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Environmental significance of raised rann sediments along the margins of Khadir, Bhanjada and Kuar Bet islands in Great Rann of Kachchh, Western India

The harsh, inhospitable and difficult terrain of the Great Rann of Kachchh occupies almost half of the area of the seismically active Kachchh paleorift basin (Figure 1 *a*). Geomorphologically, the rann (meaning saline wasteland in local dialect) comprises a salt-encrusted flat expanse that is connected to the Arabian Sea to the west. The surface gets inundated by storm tides from the west and by annual monsoon precipitation while it presents itself as a dry, desolate, never-ending land devoid of life[1]. Historical accounts suggest that the rann was occupied by a shallow navigable sea[2]. This is also confirmed by the presence of several archaeological sites belonging to the Harappan civilization, including the port town of Dholavira located on the Khadir Island[3,4]. The upliftment of the rann surface and the subsequent drying up of the ranns are attributed to the recurrent seismic activity in the region[2,5–7]. Previous workers have described the Great Rann as 'intriguing' to 'without any counterpart in the world'[1,8]. However, no precise data exist about the geological evolution and environmental conditions of the Great Rann so far. The present study is an attempt to delineate the Holocene environmental conditions in the Great Rann based on the study of raised rann sediments occurring along the margins of the tectonically active and fault-bound Khadir, Bhanjada and Kuar Bet islands.

The rocky islands form part of the E–W trending linear series of islands called the Island belt, with rugged hilly topography rising above the flat, salt-encrusted rann surface. The Island belt consists of four major islands, viz. the Pachcham, Khadir, Bela and Chorar, and smaller ones like the Bhanjada island to the west of Khadir and the Kuar Bet island to the northwest of Pachcham island (Figure 1 *b*, *c*). Each major island is a discrete tilt block that exposes south-dipping Mesozoic and Neogene marine sedimentary rocks[9]. All islands are characterized by steep, north-facing escarpments which mark the geomorphic expression of the E–W trending Island Belt Fault (IBF) that lies buried under the rann sediments further north[10]. Geomorphic studies show a strong control of structural set-up on the landscape of these islands, and active titling in the recent past based on the raised notches and other marine erosional features at the base of the escarpments has been suggested[11]. The raised rann sediments occur all around the fringes of the islands and gradually slope away from the islands to imperceptibly merge with the rann surface. However, incised vertical cliffs comprising these sediments are found at the western margin of the Khadir, eastern margin of the Bhanjada and southern margin of the Kuar Bet island (Figure 2). The sediments form flat terraced surfaces whose continuity is broken by deep erosional gullies.

The three exposed cliff sections of the rann sediments in Khadir, Bhanjada and Kuar Bet islands were selected for the present study (Figure 2). Vertical lithologs of the sections were prepared and their sedimentary characteristics were noted by observing the entire length of the cliffs. For sampling, the exposed sections were trenched 1–1.5 m into the cliffs to eliminate the effect of contamination due to exposure to present conditions, including the ~1 m deep saline waters that flush the basal part of the sections during periods of inundation of the rann surface. All the three sections were sampled at 5 cm interval for micropalaeontological, sedimentological and mineralogical studies. For micropalaeontological studies, the selected samples were processed by following standard conventional methodology[12]. Almost 300 foraminiferal tests were picked from > 63 μm fraction from most of the samples, wherever possible. The generic-level identification was attempted using standard references[13]. Two samples each from Khadir and Bhanjada islands were dated by optically stimulated luminescence (OSL) technique. In the following paragraphs, we first describe the sedimentary characteristics of the raised rann sediments at each of these locations followed by the results of micropalaeontological analyses, chronology and palaeoenvironmental implications.

