Evidence of Land-Sea Interaction during Mid-Late Holocene from Sedimentary Records, Western India

Upasana S. Banerji[1,✉], Ravi Bhushan[2], Shilpa Pandey[3]

[1] National Centre for Earth Science Studies, Thiruvananthapuram-695583, Kerala, India
[2] Physical Research Laboratory, Ahmedabad-380009, Gujarat, India
[3] Birbal Sahni Institute of Palaeosciences, Lucknow-226007, Uttar Pradesh, India
✉ upasana.s.banerji@gmail.com

Keywords: mid-late Holocene, Sea-level, tectonics, Saurashtra, Geochemical Proxies

1. Introduction

The investigation of Holocene sea level histories and coastal landscape responses can yield vital information on the coastal environment and future sea-level rise (Sloss et al., 2018). However, Holocene sea-level records are fraught due to lack of regional geological investigations and constraints in tectonic setting (tectonic upheaval or hydro-isostatic warping) of the coastal track (Williams et al., 1998). Such lacuna leads to discordance in the Holocene sea-level at the regional scale (Li et al., 2012). Further, on the contrary to the glacial-interglacial period, the mid-late Holocene Period remained deprived of drastic sea level variations. Thus, local or regional coastal tracts responded distinctly during the mid-late Holocene Period, which in turn demands localised sea-level curves instead of generalised sea level changes generated for other regions (Hashimi et al., 1995). However, based on the available local or regional sea level curve this can be collated to produce a generalised sea level variability. On the basis of coastal geomorphic features (Pant and Juyal, 1993; Rust and Kershaw, 2000), stable isotopic variation (Waelbroeck et al., 2002; Lamb, Wilson and Leng, 2006) and instrumental records (Douglas, 1991; Holgate, 2007) several studies have addressed sea level changes.

Sheltered coastal environments such as mudflats, estuaries, lagoons, bays, inlets, rias, and isolation basins are potential regions for preserving thick sequences of Holocene sediments and respond in accordance with the pace of sea level and coastal changes during the Holocene (Allen and Haslett, 2002). Several studies constraining Holocene sea level variability have conducted investigations on the intertidal region (Wilson et al. 2005; Zhan et al. 2011 and references therein). In the present study we conducted a geochemical investigation on the mudflats of Gujarat, Western India to address sea level variability and possible tectonic influences during the mid-late Holocene period.

2. Study Area

The coastal landscape of Saurashtra, western Gujarat, India is a result of both, eustatic sea level changes and tectonics (Ganpathi, Patel and Merh, 1982). The southern Saurashtra coast is marked by 40 to 50 m vertical cliffs of limestone. The coast is irregular and dissected further east up to Diu. The northeast of Diu Island consists of extensive tidal flats and the southern coast is cliffy. Beyond Diu, the coast is characterised by the presence of a rocky foreshore with occasional beaches and limestone cliffs. An extensive mudflat is located along the Saurashtra coast near Diu Island and Jaffrabad. The limestone (miliolitic) cliffs are located along the southern coast of Diu Island. The age of the miliolites was estimated to be of three generations: 200–140, 115–75, and 70–50 ka BP (Baskaran et al., 1986).

3. Material and methods

Both, relict Vasoj (VV) and active Diu (DV) mudflats (Fig. 1) located in the NE of Diu Island, near the southern Saurashtra coast, were investigated to study the Holocene sea-level changes along Saurashtra coast. Sampling details and chronology for VV and DV have been discussed in Banerji et al. (2015) and Banerji et al. (2017), respectively. The relict mudflat VV recorded a depositional history from 4700 to 1500 cal BP and the sedimentation ceased after 1500 cal BP (Banerji et al., 2015). The core location DV inundates and receives sediment only during exceptionally high tide and has recorded a depositional history between 4100 and 71 cal BP (Banerji et al., 2017).

