There is a tank hewn into coastal Pleistocene limestone near Diu city on the Saurashtra Peninsula of western India. Site survey and a review of similar structures worldwide provide evidence that this tank could have been used for holding fish or *Murex* snails. The approximately 5 × 5 m tank is connected to the sea by a 1-m-deep canal; today it would be impossible to use the tank, given that not even the high spring tides can fill it. It is suggested that the Diu coast was uplifted by ∼0.5 m after the tank was hewn in the coastal platform. Since that time, the carved surfaces have been modified by coastal karst dissolution and have developed deep gouge marks. Uplift of the Diu coast raises the possibility of a major seismic event in Diu during the latter part of the last millennium. © 2016 Wiley Periodicals, Inc.

**INTRODUCTION**

Indicators of past sea levels have excellent records effectively preserved in rocky coasts (Pirazzoli, 1986; Rust & Kershaw, 2000; Stiros et al., 2000; Kershaw & Guo, 2001; Furlani et al., 2011). Relative sea-level changes—caused either by eustatic or tectonic movements—leave traces in geomorphology, bioerosion, and even in human-made features (Flemming & Webb, 1986; Papageorgiou et al., 1993; Stiros, 1998; Faivre, Bakran-Petricioli, & Horvatinič, 2010; Evelpidou et al., 2012; Mourtzas, 2012a; Özdağ & Kızıldağ, 2013; Seeliger et al., 2014; Kázmer et al., 2015). The respective methodologies applied in these studies have been developed mostly on sites within the environs of the Mediterranean Sea and applied worldwide (Pirazzoli, 1996; Morhange & Marriner, 2015). During a systematic survey of the coastal morphology near the city of Diu on the Saurashtra Peninsula, in the west of India, a human-made, rock-hewn tank-like structure was found. This paper provides a detailed description and interpretation of this structure with reference to tectonically induced coastal uplift along the coastal region near Diu.

**Archaeological Sea-Level Markers**

Archaeological objects can serve as indicators of coastal change. Buildings—originally constructed on land—are sometimes discovered underwater, thus indicating subsidence after construction (e.g., Flemming & Webb, 1986; Faivre, Bakran-Petricioli, & Horvatinič, 2010; and many others). There are also structures originally built on the coast, such as ports, which have subsequently been elevated above their functional level, indicating coastal uplift (e.g., Papageorgiou et al., 1993; Stiros, 1998). There are locations that suggest a history of both subsidence and uplift in repeated episodes, such as the iconic columns of the Serapeum in Pozzuoli, Italy (see a range of studies from Lyell, 1837 to Morhange et al., 2006). Archaeological sea-level markers—if studied in conjunction with biological sea-level markers—can also be very reliable in the
description of relative sea-level change. For recent studies with further references, see Morhange et al. (2013) and Morhange and Marriner (2015).

STUDY AREA

The Saurashtra Peninsula was still considered to be an integral part of the Indian Shield up until quite recently (Rao, 2000), and it was assumed that it belonged to the stable continental interior of western peninsular India (Singh et al., 2014). It is covered by deeply weathered, lateritised Upper Cretaceous-Palaeocene Dec- can trap basalts. Along the southwestern and southeastern coasts, late Quaternary Miliolite limestone forms coastal cliffs, beach ridges, and eolianites (Bhatt, 2003).

Recent intensive surveys related to hydrocarbon exploration, as well as seismological studies, have provided a picture of tectonic mobility. Saurashtra is bound by the N–S trending Cambay Basin in the east, the Narmada fracture in the south, the Kachchh rift in the north, and a major WNW–ESE fault in the west (Bhattachariya et al., 2004: Figure 1). Diu is just north of the NE–SW Narmada Son Fault; this fault lies offshore and south of some on-land faults, namely the Chachhar and Rupen faults (Bhatt et al., 2006). Recently, a few faults have been mapped on land (Gandhi et al., 2015), along with conspicuous joint sets in the late Quaternary limestone, and these manifest the effects of stress (Bhonde & Bhatt, 2009).

The Kachchh district of Gujarat is the only region outside the Himalaya–Andaman belt that has a high seismic hazard of magnitude 8; this corresponds to zone V in the seismic zoning map of India. The other parts of Gujarat have respective seismic hazard magnitudes of 6 or less. While potential earthquake source zones in Kachchh have already been recognized (Chopra et al., 2013: Figure 2), those in Saurashtra are practically unknown; this is due to the lower magnitude of seismicity that has so far been observed. Earthquakes up to \( M_{w} \) 5.7 occur infrequently along the poorly defined faults of the area (Rastogi, Kumar, & Aggrawal, 2013). Furthermore, the Cambay Basin faults in the east have shown only moderate seismic activity in the last 200 years, while the Narmada–Son trend and the SW-West Coast trend of faults have shown very moderate seismic activity (Rastogi, Kumar, & Aggrawal, 2013a).

