Evidences and radiocarbon (14C) ages of palaeo-high sea-level position around Mandapam, southeast coast of India

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A well-laminated, cross-bedded and coarse to very coarse-grained calcareous (beach rock) sandstone unit is exposed on either sides of Mandapam foreland along the Palk Bay and the Gulf of Mannar coasts at about 2 m asl. Presence of abundant coral debris and pelecypod shells in the sandstone indicates its formation under high-energy beach facies. Coral debris Acropora sp. and pelecypod shells, Arca sp. in living positions collected from the sandstone unit yielded 14C ages of 6110 and 5650 yrs BP respectively. The level of occurrence of calcareous sandstone and 14C ages of coral debris and pelecypod shells confirm that the mid-Holocene high strandline stood at about 2 m asl in this coastal segment between 5650 and 6110 yrs BP.

Keywords: Beach rock, palaeo-high sea-level, radiocarbon ages, sandstone unit.

The thrust on the study of past, present and future sea-level positions is gaining momentum worldwide because it concerns not only earth scientists, but climatologists, glaciologists, biologists, environmentalists, city and town planners, administrators, etc. In India, along the coastal areas, evidences of palaeo-high sea-level positions from the Pleistocene onwards are well established by remote-sensing studies followed by ground-truth collection. The datable materials collected from the palaeo-high sea-level positions from western and eastern coastal segments have yielded 14C ages between 120,000 and 5100 yrs BP. These 14C ages reveal that the Holocene sea level reached a maximum between 6500 and 5100 yrs BP.

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Studies pertaining to palaeo-high strandline positions, coastal geomorphology and neotectonic activities along the Palk Bay and the Gulf of Mannar in the southeastern coast of India have been carried out. Occurrences of beach rocks along the shoreline of the Gulf of Mannar as evidence of palaeo-highstand have been described\(^1\). Coastal geomorphology of southern Tamil Nadu\(^2\), indicators of formerly higher sea levels along the east coast of India and on the Andaman Islands\(^3\), remote sensing application in the study of sea-level variation along the Tamil Nadu coast\(^4\), seasonal shoreline oscillation of Tamil Nadu\(^5\), Holocene and Late Pleistocene relative sea-level fluctuations along the east coast of India\(^6\), evolution of Quaternary sediments along the coast between Vedanayam and Rameswaram, Tamil Nadu\(^7\), thermal springs in Indian coastal areas of the Palk Bay and their implications in relation to lineaments, coastal geomorphology and seismicity\(^8\), and evidence of subsidence of the southern part of erstwhile Dhanushkodi township, Tamil Nadu\(^9\) have been well documented. The reliable datable materials collected from some of these locations have been radiocarbon-dated. However, the age of the sandstone exposures at 2 m asl at the tip of Mandapam, indicative of palaeo-strandline position is hitherto unknown. In this communication, evidences of palaeo-high sea-level positions around Mandapam and their \(^{14}\)C ages in relation to Mid-Holocene transgression are discussed.

Geological and coastal geomorphological set up of the southeastern coastal segment of India, i.e. around Mandapam, Rameswaram Island up to the tip of Dhanushkodi was studied in detail by extensive field traverses. During the field traverse, Mandapam foreland (Figure 1), an easterly stretching, narrow land mass separating two marine domains, viz. the Gulf of Mannar in the south and the Palk Bay in the north drew much attention, in view of huge exposures of sandstones of marine affinity on either sides, occurring up to an altitude of about 2 m asl. These sandstone exposures were studied in detail and datable materials such as coral debris and molluscan shells embedded in living positions within this litho-unit were collected. Coral pieces belonging to *Acropora* sp. and molluscan shells of *Arca* sp. collected at about 1.5 m asl were cleaned thoroughly to avoid contamination and their mineralogy determined by X-ray diffractometry using CuK\(_\alpha\) radiation. The coral and shell pieces were \(^{14}\)C-dated at Birbal Sahni Institute of Palaeobotany (BSIP), Lucknow following the Radiocarbon Calibration Program Rev. 3.0.3 of the University of Washington\(^{10}\), taking the half-life of carbon as 5730 ± 40 years. On the basis of \(^{14}\)C ages, the Mid-Holocene high sea-level positions around Mandapam have been inferred.

