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Geochemical signatures up to the maximum inundation of the 2011 Tohoku-oki tsunami — Implications for the 869 AD Jogan and other palaeotsunamis

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ABSTRACT

The geochemical signature of the Tohoku-oki tsunami deposit and underlying soil was assessed two months, five months and seven months after the 11 March 2011 tsunami inundated the Sendai Plain. The extent of the recognisable sand deposit was traced up to 2.9 km inland while a mud deposit was found up to 4.65 km inland, representing 60% and nearly 95% of the maximum tsunami inundation, respectively. The limit of tsunami inundation was identified 4.85 km from the shore using geochemical marine markers (S and Cl) two months after the tsunami, in the absence of any sedimentological evidence. Concentrations of other geochemical markers (K, Ca, Sr) indicative of the marine incursion and associated minerals were found to decrease landward. $\delta^{13}C$ and $\delta^{15}N$ and C/N ratios suggested a mixture of terrestrial and marine organic sources in the sediment, while $\delta^{34}S$ of sulphate reflected the marine source of water soluble salts. The chemical composition of the 869 AD Jogan tsunami sand deposit was characterised by high Sr and Rb concentrations and was comparable to that of the Tohoku-oki tsunami deposit, suggesting that the sources of sediment may be similar. Marked decreases in S and Cl with time indicated that rainfall resulted in the leaching of salts from the sandy sediments. However, both S and Cl markers as well as Sr were still well preserved in the muddy sediments and underlying soil beyond the limit of the recognisable sand deposit seven months after the tsunami. This suggests that geochemical indicators may well be useful in identifying the extent of historical and palaeotsunamis by determining the marine origin of fine grained sediments beyond the limit of recognisable sand deposition, in particular when marine microfossils are sparse or lacking as is the case on the Sendai Plain. This would allow researchers to redraw palaeotsunami inundation maps and re-assess the magnitude of events such as the Jogan tsunami and other palaeotsunamis, not only on the Sendai Plain but also elsewhere around the world. This has important implications for tsunami risk assessment, hazard mitigation and preparedness.

1. Introduction

Researchers study modern tsunamis as analogues for earlier events, using the knowledge gained through these investigations to better understand the nature and extent of their predecessors. The 11 March 2011 Tohoku-oki tsunami is just such an example. The tsunami generated by the M_W9.0 megathrust earthquake off the East Coast of Japan (Fig. 1a) (e.g. Ozawa et al., 2011) devastated hundreds of kms of the Pacific Coast of Honshu, reaching more than 5 km inland in some areas of the Sendai Plain (Mori et al., 2012). However, the recognisable sand deposit (>0.5 cm thick) did not extend inland to the maximum point of inundation. For example, just to the north of Sendai airport it was found only up to 2.8–2.9 km inland (Goto et al., 2011; Chagué-Goff et al., 2012–this issue, this study). Analysis of water leachable ions revealed that tsunami inundation reached 4.85 km in this area, beyond Tobu Highway (Chagué-Goff et al., 2012–this issue), in agreement with the inundation limit mapped by survey teams immediately after the event (Association of Japanese Geographers, 2011). So the question arises: could we use geochemical markers to assess the true limit of palaeotsunami inundation, since using the inland extent of sand deposits seems likely to result in what could be significant underestimates of tsunami inundation and by association, the magnitude of the generating event (Goto et al., 2011).

At least four tsunamis up to 3800 years old are preserved in the sediments of the Sendai Plain (Sawai et al., 2008). One of these, and the best studied, is the 869 AD Jogan tsunami (e.g. Minoura et al., 2001; Sugawara et al., 2011). The characteristics of the deposit are

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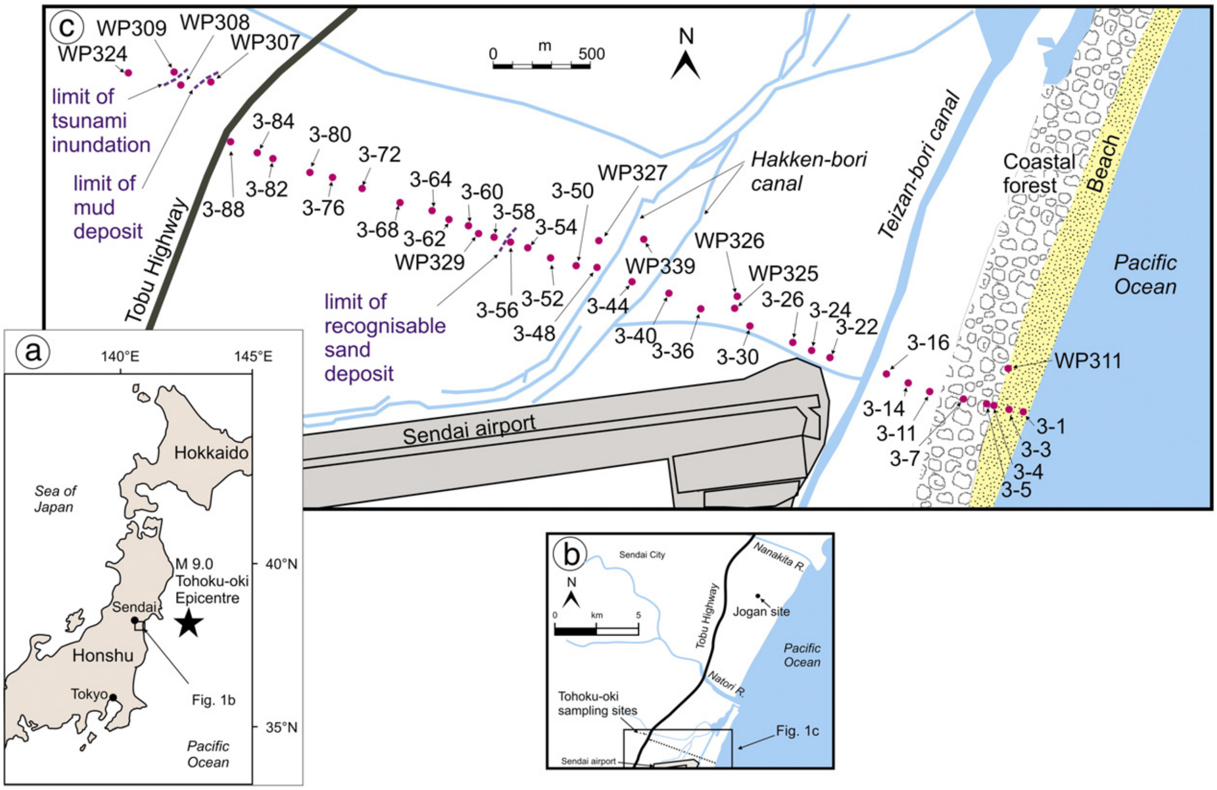