Nevertheless, since these earlier assumptions were made, late Quaternary coastal changes have been extensively studied along the southern Saurashtra coast. As a result of this research, there is now ample evidence for sustained uplift. For example, since the last interglacial, it appears there has been uplift of up to 15 m above mean sea level, and this can be observed in the form of Holocene marine terraces and notches (Gupta, 1972; Bhatt & Bhonde, 2006).

These conclusions with respect to uplift follow in the light of widespread underwater and onshore archaeological surveys carried out in the western part of Saurashtra (Rao, 1996, 1996; Gaur & Vora, 1999; Gaur & Tripati, 2006; Gaur, Tripati, & Tripati, 2007). The archaeological surveys found submerged living quarters and ports, and even a submerged Hindu temple in the northwestern part of Saurashtra (Gaur, Tripati, & Tripati, 2007). Such discoveries are further evidence for active coastal change.

Along the southern coast of Saurashtra, on Diu Island, a rectangular tank-like structure was found, and it had clearly been hewn into the local Miliolite limestone. The research recorded in this paper shows that during high tides the tank was only partly filled by the sea through a canal, and fully emptied during low tides. This tank was examined and special emphasis was placed on its position relative to sea level, with the aim of being better able to quantify the Holocene vertical displacement of the coast.

METHODS

The location was surveyed between September 18 and 22, 2012, using a compass, tape measure, and a laser distance meter. These measures routinely provide \( \pm 1 \) cm accuracy. Unfortunately, the rough rock surface prevented precise fitting of the laser distance meter and because of this the estimated accuracy of measurement was \( \pm 3 \) cm. Elevations were related to current sea level and calibrated to the nearest tide gauge; that is located approximately 50 km to the east, at Nava Bandar (20°4’09” N, 71°05’30” E). The tidal table was provided by http://tides4fishing.com (for September 2012).

THE TANK

West of Diu, the rocky coastline is, in most of its sections, bordered by a tidal platform tens of metres wide. In a few places the remnants of older, uplifted platforms have been preserved. The tank was cut into one of these older platforms, near a place called Chakrathirtheshwar (Figure 1). A detailed description and interpretation of the tank is given below.

The rectangular tank or basin found on the small promontory north of Chakrathirtheshwar sanctuary (20°42’19” N, 70°58’45” E) is entirely carved in the bedrock. This bedrock is indurated Middle-to-Late Pleistocene Miliolite limestone that forms the island of Diu (Figure 2). The tank has a rectangular plan, being approximately 3 × 3 m at the bottom, >5 × 5 m at the top,
Figure 1: Map showing the geomorphological setting of the Diu Island. (A) Location of Diu in India and Gujarat state along with bounding faults of the Saurashtra Peninsula. (B) Location of the fish tank near Chakratirthwar temple.
Figure 2. Fish tank and inlet canal after high tide. View toward the east. Conspicuous bedding of the Miliolite limestone (Pleistocene calcareous sand dunes) is tilted toward the east. Steps surround the tank. The person in the photograph is standing on the lowest step. A further three steps (equivalent of Roman crepidini), leading to the loading platform, are visible to the right of the person. The cross section of Figure 7 is a representation drawn along the axis of the canal. Tide at 225 cm, ~5 cm above the canal bottom at time of photographing. The highest astronomical spring tide at 270 cm is 45 cm above tide level as shown on the photograph, barely covering the step where the person is standing. Photo: M. Kázmér, #P9220375.

and widening upward in a stepwise fashion. Its sides are oriented N–S and E–W and the survey indicated that it was ~1 m deep at the time of construction. All sides of the tank are stepped; however, now only the southeastern half is fully preserved.

An entrance for sea water was cut on the eastern side of the tank. The canal of this entrance is 0.5 m wide, 1.0 m deep, and about 5 m long. It is horizontal near the tank, and slopes distally toward the sea. A vertical, semicircular groove of 50 cm diameter was cut in the northern wall of the canal. There are three holes of 5–10 cm diameter at the bottom of this site and these probably held the poles of some kind of a barrier (perhaps a movable “gate”). This barrier would have retained the water in the tank during low tide.