No other rock exposures of either crystalline or sedimentary nature occur on the coastline of Mandapam or Rameswaram Island. The sandstone occurrence known as
Mandapam sandstone is well exposed around the tip of Mandapam foreland (Figure 1) for about 3 km stretch towards the west along the coastline of Palk Bay and along the coast of Gulf of Mannar and further south. The northern and southern coastlines of Mandapam foreland are more or less straight, but cliffed due to the exposures of Mandapam sandstone up to 2 m asl. Owing to intensive wave action, patches of sandstone are collapsed and small-scale caves are formed. This sandstone exposure extends up to the Pamban (pass) channel, but surficially do not seem to extend further east into Rameswaram Island. But it is expected to occur at sub-surface levels in Rameswaram Island. Hence, it is presumed that the easterly extension of Mandapam sandstone at depth might be the basement for younger coral reefs of Rameswaram Island.

Field observations reveal that the sandstone trends E–W and dips 5–10° south, suggesting that the exposure at the northern side is older. Generally, it is gravely to very coarse-grained, well-laminated (Figure 2a) with carbonate cementing, well-indurated, and cross-bedded at lower levels (Figure 2b). The thickness of cross-bedded units at the bottom varies from 30 to 40 cm (Figure 2b). The older sequence exposed at the northern (Palk Bay) side contains laminations of heavy minerals, quartz pebbles of 0.5–1 cm size (Figure 2c), brown dolomite gravels, abundant coral debris (Figure 2d), and pelecypod shells and shell fragments (Figure 2e). The quartz pebbles are well rounded. The sandstone becomes coarse-grained towards the top level. The coarse sand grains are mainly composed of quartz. According to the observations, the exposure is a shelly calcareous sandstone and formed under high-energy beach facies; hence it is a beach rock.

Scanning of the coral debris collected from the lower level revealed that it belongs to Acropora sp., Pocillopora sp., Favites sp. and Favosites sp. The molluscan shells mostly belong to pelecypods, including Arca sp., Pecten sp. and Cardium sp. The mode of occurrence and the embedded nature of corals and shells with carbonate cementing confirm that they do not belong to the present-day beach assemblage, but have been deposited earlier as beach rock at the inter-tidal zone. Acropora sp. which generally thrives within 5 m water depth and Arca sp. known to thrive within inter-tidal limits are considered the best indicators of shore facies. The mineralogy of the coral Acropora sp. and pelecypod shell Arca sp. determined by X-ray diffractometry confirms that their aragonite content is 95%, thus indicating no recrystallization of primary aragonite. Considering the above aspects, the coral Acropora sp. and shell Arca sp. were selected for radiocarbon (14C) dating. Acropora sp. yielded a calibrated 14C age of 6110 yrs BP (BSIP Lab. No. 2208) and Arca sp. yielded 5650 yrs BP (BSIP Lab. No. 2205).

On the basis of 14C ages, it is evident that the Mandapam sandstone unit formed as beach rock between 5650 and 6110 yrs BP. The Porites sp. from the relict coral colony at Munaikadu located about 10 km west of Mandapam on the Palk Bay coast has yielded a calibrated 14C age of 5750 yrs BP. Beach-rock sample collected from Pamban channel further east of Mandapam has yielded an uncalibrated radiocarbon age of 3650 ± 65 yrs BP.

The coral debris Acropora sp. within the Mandapam sandstone (beach rock) is not considered to be an in situ growth, but drifted from the vicinity and deposited with the sandstone, whereas the occurrence of Arca sp. in living position clearly indicates that it thrived with the deposition of sandstone. The age of Acropora sp. (6110 yrs BP) provides the clue that the Mandapam beach rocks were formed subsequent to the growth of Acropora sp. in the vicinity. A fresh look at this coral sample indicates its short transportation, preferably from the adjacent Rameswaram Island or north of Pamban, where some generation of coral reef has been radiocarbon dated around 5660 yrs BP6. Although the age of coral debris (6110 years) collected from the Mandapam beach rock does not fit to be the age of sandstone under study, it is considered to be its nearest age.