The sediment samples from different depths of the VV relict section (~ 100 cm, ~ 10 samples) and DV sediment core (~ 70 cm, ~ 35 samples) were dried (at ~ 80 °C), crushed and homogenised with the help of an agate mortar to avoid any metallic contamination. The chronology of VV was estimated from three carbon-14 ages (Banerji et al., 2015), while in the case of DV, the chronology was supported by carbon-14, caesium-137, and lead-210 dating techniques (Banerji et al., 2017). Nearly 300 mg of bulk, dried

Proceedings of the 5th International YES Congress
DOI: 10.2312/yes19.07

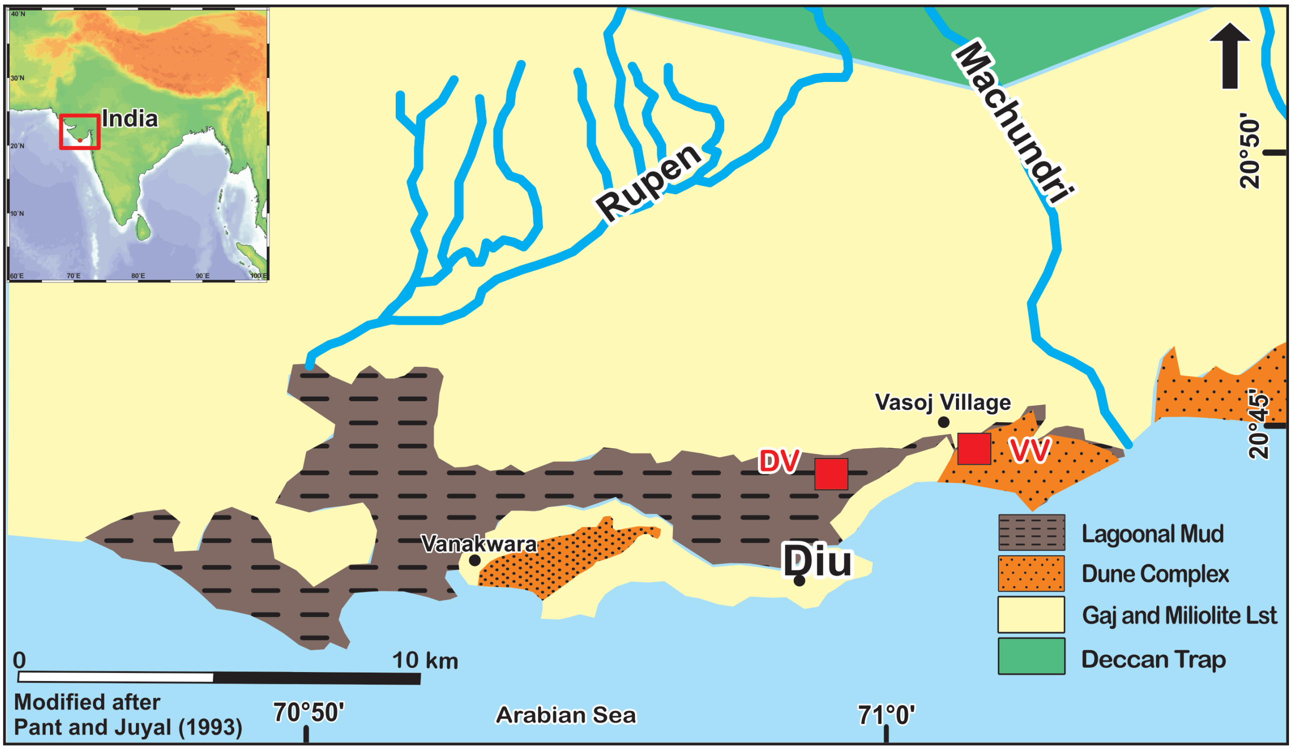

Figure 1: Map showing the geology of the relict (VV) and active (DV) mudflat region along the southern Saurashtra, Gujarat, western India.

