860	50 BC – AD 100

**Figure 7.** Possible outline of Bet Dwarka island during 2000 yrs BP.

about 1 m, which is an indication of a rise in sea level after the settlement in the island. Similarly, site BDK-V near Khuda Dost Dargah is presently also flooded during high tide. And these sites (BDK-I, II and V) have a time span between 2nd century BC and 4th century AD. It is during an early phase of the historical period (5th to 2nd century BC) settlement, when habitation was extended towards the present offshore and gradually extended landwards during a later phase. However, the sea destroyed the remains of the later phase. This suggests that up to the 4th century AD sea level was lower than the present one. These evidences are in agreement with many other archaeological sites situated along the Indian coasts, such as Poompuhar<sup>21</sup>, Mahabalipuram<sup>22</sup> and Arikamedu<sup>23</sup>.

While hypothesizing on the shoreline changes in the Gulf of Kachchh, it should be remembered that the area has been subjected to tectonic disturbances which may have affected the sea level. However, based on archaeological records of the region, the following sequence of episodic sea level changes is suggested for the area.

(a) Sea level was higher than the present one at around 6000 yrs BP and remained there until 3500 yrs BP or so; as

a result, a large number of Harappan port towns in Gujarat and Pakistan are now located inland, far away from present-day shoreline and at a higher position than the present sea level<sup>24</sup>. Similarly, a late Harappan site datable to 3800 yrs BP in Bet Dwarka (BDK-VI) is located about 4 m above the high waterline. This corresponds well with the geological findings of the area<sup>25</sup>.

(b) Sea level continued at the present state from 3500 to 2300 yrs BP, as an early historical period site (BDK-III) dated to 2600–2300 yrs BP is situated a little higher than the present high waterline. Similarly, a well-known early historical port town at Sopara, north of Mumbai<sup>17</sup>, was an active port and had international trade relations.

(c) After 2300 yrs BP, the sea level fell by 2 to 3 m along the Bet Dwarka coast, as the oldest habitations of BDK-I, III and BDK-V are located below the present sea level. And perhaps around medieval period (10th century AD), the sea level reached the present state when a number of ports came into existence along the Gujarat coast.

Based on present-day bathymetry and the above discussion, it can be summarized that during historic period sea level around Bet Dwarka was lower by 2–3 m. There-

fore a large area would have been aerially exposed towards the northern and eastern parts of the island and a land bridge would have functioned during low tide towards the eastern side of the island, which is close to the mainland. Similarly, a large area would have been exposed even in the southern area where early historical period habitation took place and a large number of archaeological artifacts can be collected during low tide as far as 500 m from the high waterline. Figure 7 suggests that Bet Dwarka has a larger exposure towards the northeastern side, followed by the southern side; while on the western side there may not be much difference, as isobaths suggest a steep depth and high cliffs can be seen on this side of the island.

While it is easy to infer what changes took place in the recent past on and around the shore of Bet Dwarka, it is difficult to attribute reasons for it. There are various possible causes for changes in the shoreline such as tectonic disturbances, coastal erosion and glacio-eustatic sea-level fluctuation, etc.

It is well known that Gujarat peninsula is sensitive to tectonic disturbances. Evidences from archaeological sites like Dholavira<sup>26</sup> and Bet Dwarka<sup>12</sup> have been recorded. Several earthquakes affected various parts of Gujarat<sup>27</sup>.

Coastal erosion is one of the prime causes of shoreline changes along the Indian coast. Studies have indicated that Bet Dwarka and Dwarka have been prone to coastal erosion during the last couple of centuries<sup>28</sup>.

Sea-level fluctuation is one of the important factors responsible for shoreline changes in the past. As stated earlier, minor sea-level changes during the last 3000 years may have affected human settlement in the coastal areas<sup>16,17</sup>.

Archaeological evidence has helped determine changes in shoreline during the last 2000 years. Human artifacts and radiocarbon dates from Bet Dwarka island gave some interesting conclusions about the sea level and shoreline changes along the Bet Dwarka Island.