All around the tank, there are stepped walkways that are 25 to 55 cm wide and 20 to 25 cm high. Stairs (20 cm high) were inserted in the lowermost walkway on each side to facilitate access to the bottom of the tank.

It appears that the promontory bearing the tank was modified at some time on the eastern and the southern sides. There are visible remnants of rock-hewn steps and these are 3 m long along the eastern side, and 5 m long along the southern side; the steps are 26 cm high and 30 cm wide. A flight of six steps leads down to the level of the coastal platform (Figure 3). There are similar steps along the southern rock of the small embayment. The steps along the eastern side of the promontory display peculiar, inclined edges. These surfaces are the products of fracturing along the eastward-facing, foreset beds of the eolian Pleistocene limestone that forms the promontory. The same weakness along the bedding planes caused the fracture of the step-cut of the lowermost step on the western side of the tank.

There are conspicuous holes on top of what appears to have been a loading platform, as well as on the uppermost steps along the eastern and southern sides of the promontory (Figure 4). Steep walls and a mostly flat floor down to a depth of 16 cm indicate that these are solution features of the supratidal spray zone (kamenitza, Taboroši & Kázmér, 2013). The evidence of bioerosion caused by grazing littorinid snails in the supratidal zone and by grazing limpets in the upper intertidal zone (Kázmér & Taboroši,
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2012) explains the irregular pitting and lowering of the originally flat, rock-hewn surfaces of the steps. There is a conspicuous pink crust of corallinacean red algae covering the rock surface in the lower part of the intertidal zone (Figure 3). Along its irregular upper boundary is the Biological Mean Sea Level (BMSL), as defined by Laborel and Laborel-Deguen (1994, 1996).

Figure 2 was photographed at 16.33 local time on September 22, 2012, 1 hour before a high tide of 2.3 m. The maximum astronomical high tide reaches 2.7 m. The top of the platform in which the tank was cut is at a level of 330 cm. The photograph shows clearly that the high tide is unable to fill the tank to any reasonable level and Figure 3 shows that low tide leaves the coastal platform dry.

DATING

The dating of (fish) tanks derives indirectly from the age of the settlements they served (Mourtzas, 2012b). Diu was a rich merchant settlement during the reign of the Cambay sultan in the late Middle Ages. The town was captured by the Portuguese in 1531 and a major fort was built in 1537. The town and the fort controlled Portuguese interests on the west coast of India throughout the 16th and 17th centuries (Shokoohy & Shokoohy, 2003, 2010). The supposition of the present study is that the small port and tank at Chakratirtheshwar were constructed during the period of Portuguese rule; this is based on the analogous structure of the tank with Roman-age fish tanks in the Mediterranean (Table 1).

The deep solution pits on the carved top of the platform and on the steps are the result of the constant spraying of seawater (Taboroši & Kázmér, 2013). The depth of these pits has increased proportionally with time. In order to assess the magnitude of change the present study considered the erosion rate of about 10–35 μm/yr, which was measured at an analogous site in the Ryukyu Islands of Japan. There the lithology and the environment are similar to those discussed in this paper: namely, moderately indurated, highly porous Pleistocene limestone that has been dissolved by spraying seawater in tropical conditions (Aoki, 2009). The conditions outlined in this paper suggest that the 16-cm-deep pits on the stairs needed several centuries to develop under subaerial conditions—that is, the tank and its associated stairs are at least a few hundred years old. This is supported by the

Figure 3 Irregular steps (26 to 51 cm high) along the southern side of the promontory holding the fish tank, as seen at low tide. The irregular corners are products of extreme karstic dissolution in the spray zone. The biological mean sea level (BMSL) is along the top of the pink crust of corallinacean algae, at knee elevation of the person in the photograph. Photo: V. Ukey, #DSCF1459.
Figure 4 Actively growing solution pits on the southern flight of steps in the spray zone. The higher the elevation of the step, the deeper is the pit. Those on the uppermost step are up to 16 cm deep. The rough and irregular surface of the stairs is the result of a combined action of wave splash, seaspray, and grazing by littorinid snails (Kázmér & Taborosi, 2012). Photo: M. Kázmér, #P9220384.

historical sketch of a tank of the kind being discussed here (Figure 5).