crushed sediment samples were subjected to closed digestion (Thermo Microwave digestion system) by treating them with concentrated acids (HCl, HF, and HNO_3). The digested sample solution was aspirated in the ICP-AES (Jobin Yvon 38S) for the measurement of Al, and in the ICP-MS (Thermo-X series2) for the measurement of Mn, Ni, Mo, V, Cr, and Co. The analytical precision and accuracy were better than ±5 % for major and trace elements (Agnihotri, 2001; Banerji et al., 2017). The sediment samples for estimation of Total Organic Carbon (TOC) were decarbonated with 10% HCl and thoroughly washed with distilled water and dried. The TOC was estimated in FISONS NA1500 NC Elemental Analyzer (Fisons Inc.) by introducing ~ 10 to 20 mg decarbonated sediment samples packed in a tin capsule into a combustion tube through an auto-sampler. The analytical precision and accuracy for TOC were better than 4 % (Bhushan et al., 2001).

4. Results and Discussion

4.1. Geochemical Variations

Sediments record only a fraction of total biological productivity, as the organic matter that is delivered to the water-sediment interface passes through bacterial degradation within the water column (Tribovillard et al., 2006). Generally, mangrove forests in the intertidal region are extensively productive areas with high rates of organic carbon accumulation (Kristensen et al., 2008; Marchand, Lallier-Vergès and Allenbach, 2011). High TOC during 4710 to 3200 cal BP in VV (Fig. 2a) suggests improved productivity associated with extensive mangrove forests that flourished in the region due to high sea level and enhanced monsoon intensities (Banerji et al., 2015). A similar observation of high productivity supported by TOC, Cu/Al_2O_3, and Ni/Al_2O_3 during 4105 to 2640 cal BP with high sea level has been delineated from DV (Banerji et al., 2017).

The simultaneous enrichment of V/Al_2O_3 and Mo/Al_2O_3 (Fig. 2a) in the VV section during 4710 to 4000 cal BP implies anoxic conditions, but depleted values for Ni/Al_2O_3 suggests that Ni is not scavenged by settling organic particles (Tribovillard et al., 2006). The marginal increase of Ni/Al_2O_3 observed between 4000 and 3200 cal BP indicates the possible formation of insoluble sulphides that can be taken up by authigenic pyrite (Algeo and Maynard, 2004) and thereby suggests euxinic conditions (Banerji, Bhushan and Maurya, 2016). The prevalence of euxinic conditions in VV is further supported by the increasing trend in Mo/Al_2O_3 and V/Al_2O_3, as V resides predominantly in the sulfidic fraction under euxinic conditions (Algeo and Maynard, 2004). However, the simultaneous enrichment of V/Al_2O_3 and TOC with low values in Mo/Al_2O_3 in DV (Fig. 2b) during 4100 to 3000 cal BP suggests anoxic conditions (non-sulfidic), as the V mainly resides in TOC (Algeo and Maynard, 2004).

Under anoxic conditions, Cr^{4+} reduces to Cr^{3+} forming aquahydroxyl and hydroxyl cations that readily form a complex with humic/fluvic acids or gets adsorbed to Fe- and Mn-oxyhydroxides (Breit and Wan-