Vertical cliff section of raised rann sediments is found to occur along the western margin of the Khadir island (Figure 1 *b*). The section abruptly rises from the salt-encrusted surface of the Great Rann and abuts against the Mesozoic and Tertiary rocks inland ward (Figure 2 *a*). The sediments form a narrow, terraced surface that slopes down southwards, finally merging with the rann surface. The southward tilt of the surface is in conformity with the tilt structure of the island, which indicates active tilting during the Holocene[11]. The maximum thickness is ~5 m near Muchi at the northwestern tip of the island, where they directly rest over the Mesozoic rocks with ~20 cm thick pebbly gravel at the base. The overlying sediments show remarkable homogeneity in terms of grain size along with a strong

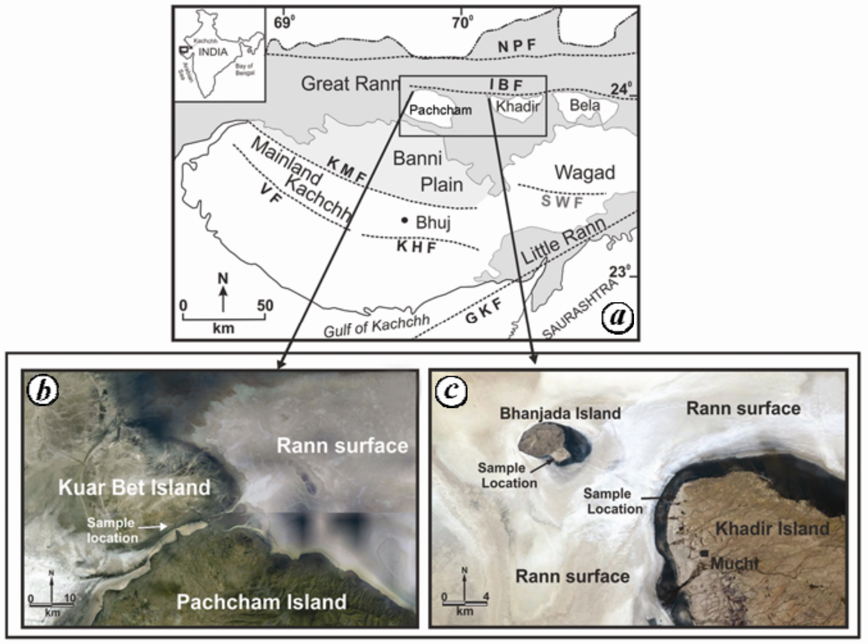

Figure 1. ***a***, Map of Kachchh basin showing the fault-controlled geomorphic set-up. Note the vast extent of the Great Rann forming the northern part of the basin. Unshaded areas are occupied by Mesozoic and Tertiary rocks. Boxed area shows the rocky islands of Pachcham and Khadir within the Great Rann. (Inset) Location map. ***b***, Satellite image of the northwestern part of Khadir and Bhanjada islands showing the location of the sections studied (source: www.googleearth.com). ***c***, Satellite image of the northwestern part of Pachcham and Kuar Bet island showing the location of the sections studied (source: www.googleearth.com).

