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Characterization of paleotsunami deposits along the western coast of India

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Sedimentary deposits bearing potential paleotsunamis and/or cyclonic-storm records were studied along the western shoreline of India using a multi-proxy approach, as this helps to better assess the source of the wave(s).

The northern Arabian Sea hosts a major tsunamigenic source, i.e. the Makran Subduction Zone (MSZ), which has produced instrumental, historical and paleo-period tsunami waves that have caused damage on the shorelines of western India, Pakistan, Iran, and Oman (Fig. 1a). However, the shoreline of western India in this context has remained unexplored. The western coast of India, owing to its varied geomorphology (rocky coastline to sandy beaches/mudflats) has been impacted by past tsunamis; those footprints are preserved in the form of boulder blocks to sand sheets deposited far inland from the present-day shoreline (Bhatt et al. 2016; Prizomwala et al. 2015, 2018, 2021, 2022). Although the recurrence and larger catalog for the Holocene period are yet to be completed, the evidence of several major tsunamis generated by MSZ has been discussed briefly in recent literature (Prizomwala et al. 2021).

One problem in the study of sandy onshore deposits is that tsunamis are difficult to distinguish from storm deposits (Gouramanis et al. 2024; Yap et al. 2021). However, a combination of multi-proxy techniques can help to better assess the origin of the wave(s) that lead to the sedimentary deposit in question. This paper highlights the use of multi-proxy records in sand deposits to distinguish tsunamigenic sources from other coastal processes, most notably the cyclonic storms, on the western Indian shoreline. The coastlines of Kachchh and southwestern Saurashtra show beach-ridge dune-type assemblages suitable for preserving signatures of such events. Thus, they were used as study sites for the investigation of past extreme events (Fig. 1b).

Tsunami and storm deposits: Process, source, and character

Tsunamis can erode the seabed due to their high energy, and transport the eroded sediment in suspension onshore (supratidal regime). While receding after the maximum inundation, a significant part of the sediment/debris load is often deposited, while a minor part is transported offshore (Fig. 1b). Apart from tsunami waves, cyclonic storm surges also possess a similar character; however, they are of relatively lower intensity compared to tsunami waves. Storm surges are also often known to erode the seabed, but at relatively shallower depths (<10–20 m). Hence, the sedimentary deposits of a tsunami differ from a storm, or other coastal process-derived deposits, by 1) their inland extent; 2) the presence of deeper sediment and fauna; and 3) the chaotic nature of the deposits (debris filled, lack of sorting) (Chagué-Goff et al. 2011; Dawson and Stewart 2007; Kortekaas and Dawson 2007; Morton et al. 2007; Prizomwala et al. 2018). However, several storms (e.g. Typhoon Haiyan in 2013) deposited sediments with similar characteristics to those from tsunamis, making them more challenging to distinguish (Soria et al. 2017). Therefore, it is crucial to assess the recorded (instrumental) storm history of a region together with a probable worst-case scenario (most intense storm and its characteristics), while comparing and assessing a probable tsunami-deposit inference.

Multi-proxy record of sedimentary deposits from the western coastline of India

Sediment geochemical proxies can be very reliable for discriminating different source signals, particularly when there is a mixing of tsunami-derived sand and local processes (Chagué-Goff 2010; Prizomwala et al. 2018, 2022; Srinivasalu et al. 2008). For example, the sand derived from shallower offshore sand shoals in the Gulf of Kachchh off the Pindara (site-P) and Kachchh (site-M) coastline comes from the Deccan Basalts (Fig. 2a). These sediments are richer in Fe_2O_3, TiO_2, Zr and Sr, owing to their provenance from the Deccan Basalts (see Prizomwala et al. 2018 for details). Their higher concentration in $CaCO_3$ is due to the high content of broken shells and foraminifera in sandy sediments, which are likely derived from offshore erosion. Previous researchers have inferred that these sands were eroded during historically known tsunami events, such as the 1945 CE tsunami event and the 1008 CE event along the MSZ, and deposited in the form of a sand layer at the Pindara (site-P) and Kachchh (site-PJ & M) coastlines (Prizomwala et al. 2018, 2022). The geochemical signatures are a useful tool for linking offshore geological provenance to the sand layer deposited inland, owing to the extreme event. For the Kachchh coast in particular, the sediments from the Deccan Basalts overwhelms the signature in inferred tsunami sand horizons.