The relative sea-level curve of the east coast of India for Mid–Late Holocene period, on the basis of evidences and their 14C ages from Cape Comorin to Godavari Delta6, proves that the sea level stood approximately at 3 m above the present LTL around 7300 ± 130–110 yrs BP and at about 2 m above the present LTL around 5500 yrs BP. The radiocarbon ages of coral reefs around the adjoining Rameswaram Island also range6 from 7300 to 5660 yrs BP. Similarly, the radiocarbon dates of coral colonies along the adjacent southwest coast of Sri Lanka also indicate6 that the sea level reached about 2–3 m above the present sea level during 6170–5100 yrs BP. On comparison of the above with the 14C ages of Acropora sp. and Arca sp. from the Mandapam (sandstone) beach rock, it is evident that in the study area also during Mid-Holocene period, the high standline position was at 2 m asl, between 5650 and 6110 yrs BP. The above conclusion corroborates well with the world glacio-eustatic sea-level curve12.

Earlier studies suggested that the sea-level fluctuations all along the east coast of India have been caused by a combination of neotectonic movements and glacio-eustatic sea-level changes. The recorded levels of occurrence of high standline positions with reference to the present sea level vary from one coastal segment to other, possibly due to post-formational tectonism. Evidence of vertical neotectonic movements in the Palk Bay and the Gulf of Mannar coastal segments, and around Dhanushkodi in Rameswaram Island are established. Occurrence of five thermal springs under artesian condition around Manamelkudi in central Palk Bay, their association with E–W trending faults and the upliftment of unconsolidated seabed sediments by vertical neo-tectonic movement along these E–W trending faults are documented. Similarly, subsidence and submergence of the southern part of erstwhile Dhanushkodi township nearly 57 years ago
along an WNW–ESE trending fault has been established. The above observations indicate that the coastal segments of the Palk Bay and the Gulf of Mannar have undergone neotectonic movements. However, the level of occurrence
of Mid-Holocene high strandline position at Mandapam Foreland and its matching ages with other coastal segments of the east coast of India envisage that the area around Mandapam did not undergo any significant vertical movement. Hence it is a neotectonically unaffected block.


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## Drained and undrained responses for Koyna–Warna earthquakes from 1993 to 1994 following impoundment of the Warna reservoir in India

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The Koyna region along the west coast of India in Maharashtra, is a unique case of reservoir triggered seismicity, where seismicity has been reported since 1963 after the initial impoundment of the Shivajisagar reservoir behind Koyna dam in 1961. The region was further destabilized following the filling of the Warna reservoir, situated 25 km south of Koyna, during the late 1980s. Increase in pore pressure by drained and undrained effects is known to weaken the substratum below a water reservoir, facilitating the onset of seismicity. Although their relative influences may vary with time and space, it is difficult to separate their individual contributions. The present study, using the well-located earthquakes of $M \geq 5$ for the period 1993–94, is a preliminary attempt to identify these effects after impoundment of the Warna reservoir. It could provide a good opportunity for further modeling the strength changes due to reservoir impoundment.

**Keywords:** Drained and undrained responses, earthquakes, impoundment, Koyna–Warna reservoir, pore pressure.

**EARTHQUAKE activity in the Koyna region was triggered in 1963 following the initial impoundment of the Shivajisagar reservoir behind Koyna dam in 1961. Later, following impoundment of another reservoir in Warna, which began during the monsoon season in 1987 and afterwards in 1988, seismicity increased in the region. In 1993, seismicity increased significantly after attaining the highest water level in Warna reservoir. During 1993–94, a southward shift in the concentration of seismicity was noticed from Koyna to Warna reservoir*. Pore-pressure changes occur in the vicinity of a reservoir in response to lake-level changes. This change occurs in two ways; the rapid effect due to the undrained processes (rapid increase in pore pressure in response to load) and the delayed effects due to diffusion*. Although these processes are at work in the vicinity of almost all reservoirs, only at some locations do they lead to perceptible seismicity. The mechanism of reservoir triggered seismicity (RTS) is controlled by various factors like the ambient stress field, availability of faults/fractures, hydrogeologic properties of the medium and the hydraulic and spatial characteristics.

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