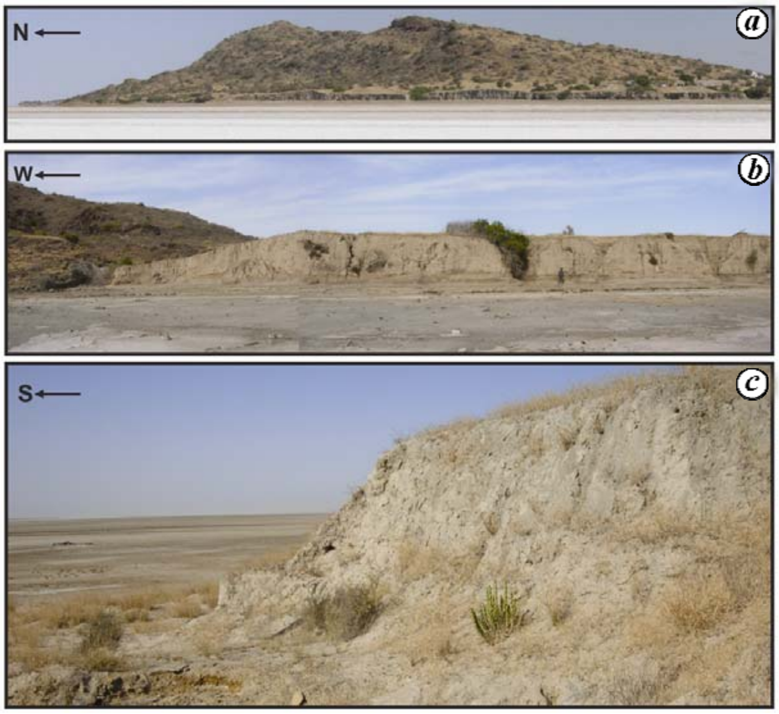

Figure 2. ***a***, View of the northwestern margin of the Khadir island. In the foreground is the salt-encrusted rann surface and the vertical cliff section of the raised rann sediments at the base of the island. The southward dips of the Mesozoic rocks forming the island are visible. ***b***, View of the southern cliff face of the raised rann sediments rising above the rann surface at the eastern fringe of the Bhanjada island. Part of the rocky island is visible to the left. ***c***, View of the raised rann sediments at the southern margin of the Kuar Bet island. Rann surface is seen in the background.

horizontal stratification. Lithologically the sediments range from silty sand to sandy silts, with clay as the minor component (Figure 3). Grain sizes is very fine and mainly comprises grains of quartz, mica, salts and few dark-coloured minerals. The grains show angular to subangular nature with moderate sorting. Quartz is angular in nature and so is the case with other minerals, except the salts. Mica is mainly in the form of muscovite flakes, but few biotite flakes are also observed. The salts are white-coloured and lenticular-to-discoidal in shape. Few nodular salt grains are also seen. Amongst salts, gypsum appears in the crystallized form as rosettes and large disc agglumates. The bottom ~ 0.5 m thick massive clay is devoid of any microfauna and contains gypsum crystals in large proportion. The clay is underlain by basal gravel.

The biotic component of the sediments in the Khadir island section includes benthic foraminiferal tests, tiny vegetative remains, ostracod shells, few gastropods and occasional pteropods. The foraminifera identified from the section include *Ammonia*, *Trochammina*, *Anomalinoides*, *Elphidium*, *Nonian* and *Epistominella*. *Ammonia* forms the monodominant genus throughout this section. The overall foraminiferal assemblage of the sequence indicates shallow marine environment. The vertical distribution of foraminifera throughout shows significant variations in the abundance of the foraminifera. Three zones are identified, viz. the maximum abundance zone, fluctuating abundance zone and the barren zone which is almost devoid of any fresh foraminiferal tests (Figure 4). The first zone (0– ~ 2 m) is characterized by the fine-grained sediments and the maximum abundance of foraminiferal tests with its maximum > 8,000/g to minimum up to 2,000/g. Morphologically, majority of the foraminiferal tests are small, rounded, trochospirally coiled or sometimes spherical. Most of the tests are intact and morphological features are well-preserved, suggesting *in situ* nature. The intermediate abundance zone (~2–3.5 m) is characterized by low abundance. This zone also shows mixing of the older, reworked foraminiferal tests with *in situ* tests. The older tests, derived from marine Tertiary rocks exposed inland, are relatively large-sized and are reworked as indicated by loss of morphological characters and pinkish to brownish-red colour. Although