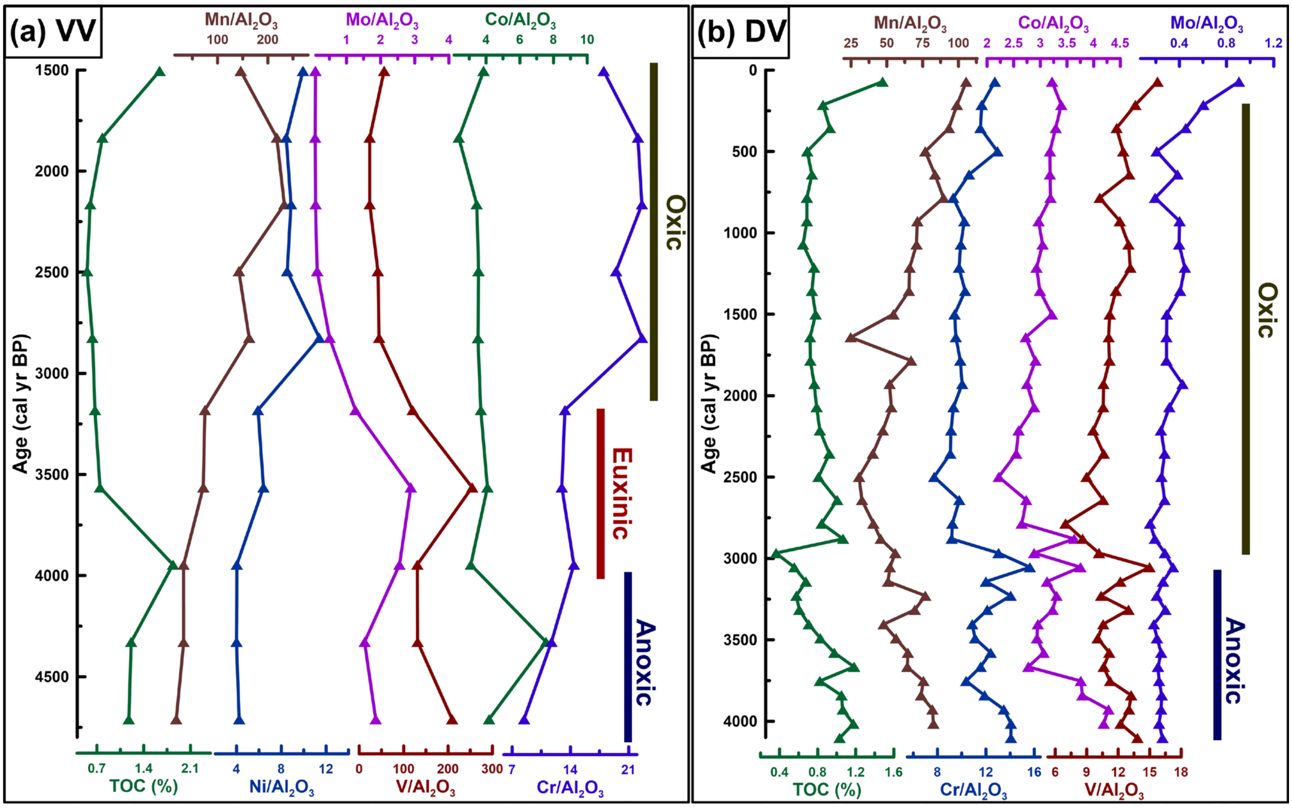

Figure 2: Enriched redox sensitive elements in VV (a) and DV (b) mudflat sections during 4710 to 4000 cal BP and 4100 to 3200 cal BP suggests anoxic conditions, while an intermittent euxinic environment during 4000 to 3200 cal BP prevailed in VV. Since 3000 cal BP, both regions (VV and DV) witnessed oxic conditions.

ty, 1991; Algeo and Maynard, 2004). In DV, the high Cr/Al_2O_3 during 4100 to 3000 cal BP suggests anoxic conditions. But the low Cr/Al_2O_3 in VV during 4000 to 3200 cal BP (Fig. 2b), in spite of the euxinic conditions, has been attributed to the limited uptake of Cr^{3+} by Fe-sulphides due to the incompatibility of Cr with pyrite (Huerta-Diaz and Morse, 1992; Morse and Luther, 1999). Under anoxic conditions, Co forms insoluble sulphides (CoS), which are taken up as solid solution by authigenic Fe-sulphides (Huerta-Diaz and Morse, 1992). Thus, the increased Co/Al_2O_3 in VV and DV confirms the prevalence of oxygen-deficient/ anoxic conditions in the region.