The onshore (landward) extent of sedimentary deposits is one of the most common approaches for distinguishing a tsunami deposit from a probable storm surge deposit (Kortekaas and Dawson 2007; Morton et al. 2007; Prizomwala et al. 2018, 2022). The coastal remnants of the deposits along the Pindara (site-P) coast are observed in the form of sand sheets, reaching up to 580 m inland from the high-water line (HWL) (Fig. 2b). The sand-sheet geometry was probed using multiple shallow pits across the coast. Available records of the most intense storms in the Arabian Sea show a much more limited spatial extent in their inland sediment transport deposit (Prizomwala et al. 2018).

The sedimentological signature of these tsunamis is characterized by the lack of sorted grains, with overall landward fining along with the presence of mud intraclasts, broken shell and foraminifera. These observations demonstrate the high-energy wave

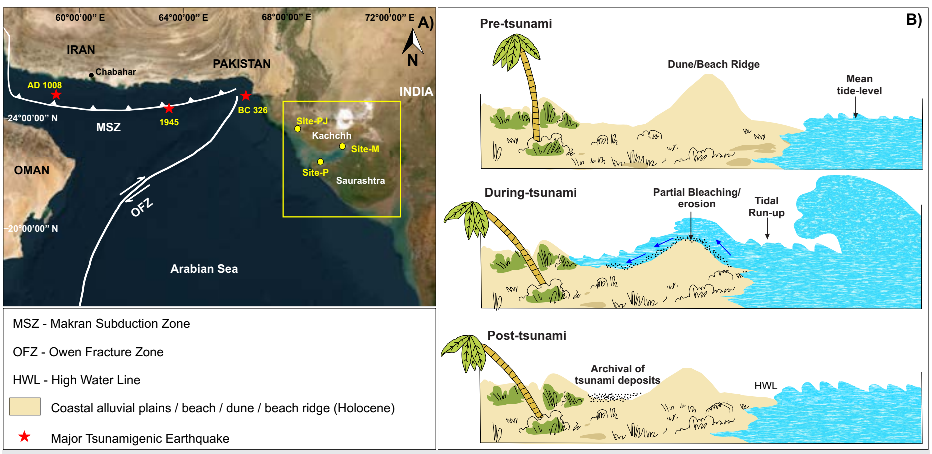

Figure 1: (A) Tectonic setup of the northern Arabian Sea with tsunamigenic sources. **(B)** Schematic scenario for a pre-, during- and post-tsunami event, along a with beach-ridge-dune configuration.