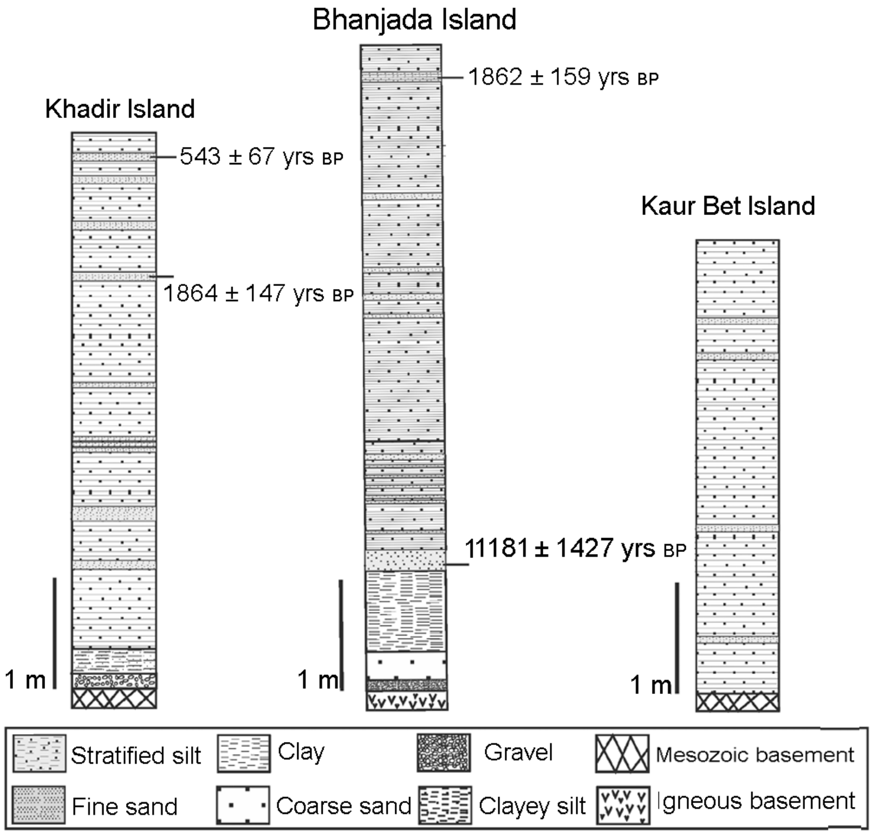

Figure 3. Lithologs of the raised rann sediments in Khadir, Bhanjada and Kuar Bet islands in the Great Rann. Note the dominantly fine-grained lithology and the similarity in gross lithology in all the three islands. OSL dates obtained are also shown.

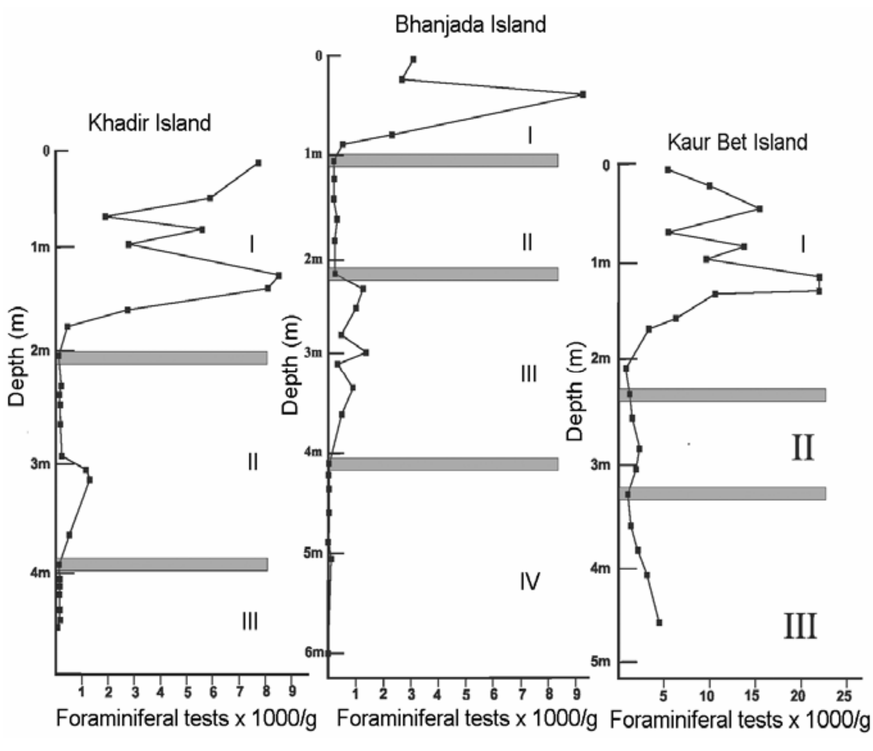

Figure 4. Graphs showing vertical distribution and abundance zones of foraminiferal tests throughout the cliff sections at Khadir, Bhanjada and Kuar Bet islands.