Surprisingly, Mn/Al_2O_3 is low in VV but high in DV, even though both witnessed anoxic conditions. Generally under anoxic conditions, Mn reduces to Mn^{2+}, which is a soluble cation (Mn^{2+} or $MnCl^{+}$). As the dissolved Mn is not readily taken up by the organic matter or sulphide phase, it diffuses upwards till oxic conditions are encountered. The reduced Mn/Al_2O_3 in the DV suggested the prevalence of anoxic conditions. However, the increased Mn/Al_2O_3 in VV under anoxic conditions must be a result of the formation of $MnCO_3$ or Mn-Ca carbonate (Calvert and Pedersen, 1993). The possible formation of $MnCO_3$ or Mn-Ca carbonate can be confirmed from the high values of CaO, $CaCO_3$, and CaO/Al_2O_3 (Banerji et al., 2017, 2019).

4.2. Evidence of tectonic uplift

The southern Saurashtra coast has provided evidence of past sea level highstands and tectonic imprints (Pant and Juyal, 1993; Juyal et al., 1995). The palynological investigation of the VV section suggests high sea level with dense mangrove forest during 4710 cal BP. The mangrove forest led to anoxic conditions in VV, which is in agreement with the enriched redox-sensitive elements in the DV core, as they were part of the same lagoon. The present day elevation of VV and DV are ~ 5 m and ~ 3 m respectively and both witnessed a high sea level during 4710 to 1500 cal BP. The marine influence in VV ceased after 1500 cal BP, whereas the DV continued to receive sediment under exceptionally high tide conditions. Thus, there was a sea regression of ~2 m during 4710 cal BP. The estimated high sea level is in line with the radiocarbon age of an oyster bed (3.4 ± 0.05 ka) located at an elevation of 2 m above the present-day sea-level in Rupen River near Diu (Juyal et al., 1995). However, the sea level during the mid-Holocene could be an interplay of sea level and land level changes, as the southern Saurashtra coast near Diu and adjoining areas witnessed pulsating uplift during the late Quaternary period (Pant and Juyal, 1993). The prevalence of a tectonic component during the last 3 ka was inferred by the study conducted on the tidal notches around Diu Island (Bhatt and Bhonde, 2006). Further, two tidal notches of Diu Island were examined near Vankwara (Diu), which suggested ~1 m of tectonic uplift (Banerji et al., 2015). This implies that the effective sea-level was ~2 m high during the ~4710 cal BP, which included ~1 m of tectonic uplift (Banerji et al., 2015).

4.3. Phases of sea level and tectonics along southern Saurashtra coast

The present study interprets four phases of transformation of the coastal lagoon into mudflat during the mid-Holocene period along the southern Saurashtra coast. The palynological investigation on the relict mudflat section VV demonstrated several mangrove species (Banerji et al., 2015), while the presence of shells in DV (Banerji et al., 2017) suggested high sea level during 4710 to 4000 cal BP.

The presence of mangroves led to high *in-situ* productivity resulting in anoxic conditions as seen from the enriched redox-sensitive elements (Fig. 3a). Thus, a lagoonal condition prevailed at both study locations and they formed part of a single lagoon system. Marginal sea regression during 4000 to 3200 cal BP led to poor water ventilation at VV site resulting in euxinic conditions, but the anoxic condition continued till 3200 cal BP at DV (Fig. 3b). Further sea regression after ~3200 cal BP transformed the lagoon into a mudflat region as the VV showed the presence of Turritella sp. between 3200 and 2825 cal BP (Fig. 3c) (Banerji, Bhushan and Maurya, 2016; Banerji et al., 2015) and the oxic conditions started prevailing in both locations (VV and DV). The sea regression after 3200 cal BP was also accompanied by a tectonic uplift which can be elucidated from the elevation of the older tidal notch of Vanakwara (Diu Island). The VV mudflat remained active till 1500 cal BP after which sediment deposition ceased due to sea regression and/or tectonic uplift, while DV continued to receive sediment under exceptionally high tide conditions (Fig. 3d). The sea regression and transformation of the lagoon to mudflat was accompanied by tectonic uplift in the region.