- Sea level was lower than at present by more than a metre between 2040 and 1820 yrs BP.
- During that time a large area on the northern part of the island was exposed and the island was probably connected with the mainland towards its eastern side during low tide.
- Sea level rose up to its present state around 1000 yrs BP when most of the coastal sites of early historical period got submerged in the sea.

The above inferences correspond to many other sites along the Indian coast; however, in contrast such sites situated along coastal areas during the historical period are now situated far inland, perhaps due to siltation as most of them were located at estuaries. It would be interesting to see the outcome of a study of a similar kind where the possibility exists, on both eastern and western shelves of India, where man-made sites/structures are re-

ported underwater or port sites are reported away from the shoreline.

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## An electromagnetic moving source system for detection of subsurface mineralized zones

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**A frequency-domain electromagnetic prospecting moving source device is designed to detect shallow subsurface conductors. Towards this, a microprocessor-based electromagnetic modelling instrument is developed with high degree of accuracy in measurement. The equipment is tested in the laboratory to check its design and performance. In this device, the transmitter and receiver coils are parallel but non-coplanar. The receiver coil is positioned strategically in such a manner that it is not affected by the primary field and senses only the secondary field generated by the conductor. In dipole–dipole set-up, it measures the amplitude of the anomalous field. The operating frequency can be varied from 1 to 30 kHz and separation between the transmitter and receiver coils can be moved from 0.12**

**to 0.29 m. Measurements can be made to within  $\pm 1\%$  of the free-space field, though absolute accuracy is less. It is found that depth of exploration this moving source system is about 40% more compared to that of a similar conventional moving dipole EM system.**

**Keywords:** Depth of exploration, electromagnetic prospecting, moving source system, subsurface mineralized zones.

IN frequency-domain electromagnetic (EM) exploration, several moving source–receiver systems have been fruitfully used for nearly six decades to detect shallow massive sulphide ore bodies. Depth of exploration for most of the moving source systems is 0.6–0.8  $l$  ( $l$  is the transmitter–receiver separation), as the secondary field produced by a conducting body is quite small in comparison to the strong primary field; accurate measurement of resultant field to primary field ratio is always difficult. To circumvent this problem, time-domain methods were developed where the secondary field is measured during the period when the primary field is switched off.

In this communication, a device is proposed wherein the transmitter ( $T$ ) and receiver ( $R$ ) coils are kept parallel but non-coplanar. In this set-up, one of the parallel components of the time-varying EM field surrounding a circular transmitter coil is zero at certain locations. If the receiver coil is located at these strategic points and parallel to the transmitter, the primary field does not induce currents in the coil. Thus the induced currents are only due to the secondary field from the target. In the absence of the primary field, it can be measured with high accuracy.

The magnetizing forces parallel and perpendicular to the dipole of magnetic moment  $m$  are given by Parasinnis<sup>1</sup> as:

$$H_{\parallel} = \frac{m(3\cos^2\theta - 1)}{4\pi L^3}, \quad (1)$$

$$H_{\perp} = \frac{3m\sin\theta\cos\theta}{4\pi L^3}, \quad (2)$$

where  $\theta$  is the angle and  $L$  the separation between  $T$  and  $R$ , as shown in Figure 1.

Equation (1) shows that  $H_{\parallel}$  is zero if  $\cos\theta = \pm 1/\sqrt{3}$ , or  $\theta = 54.736^\circ$ . In the Cartesian coordinate system,  $T$  and  $R$  are parallel but displaced by  $\pm 0.7071 l$  (where  $l$  is the  $T$ – $R$  separation in coplanar configuration) along the coil axis. In this situation, the separation between  $T$  and  $R$  is  $L = 1.225 l$ . Thus if the  $R$  and  $T$  are separated laterally by  $l$  and displaced by  $\pm 0.7071 l$  with reference to the plane of coils then the parallel component of  $T$  will not induce any current in  $R$ . This property is clearly independent of the magnitude and frequency of the current in the transmitter coil. Further, due to reciprocity, the locations of  $T$  and  $R$  are interchangeable.

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