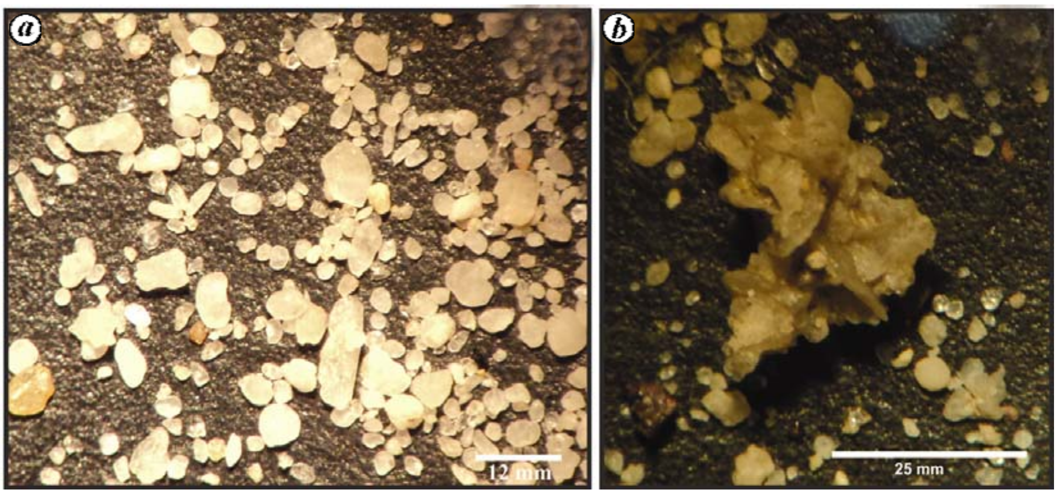

Figure 5. ***a***, Photomicrograph of the sediments showing discoidal and nodular gypsum crystals. ***b***, Photomicrograph showing discoidal gypsum forming large agglumates in the sediments.

the relative proportion of reworked foraminifera varies, their abundance is consistently less than the *in situ* tests. The third zone (below 3.5 m) is almost devoid of the *in situ* foraminiferal tests, but very few older foraminifera continue to occur. This zone is therefore identified as the barren zone.

The Bhanjada island is a small, rocky mass close to the western margin of the Khadir island and comprises basic intrusive igneous rocks[10]. The island is separated from the Khadir island by ~ 4 km stretch of salt-encrusted rann surface (Figure 1 *b*). The raised rann sediments form a rectangular-shaped terraced surface attached to the eastern margin of the Bhanjada island (Figure 1 *b*). However, the surface is uneven owing to the formation of small channels and gullies meeting the rann. Continuous vertical cliff sections are seen rising 3–4 m above the rann surface. Maximum exposed thickness of ~ 6 m is found preserved along the southern margin of the rectangular-shaped terraced surface (Figure 2 *b*). Visually, the sediment succession shows uniform characteristics with strong horizontal stratification and appears similar to the Khadir island section. Lithologically, the succession comprises alternate layers of silty sands and sandy silts with salt grains (Figure 5). Microscopic examination of the samples reveals the presence of quartz, salts and locally derived dark minerals and small amount of rock fragments. The quartz grains are subangular in nature, whereas the dark minerals are elongated. Micas comprise dominantly muscovite and lesser amount of biotite. Salt grains are of discoidal shape with infrequent lenticular shape present with gypsum rosettes and discoidal agglumates (Figure 5). The sediment succession overlies a basal gravel horizon whose clasts are derived from the igneous rocks that make up the Bhanjada island.

The microfauna recorded include benthic foraminifers, ostracods, gastropods and occasional pteropods. The microfaunal assemblages are similar to those of the Khadir island section, but show greater consistency vertically through the sequence. The foraminiferal assemblage recovered from the Bhanjada island section includes *Ammonia*, *Trochammina*, *Anomalinoides*, *Elphidium*, *Nonian* and *Epistominella*. *Ammonia* is the most dominant genus here as is the case with the sediments of Khadir island described above. The assemblage is indicative of shallow marine depositional environment. Based on the variations in vertical distribution of foraminifera, the Bhanjada island section is divisible into four zones of abundance, namely the zone of maximum abundance, the zone of intermediate abundance, the zone of fluctuating abundance and the zone of minimum abundance (Figure 4). The topmost zone is the zone of maximum abundance (0–1 m), which shows the highest number of tests (about 9,000/g). In this respect, this zone is comparable to the upper zone of the Khadir island section. The second zone is the zone of intermediate abundance (1–2 m depth), which shows less than thousand tests per gram of the sediments (Figure 4). The third zone (2–4 m depth) is identified as the zone of fluctuating abundance. This zone shows variation in the foraminiferal count from a few hundred to two thousand tests per gram sediment. The occurrence of the reworked foraminiferal tests is noted from the lower part of this zone. The abundance of the reworked older tests is relatively more compared to the Khadir island section. Since the Bhanjada island is made entirely of igneous rocks, the older foraminifera are obviously derived from the Tertiary rocks exposed in the nearby Khadir island. *In situ* foraminafera are small in size, but their morphology is well-preserved. Below 4 m is the zone of minimum abundance. Here, the abundance of *in situ* foraminiferal tests is reduced, but they continue to occur in association with the older foraminifera. The generic assemblage is similar to the Khadir island section. The similarity of the sediments and foraminiferal assemblage of the Khadir and Bhanjada islands points to identical depositional environments, which is also corroborated by the identical geomorphic settings of the sediments.