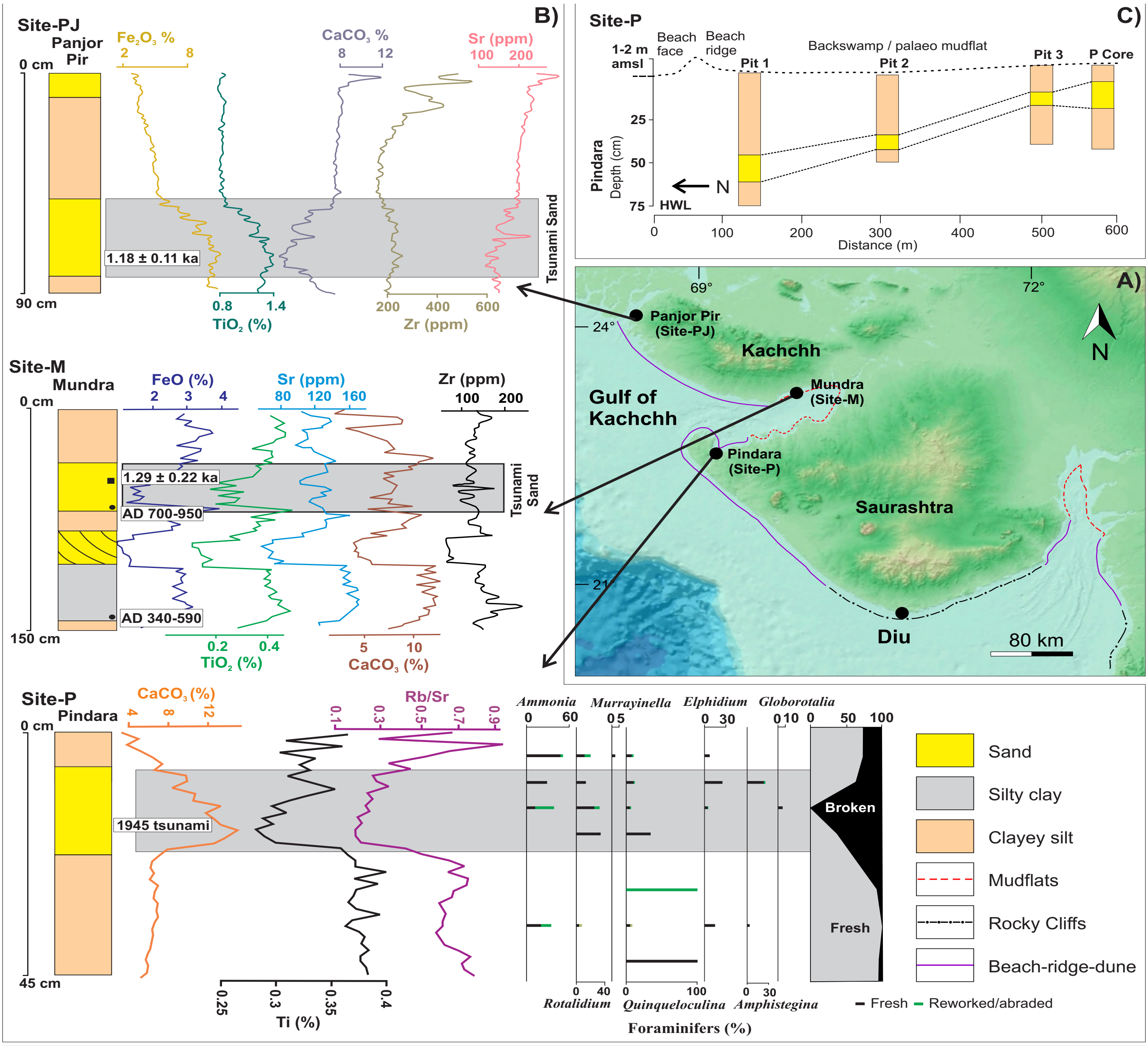

Figure 2: (A) Inset shaded relief map of Gujarat (western India). **(B)** Temporal geochemical and foraminiferal distribution of sedimentary deposits at sites P, PJ and M. **(C)** An onshore extent of tsunami sand layer with across-coast profile of site-P.

character, which essentially eroded the bottom of the offshore seabed (Kortekaas and Dawson 2007; Morton et al. 2007; Shanmugam 2012). Storms, on the other hand, exhibit a comparably better sorting, the absence of mud-intraclasts and the presence of several sedimentary structures. The increase in benthic foraminiferal diversity, and the presence of species occurring offshore, consolidates the assumption of the tsunami origin of these sand layers (Chagué-Goff et al. 2011; Prizomwala et al. 2022).

Outlook

The debate regarding the differentiation of sedimentary deposits from tsunami and cyclonic storm surges from the Arabian Sea requires an investigation of more modern analogues (e.g. Gonu, the only super cyclone in the instrumental history of the Arabian Sea, which occurred in 2007). There is a need to study more of these past tsunamigenic events from the Arabian Sea in order to build a catalog spanning at least the Holocene period. Similarly, compared to tsunamis, the available data of storms is extremely limited and needs to be augmented using geological records. More robust and complete information regarding the extent, type and nature of super cyclonic storm-surge deposits would help to assess the threshold for differentiating both wave types. Such information is a prerequisite for a better coastal hazard assessment, which is crucial for the safety of the fast-developing coastal infrastructure. A multi-proxy approach involving sedimentology, geochemistry, micropaleontology, and the landward extent of the deposits plays a vital role in determining the source of the wave(s).

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