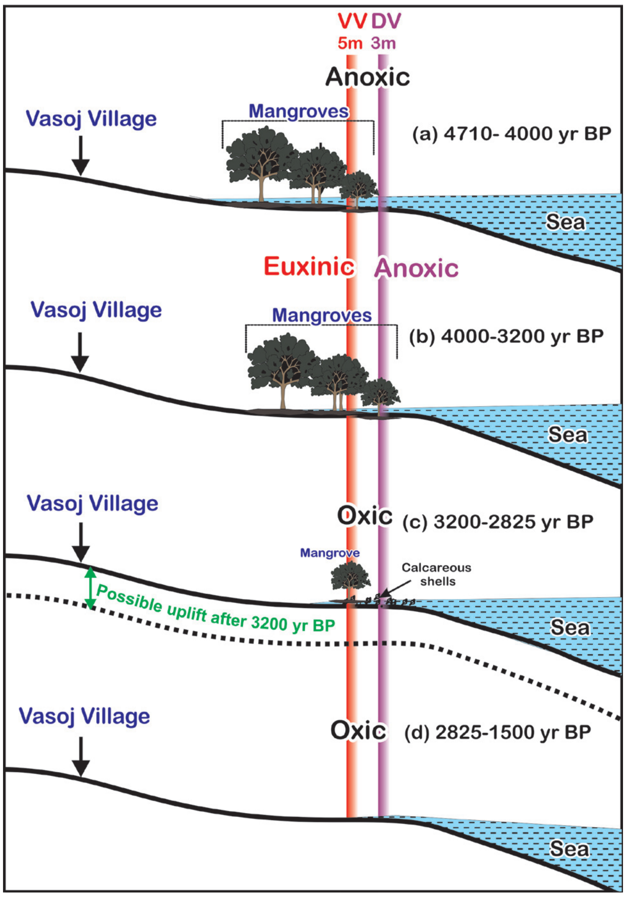

Figure 3: A schematic drawing of changing redox conditions at VV and DV locations wherein (a) the coastal lagoon with anoxic conditions prevailed due to high sea level and mangrove forest during 4710 to 4000 cal BP. (b) Gradual sea regression resulted in euxinic and anoxic conditions at VV and DV till 3200 cal BP, respectively. (c) An upliftment accompanied by sea regression transformed the coastal lagoon into a mudflat causing an oxic environment after 3200 cal BP. (d) A possible tectonic/sea regression after ~ 1500 cal BP terminated the sedimentation at VV.

5. Conclusions

The present study attempts to identify mid-late Holocene sea-level change accompanied by a tectonic component. The study demonstrated that the high sea level led to the prevalence of lagoonal conditions behind the barrier bars of the southern Saurashtra coast during 4710 cal BP. The high sea level supported the extensive mangrove forests thereby leading to an anoxic environment during 4710 to 4000 cal BP. Later, the sea regression leading to poor water ventilation at VV caused the prevalence of euxinic conditions, but the DV continued to witness an anoxic environment. After 3200 cal BP, both sites were transformed from lagoon to mudflats as a result of sea regression and tectonic influence. Further, sea regression and/or tectonic uplift after 1500 cal BP transformed VV region into a relict mudflat while DV continued receiving sediment under exceptionally high tides. Thus, the present coastal configuration was attained possibly after ~1500 cal BP and since then the coast seems to be stable. Nevertheless, other mudflats of coastal Saurashtra need to be investigated to ascertain the mid-late Holocene sea level fluctuations along with the tectonic components and should be compared with other regional and global coastal environments to generate a sea level curve exclusively for the mid-late Holocene Period.

6. References

Agnihotri, R., 2001. Chemical and Isotopic studies of sediments from Arabian sea and Bay of Bengal. PhD thesis. Faculty of Science. Mohanlal Sukhadia University. 131 pp.

Algeo, T.J. and Maynard, J.B., 2004. Trace-element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems. Chemical Geology 206(3), pp. 289–318. https://doi.org/10.1016/j.chemgeo.2003.12.009.

Allen, J.R.L. and Haslett, S.K., 2002. Buried salt-marsh edges and tide-level cycles in the mid-Holocene of the Caldicot Level (Gwent), South Wales, UK. The Holocene 12(3), pp. 303–324. https://doi.org/10.1191/0959683602hl537rp.