DISCUSSION

The Tank

Observations on the tank at Chakratirtheshwar leave little doubt about its function. Entirely carved from bedrock, there is no need for a detailed hypothetical reconstruction of its lost portions. Its purpose was certainly to hold sea water and allow a direct connection to the sea at certain times, while blocking this connection at others. The Diu tank is surprisingly small compared with similar Roman structures described as fish tanks. However, the exact kind of animal kept in the tank is a matter of speculation. Fish are most likely to be, but it should be taken into account that fish could easily have jumped out of the tank and escaped to the sea, a mere 1–2 m away. Turtles, or rather Murex snails, are both significantly less mobile than fish; furthermore, records show that these species were certainly expensive enough at the time to justify the costs of carving a tank to hold them (Mourtzas, pers. comm., 2014).

It will probably never be known exactly what was held and cultivated in the coastal tank at Diu. The following discussion is about a rich variety of analogous structures around the Mediterranean Sea considered as “fish tanks” and that have been described in detail. In the 1st–2nd century A.D. fish tanks were built by the Romans (Higginbotham, 1997; Lambeck et al., 2004a, b; Mourtzas, 2012b). Most of these were built into or on top of nearshore platforms, exhibiting various designs with hydraulic features related to the local geomorphology (Mourtzas, 2012a; Evelpidou et al., 2012). The basins of these tanks were connected to the sea by canals constructed to allow sea water into the tank. Movable gates regulated the water level in the basins. Step-like walks around and within the basin allowed maintenance to be carried out as summarized by Evelpidou et al. (2012).

In the Mediterranean, in Antiquity, purple dye was manufactured by processing the hypobranchial gland of muricid gastropods. After oxidation, the normally translucent mucus of this gland turns to various shades of red, purple, or blue (Higginbotham, 1997; Forstenpointner et al., 2007). Fishermen collected the live snails, and kept them in a tank (the vivarium) until a sufficient number had been gathered to start the dye extraction (Leadbetter, 2003). Rock-hewn tanks, not dissimilar to that at Diu, are also known from ancient Greece (Kardara, 1961). Although related mollusc species are abundant along the coast around Saurashtra (Radwin & D’Attilio, 1986), historically Murex dyeing is unknown in India, where plant dyes have been preferred (Siva, 2007). However, it is possible that Portuguese merchants started a purple dye business in Diu, and the Chakratirtheshwar tank belonged to this industry.

Elements of construction that relate to former sea levels are as follows:

- the bottom of the inlet canal, which should be below high neap tides in order to allow the passage of sea water into the basin at least daily;
- the top of the inlet canal, and the sluice gate within it, should be above the high spring tide level to prevent the loss of fish (Evelpidou et al., 2012: 275).

Coastal tanks, derived from Antiquity, are considered to be the most reliable class of archaeological monument for studying relative sea level variations (Auriemma & Solinas, 2009). A direct provenance of the technology from the Roman-age Mediterranean (of which the territory of present-day Portugal was an integral part) to Portuguese-dominated Diu in the 16th century is quite
possible. However, this needs further extensive archaeological, historical, and ethnographical research.

Certain Roman building traditions in Antiquity can be recognized that survived well into the Middle Ages and even later, and were applied very far from the territory of the former Roman Empire. For example, builders of the Crusader castle of al-Marqab in Syria, built in the late 12th century, applied Roman concrete technology (Kázmér & Major, 2010). Up to the 18th century at least, Spanish military engineers used the very same technology when constructing fortifications for military outposts in the Philippines (Cabigas, 2008).

The use of permanent seashore tanks in Diu is visible on an early engraved panoramic view from 1572 (Bruin, Novellanus, & Hogenbergius, 1572–1618; Figure 5) and on a mid-18th-century map (Salmon, 1752–1753; Figure 6). Although their purpose is not stated expressly, the word “tank or pond” on the latter do not leave much doubt that the keeping of live catches from the sea in coastal tanks was a common practice throughout the centuries of Portuguese rule. For a detailed comparison of the architectural details of the Diu tank with counterparts in the Mediterranean, see Table I.

Consideration must be given to the possibility that coastal tanks developed independently in various areas and periods, both in the Roman-age Mediterranean and in Medieval India. Analogous examples are the qanats or underground water transportation systems that developed and expanded from central Asia and Iran. These engineering constructions were independently developed in, for example, pre-Roman Italy and the Americas (Stiros, 2006).