Kuar Bet is located northwest of the Pachcham island (Figure 1 *c*). A narrow stretch (~ 1.5 km) of the salt-encrusted surface of the Great Rann separates the Kuar Bet from the Pachcham island. The raised rann sediments form ~ 5 m high vertical cliffs dissected by gullies along the southern margin of the Kuar Bet island (Figure 2 *c*). The sediments overlie the Mesozoic sedimentary rocks. The sediments consist of horizontally stratified sandy silts and silty sands (Figure

3). Marginal variations in grain size and sorting are observed. Mineralogically, the sediments comprise quartz, mica with muscovite as the dominant mineral, and salt grains of dicoidal and nodular shape. In the basal part of the section, microscopic agglumates of the discoidal salts forming various shapes like elongate branched tubes are observed. Locally derived, fine lithic fragments are also common. The biotic content includes foraminifera, microscopic vegetative remains, ostracods, pteropods and gastropods with varying abundance.

The foraminiferal assemblage recovered from the Kuar Bet island section comprise *Ammonia*, *Trochammina*, *Anomalinoides*, *Elphidium*, *Nonian* and *Epistominella. Ammonia* continues to remain the dominant genus in the Kuar Bet section as well. However, the abundance of other genera is found to be relatively more compared to the Khadir and Bhanjada island sections. The overall assemblage is comparable with the Khadir and Bhanjada island sections. The morphology of the tests is well preserved and size of the foraminiferal tests is relatively larger than those found in the Khadir and Bhanjada island sections. Based on the foraminiferal relative abundances, the Kuar Bet section is vertically divisible into three zones – the upper zone (0–2.5 m), i.e. the zone of fluctuating abundance; the middle (2.5–3.5 m), i.e. zone of intermediate abundance, and the lower zone (below 3.5 m depth), i.e. the zone of increasing abundance (Figure 4). The foraminifera indicate conditions similar to those existing at the margins of the Khadir and Bhanjada islands, though the increased size of the tests and the relatively increased abundance of genera other than *Ammonia* suggest the existence of relatively favourable conditions for shallow brackish/marine benthic forms.

The Khadir and Bhanjada island sections were dated using OSL technique. Two samples were taken from each of these sections in opaque pipes. In the Khadir island section, the samples were collected at 0.20 and 1.80 m depths, whereas at Bhanjada island section, the samples were collected at 0.20 and 4.75 m depth. The two samples from the Khadir island section at 0.20 and 1.80 m depth yielded ages of 543 ± 67 BP and 1864 ± 147 yrs BP respectively. Samples from Bhanjada island section at 0.20 and 4.75 m depth yielded ages of 1862 ± 159 and 11181 ± 1427 yrs BP respectively. The OSL dates suggest uninterrupted sedimentation around the margins of the rocky islands in the Great Rann through Holocene up to ~ 500 yrs BP.

The geomorphic setting of the sediments and the fact that the rann surface is a now dried up palaeo-sea floor suggests that the sediments were deposited during Holocene along the shorelines of the rocky islands. The sediment succession comprises horizontally stratified sandy silts and silty sands with minor variations in grain size (Figure 3). Mineralogically, the sediments contain mainly quartz, mica (mainly muscovite), salts and few dark minerals. Salts occur in fairly large proportion in all the three sediment sections. The salts are obviously derived from the marine waters that previously occupied the rann surface, as there is no source for salts on the rocky islands. The salts comprise mainly discoidal and nodular grains of gypsum typically formed in marginal marine settings (Figure 5). Overall, the salt-rich sediments suggest the prevalence of hyper-saline conditions during their deposition.