Banerji, U.S., Bhushan, R. and Jull, A.J.T., 2017. Mid-Late Holocene monsoonal records from the partially active mudflat of Diu Island, Southern Saurashtra, Gujarat, Western India. Quaternary International 443, pp. 200–210. https://doi.org/10.1016/j.quaint.2016.09.060.

Banerji, U.S., Bhushan, R. and Jull, A.J.T., 2019. Signatures of global climatic events and forcing factors for the last two millennia on the active mudflats of Rohisa, southern Saurashtra, Gujarat, western India. Quaternary International 507, pp. 172–187. https://doi.org/10.1016/j.quaint.2019.02.015.

Banerji, U.S., Bhushan, R. and Maurya, D.M., 2016. Sedimentary records of paleoredox conditions at relict mudflat of Vasoj, Southern Saurashtra coast, Gujarat. Earth Science India 9(II), pp. 114–125. https://doi.org/10.31870/ESI.09.2.2016.5.

Banerji, U.S., Pandey, S., Bhushan, R. and Juyal, N., 2015. Mid-Holocene climate and land-sea interaction along the southern coast of Saurashtra, western India. Journal of Asian Earth Sciences 111, pp. 428–439. https://doi.org/10.1016/j.jseaes.2015.06.021.

Baskaran, M., Marathe, A.R., Rajaguru, S.N. and Somayajulu, B.L.K., 1986. Geochronology of palaeolithic cultures in the Hiran Valley, Saurashtra, India. Journal of Archaeological Science 13(6), pp. 505–514. https://doi.org/10.1016/0305-4403(86)90037-3.

Bhatt, N. and Bhonde, U., 2006. Geomorphic expression of late Quaternary sea level changes along the southern Saurashtra coast, western India. Journal of Earth System Science 115(4), pp. 395–402. https://doi.org/10.1007/BF02702868.

Bhushan, R., Dutta, K. and Somayajulu, B.L.. L.K.K., 2001. Concentrations and burial fluxes of organic and inorganic carbon on the eastern margins of the Arabian Sea. Marine Geology 178(1–4), pp. 95–113. https://doi.org/10.1016/S0025-3227(01)00179-7.

Breit, G.N. and Wanty, R.B., 1991. Vanadium accumulation in carbonaceous rocks: a review of geochemical controls during deposition and diagenesis. Chemical Geology 91(2), pp. 83–97. https://doi.org/10.1016/0009-2541(91)90083-4.

Calvert, S.E. and Pedersen, T.F., 1993. Geochemistry of recent oxic and anoxic marine sediments: Implications for the geological record. Marine Geology 113(1–2), pp. 67–88. https://doi.org/10.1016/0025-3227(93)90150-T.

Douglas, B., 1991. Global sea level rise. Journal of Geophysical Research 96(C4), pp. 6981–6992. https://doi.org/10.1029/91JC00064.

Ganapathi, S., Patel, M.P., Merh, S.S., 1982. Evolution of the coastline between okha-madhi and Kodinar, western Saurashtra with special reference to Quaternary morphology and sedimentation, in: Merh, S.S. (Ed.), Geology and Geomorphology of Quaternary Terrains of Gujarat with Special Reference to Coastline Evolution. M.S. University of Baroda, Vadodara, pp. 95–122.

Hashimi, N.H., Nigam, R., Nair, R.R., Rajagopalan, G., 1995. Holocene sea level fluctuations on western Indian continental margin: an update. Geological Society of India 46, pp. 157–162.

Holgate, S.J., 2007. On the decadal rates of sea level change during the twentieth century. Geophysical Research Letters 34(1), L01602. https://doi.org/10.1029/2006GL028492.

Huerta-Diaz, M.A. and Morse, J.W., 1992. Pyritization of trace metals in anoxic marine sediments. Geochimica et Cosmochimica Acta 56(7), pp. 2681–2702. https://doi.org/10.1016/0016-7037(92)90353-K.