### Tides and the Diu Tank

The maximum tidal range in the Tyrrenian Sea—where the best-studied Roman fish tanks are found—is 45 cm; this happens to be equal to the depth of the fish pond canals that can be found there. This indicates that the flow of water into the tanks was tidally controlled (Lambeck et al., 2004b). At Diu (measured on the Nava Banadar mareograph nearby) the spring tide range is ~2 m, and the neap tide range is ~1 m; these ranges are far too large to have let the inflow and outflow be regulated by tides only. A control gate would have been essential to keep water in the tank during low tides. The 0.5-m-wide, 1-m-deep inlet canal provided an ample supply of fresh sea water to the tank, even during high neap tides. This is an important consideration given the year-round high temperatures at 20°N tropical latitude. During low tide, a water-tight barrier prevented the water level in the tank from falling to a level insufficient for the animals to survive.

Today the Diu tank is dysfunctional with respect to its original purpose, given that even the highest spring tide cannot fill it completely, and a high neap tide is barely enough to supply water to cover the basin bottom. However, if the fish tank was positioned just 0.5 m lower, it could function effectively. Therefore, the suggestion being made here is that the tank, the promontory, and the
Chakratirtheshwar portion of Diu Island have been uplifted by at least 0.5 m since its construction. This uplift probably occurred at some time during the latter part of the last millennium (Figure 7).

There is a rich literature on displaced maritime archaeological structures, indicating either coastal uplift or subsidence some time after the construction of these structures. The functionality of fish tanks, jetties, ports, and watchtowers (recently Anzidei et al., 2011, 2012; Mastronuzzi & Sansò, 2014; for a review see Evelpidou et al., 2012) is very closely related to the local sea level. This is why they are excellent markers of relative sea level change, whether in the Mediterranean or elsewhere. There is an increasing number of papers offering considerations on the tectonic and seismic background of the cause of such displacements (e.g., Stiros, 1998; Kontogianni, Tsoulos, & Stiros, 2002; Mastronuzzi & Sansò, 2014).

With regard to the site that is the subject of this study, modeling of eustatic sea level changes has shown that the present-day relative sea level is stable along the coasts of Saurashtra (Peltier, 2002). Therefore occurrences of both uplifted and submerged archaeological features in Saurashtra (Rao, 1996, 1996; Gaur & Vora, 1999; Gaur & Tripati, 2006; Gaur, Tripati, & Tripati, 2007) invite a tectonic explanation.

**Implications for Seismicity**

As mentioned before, Diu is close to the intersection of the fault sets bordering Saurashtra in the southeast and southwest. It is possible that the activity of these faults was responsible for the uplift of the Diu coast. Historical data on earthquakes date from the present back to 1668 only (Rastogi, Kumar, & Aggrawal, 2013a). Major earthquakes, having a recurrence interval of several centuries,
even millennia, are unknown in Saurashtra—this study is the first to suggest the possibility of their occurrence in historical times.

The Narmada rift zone experienced shocks of a magnitude of $M \approx 5.4$ at Bharuch in 1970. However, even this moderate earthquake is ranked as having been severely damaging due to poor construction practices (Rastogi et al., 2013b). The 2010 Talala earthquake ($M_w 5.1$) was 100 km to the NW (Yadav et al., 2011). Another $M < 5$ seismic event was a mere 50 km to the north (Rastogi et al., 2013b). An $M_w \sim 7$ earthquake in 1705 near the Cambay Basin raises the suspicion that boundary faults of Saurashtra are capable of causing major, damaging earthquakes (Bhattachariya et al., 2004).

Whether there was a single, major uplift, or several minor uplift (i.e., seismic) events at Diu cannot be ascertained at the moment. In a worst-case scenario, if a 0.5 m uplift occurred during a single earthquake, it may have been the result of a $M 6.8$ earthquake (Wells & Coppersmith, 1994)—this is greater than anything instrumentally recorded in Saurashtra. Considering the proximity of the city of Diu a few kilometres away, as well as other port cities in Saurashtra, and the proximity of the offshore oil industry in the Cambay Bay, significant human and material loss would result if there was an earthquake of this magnitude. A consequent tsunami, generated by displacement along offshore faults, would, in turn, endanger Mumbai (Bombay), the most important port city of India, and further settlements along the west coast of India.

CONCLUSION

This study suggests that a fish tank was hewn into coastal limestone during the latter part of the last millennium near Diu, Saurashtra, India. It was connected to the ocean via a 0.5-m-wide canal that enabled the free flow of seawater. The tank is now dysfunctional because it is elevated beyond sufficient reach of the high tide necessary to fill it with water. This occurred as a result of coastal uplift of about 0.5 m after construction. The uplift occurred at least a few centuries ago, as indicated by well-developed karst dissolutional features on the human-made features. This degree of coastal uplift raises the possibility of an $M_w 6.8$ earthquake in Saurashtra during the later part of the last millennium.

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