The foraminiferal assemblage recovered from the three island sections is remarkably similar, which strongly point to the existence of similar environmental conditions along the margins of the islands. The foraminiferal assemblage is characterized by small-sized tests, low diversity and predominance of *Ammonia*. The recorded genera belong to typical shallow marine environment[14]. Relative abundance record shows that *Ammonia* contributes up to 80–85% of the total recovered foraminifera. *Ammonia* is known to be tolerant to wide range of temperatures[15] and salinity conditions[14–17]. *Trochammina* is another genus commonly found in marginal marine environments[18,19] and is also recorded from salt marshes[20,21]. The survival of *Trochammina* through low oxygenated conditions is also well documented[22,23]. *Elphidium* and *Nonian* are also characteristic genera of shallow marine environment[24] and tolerant to high-salinity conditions[25].

The overall foraminiferal assemblage and vertical variations in the abundance suggest hyper-saline to brackish conditions in the vicinity of the islands in the Great Rann. The variation in abundance of the foraminifera vertically through the sediment successions is significant (Figure 4). The graphs of abundance pattern in all the sections allow us to mark the different zones based on fluctuations in the absolute abundance of foraminiferal tests. We attribute the wide variations in abundance patterns of the foraminifera to changes in the salinity conditions. The salinity changes cannot be ruled out as there is a strong possibility of periods of enhanced freshwater influx from the adjacent land mass. The largely homogeneous nature and absence of discordant sedimentary depositional feature, or any abrupt termination or change in the nature of the sediments and the foraminiferal assemblage suggest that the conditions remained uniform with short-term fluctuations from brackish to hypersaline. These conditions persisted along the island margins for a long period of time during the Holocene. The geomorphic setting, homogenous sediment nature, and vertical distribution and abundance patterns of foraminifera suggest the existence of fluctuating conditions from brackish to hypersaline along the island margins during the deposition of the sediments.

The chronological data suggest an average sedimentation rate of ~ 1.22 mm/yr for the Khadir island and ~ 0.48 mm/yr for the Bhanjada island. The lower rate of sedimentation in the Bhanjada island is in conformity with the fact that the eastern margin formed a sheltered or a shadow zone when the shallow gulf occupied the Great Rann, which was connected to the Arabian Sea in the west. This is comparable with the present-day conditions in the Gulf of Kachchh in the southern part of Kachchh, where the sediments coming from the Arabian Sea in the west are distributed along its northern and southern coastlines[26]. Assuming a similar setting in the Great Rann, it is obvious that the eastern margin of the Bhanjada Island was located in the shadow zone that resulted in low rate of sedimentation. The sedimentation at Bhanjada island terminated at around 1860 yrs BP. However, no major shift in environmental conditions is indicated by the micropalaeontological data from the Khadir island, where the sedimentation continued up to ~ 500 yrs BP. We therefore infer that the geomorphic setting of the sediment-starved eastern margin of the Bhanjada island is primarily responsible for the early termination of sedimentation, rather than a change in environmental conditions. The elevation difference of the sediment successions in the Bhanjada and Khadir islands is attributed to the differential post-depositional uplift along the IBF and associated cross-faults[27].

The chronological data indicate that active marine sedimentation continued up to ~500 yrs BP. The OSL dates obtained are in conformity with historical accounts that describe ships reaching up to a port called Verawow in Nagar Parker hills located at the northern margin of the Great Rann, which was abandoned about ~500 years as the sea dried out[28]. This suggests the existence of a shallow but navigable sea that was responsible for the deposition of sediments along the shores of the rocky islands until ~500 yrs BP. We attribute the occurrence of rann sediments along the fringes of the rocky islands, described in the present study, at 5–6 m above the salt-encrusted rann surface to tectonic uplift of the islands along the IBF during the last ~500 years. The development of vertical cliff sections and deep erosional gullies formed over these sediments testify the tectonic uplift. The findings, though of preliminary nature, are significant and need to be correlated with similar studies from the central parts of the Great Rann, for which coring is essential to obtain samples for multiple parameter studies.

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