Juyal, N., Pant, R.K., Bhushan, R. and Somayajulu, B.L.K., 1995. Radiometric dating of late Quaternary sea levels of the Saurashtra coast, Western India: An experiment with oyster and clam shells. Geological Society of India Memoir 32, pp. 372–379.

Kristensen, E., Bouillon, S., Dittmar, T. and Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: A review. Aquatic Botany 89(2), pp. 201–219. https://doi.org/10.1016/j.aquabot.2007.12.005.

Lamb, A.L., Wilson, G.P. and Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. Earth-Science Reviews 75(1), pp. 29–57. https://doi.org/10.1016/j.earscirev.2005.10.003.

Li, Z., Saito, Y., Mao, L., Tamura, T., Song, B., Zhang, Y., Lu, A., Sieng, S. and Li, J., 2012. Mid-Holocene mangrove succession and its response to sea-level change in the upper Mekong River delta, Cambodia. Quaternary Research 78(2), pp. 386–399. https://doi.org/10.1016/j.yqres.2012.07.001.

Marchand, C., Lallier-Vergès, E. and Allenbach, M., 2011. Redox conditions and heavy metals distribution in mangrove forests receiving effluents from shrimp farms (Teremba Bay, New Caledonia). Journal of Soils and Sediments 11(3), pp. 529–541. https://doi.org/10.1007/s11368-010-0330-3.

Morse, J.W. and Luther, G.W., 1999. Chemical influences on trace metal-sulfide interactions in anoxic sediments. Geochimica et Cosmochimica Acta 63(19), pp. 3373–3378. https://doi.org/10.1016/S0016-7037(99)00258-6.

Pant, R.K. and Juyal, N., 1993. Late Quaternary coastal instability and sea level changes: New evidence from Saurashtra coast, Western India. Zeitschrift für Geo-morphologie N.F. 37, pp. 29–40.

Rust, D. and Kershaw, S., 2000. Holocene tectonic uplift patterns in northeastern Sicily: evidence from marine notches in coastal outcrops. Marine Geology 167(1), pp. 105–126. https://doi.org/10.1016/S0025-3227(00)00019-0.

Sloss, C.R., Nothdurft, L., Hua, Q., O'Connor, S.G., Moss, P.T., Rosendahl, D., Petherick, L.M., Nanson, R.A., Mackenzie, L.L., Sternes, A., Jacobsen, G.E. and Ulm, S., 2018. Holocene sea-level change and coastal landscape evolution in the southern Gulf of Carpentaria, Australia. Holocene 28(9), pp. 1411–1430. https://doi.org/10.1177/0959683618777070.

Tribovillard, N., Algeo, T.J., Lyons, T. and Riboulleau, A., 2006. Trace metals as paleoredox and paleoproductivity proxies: An update. Chemical Geology 232(1–2), pp. 12–32. https://doi.org/10.1016/j.chemgeo.2006.02.012.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E. and Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quaternary Science Reviews 21(1–3), pp. 295–305. https://doi.org/10.1016/S0277-3791(01)00101-9.

Williams, M., Dunkerley, D., Deckker, P.D., Kershaw, P., Chappell, J., 1998. Quaternary Environments. Arnold, London, 329 pp. https://doi.org/10.1002/1099-1417(200009)15:6<662::AID-JQS576>3.0.CO;2-3.

Wilson, G.P., Lamb, A.L., Leng, M.J., Gonzalez, S. and Huddart, D., 2005. $\delta^{13}C$ and C/N as potential coastal palaeoenvironmental indicators in the Mersey Estuary, UK. Quaternary Science Reviews 24(18–19), pp. 2015–2029. https://doi.org/10.1016/j.quascirev.2004.11.014.

Zhan, Q., Wang, Z., Xie, Y., Xie, J. and He, Z., 2011. Assessing C/N and $\delta^{13}C$ as indicators of Holocene sea level and freshwater discharge changes in the subaqueous Yangtze delta, China. The Holocene, 22(6), p. 697–704. https://doi.org/10.1177/0959683611423685.