Fig. 1. a. Location map of the study area in Japan showing the epicentre of the M 9.0 Tohoku-oki earthquake. b. Map of the area showing the sampling site of the Jogan tsunami deposit (Jogan site) and the location of the original transect T3 and additional sites (Tohoku-oki sampling sites). c. Study area with location of sampling sites on transect T3 (all sites marked as 3-1 to 3-88), as well as sites W of Tobu Highway (WP307, WP308, WP309 and WP324). Other sites are marked with WP. The limit of tsunami inundation reported by the Association of Japanese Geographers (2011) and that inferred from concentrations of water leachable ions (Chagué-Goff et al. 2012–this issue), as well as total S and Cl (this study), the limit of the mud deposit and the limit of the recognisable sand deposit (>0.5 cm) are also shown.

similar to those of the 2011 Tohoku-oki sandy tsunami deposit, its extent is also similar, and it also impacted a similar length of coastline (Goto et al., 2011; Sugawara et al., 2011, in press). The magnitude of the Jogan tsunami however, was mostly estimated based on the extent of the preserved sandy deposit, and as suggested by Goto et al. (2011) it was therefore probably underestimated.

Based on post-tsunami surveys of recent events, MacInnes et al. (2009) reported that sandy tsunami deposits in general extend to 90% of the limit of tsunami inundation on low-relief coastlines, although the extent ranges between 54 and 100%. Morton et al. (2011) have recently reported differences of 150 m to 600 m between the limit of sand deposition and tsunami inundation for the 2010 Maule tsunami in Chile, except in Talcahuano, where the difference was nearly 2 km, based on satellite imagery. Abe et al. (2012–this issue) who examined the relationship between the maximum extent of sand deposit and tsunami inundation following the 2011 Tohoku-oki tsunami found that the maximum extent of a >0.5 cm sand deposit was 90% of the inundation distance where the tsunami inundation was less than 2.5 km, and 57–76% where the inundation distance exceeded 2.5 km. Thus, there appear to be some considerable differences between maximum inundation distances and the inland extent of sandy deposits. As such, caution should be used when inferring the size of an event from its sandy deposit. There was a difference of almost 2 km on the Sendai Plain (Goto et al., 2011; Abe et al., 2012–this issue), highlighting how significant the underestimate of the impact of the event could be. Flow depths determined by Goto et al. (2011) indicated that the water height was over 2 m above the ground at the limit of the recognisable sand layer 2.8–2.9 km inland (~60% of inundation distance). There was still major damage and destruction further inland. The mud deposit on the other hand was found up to 4.65 km inland, or 95% of the inundation limit (Chagué-Goff et al., 2012–this issue; this study). However, while the mud deposit was recognisable two months after the tsunami, will it be distinguishable from the surrounding soil and mud, once it is buried? This is of course assuming that the mud, like any tsunami deposit, will be sufficiently well preserved in the future after being exposed to ongoing post-depositional processes (e.g. Szczuciński, 2012).

Chagué-Goff et al. (2012–this issue) showed that in May 2011, water leachable salt components were in elevated and/or measurable concentrations in the muddy sediments beyond the limit of the recognisable sand deposit, and that although concentrations decreased with time, raised levels were still measured five months after the tsunami. Therefore, the geochemical signature might provide a useful criterion to help identify mud deposits laid down by tsunamis.

The use of geochemical proxies to help identify palaeo- and historical tsunamis is still in its infancy (Chagué-Goff, 2010; Chagué-Goff et al., 2011; Goff et al., 2012), despite first being reported in the 1990s (Minoura and Nakaya, 1991; Minoura et al., 1994; Chagué-Goff and Goff, 1999; Goff and Chagué-Goff, 1999). Geochemical markers however are slowly being recognised as a valuable proxy (e.g. Goff et al., 2001, 2004, 2010a,b; Chagué-Goff et al., 2002, 2012; Schlichting and Peterson, 2006; Nichol et al., 2007, 2010; Ramirez-Herrera et al., 2007, 2009, 2012; Williams et al., 2011), in particular when other diagnostic criteria are not available or are equivocal (e.g. Nichol et al., 2010). A reluctance to use geochemical proxies probably arises from the fact that they are not always straightforward. While a marine signal is often easy to identify (e.g. Cl, S, Na, Sr), as is that of shell material (e.g. Ca, Mg, Sr), the geochemical signature is also mostly source-dependent. For example, tsunami deposits derived from coral (e.g. Chagué-Goff et al., 2011; Williams et al., 2011) have a different signature than those derived from basalt (e.g. Chagué-Goff et al., 2012) or weathered granite (e.g. Ramírez-Herrera et al., 2012). Furthermore, while the identification of a marine geochemical