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2017

Pham, D. T., Gouramanis, C., Switzer, A. D., Rubin, C. M., Jones, B. G., Jankaew, K., et al. (2017). Elemental and mineralogical analysis of marine and coastal sediments from Phra Thong Island, Thailand: Insights into the provenance of coastal hazard deposits. *Marine Geology*, 385, 274-292.

<https://hdl.handle.net/10356/83331>

<https://doi.org/10.1016/j.margeo.2017.01.004>

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Elemental and mineralogical analysis of marine and coastal sediments from Phra Thong Island, Thailand: Insights into the provenance of coastal hazard deposits.

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Highlights:

- Overwash deposits cannot be identified from geochemical proxies at this site

- Mineral and trace metal data sets show very complex relationships through time
- The 2004 tsunami deposit is primarily sourced from shallow marine sediments
- The provenance of prehistoric tsunami deposits is complex and remains unclear

Keywords:

tsunami deposit; storm deposit; provenance; trace elements; mineral compositions; grain size parameters; cluster analysis; principal component analysis; bootstrap analysis; discriminant function analysis.

Abstract:

Sediment records left by coastal hazards (e.g. tsunami and/or storms) may shed light on the sedimentary and hydrodynamic processes happening during such events. Modern onshore and offshore sediment samples were compared with the 2004 Indian Ocean Tsunami, three palaeotsunami and a 2007 storm deposit from Phra Thong Island, Thailand, to determine provenance relationships between these coastal overwash deposits. Sedimentological and stratigraphic characteristics are generally inadequate to discriminate tsunami and storm deposits so a statistical approach (including cluster analysis, principal component analysis and discriminant function analysis) was used based on grain size, mineralogy and trace element geochemistry. The mineral content and trace element geochemistry are statistically inadequate to distinguish the provenance of the modern storm and tsunami deposits at this site, but the mean grain size can potentially discriminate these overwash deposits. The 2007 storm surge deposits were most likely sourced from the onshore

sediment environment whereas all four tsunami units statistically differ from each other indicating diverse sediment sources. Our statistical analyses suggest that the 2004 tsunami deposit was mainly derived from nearshore marine sediments. The uppermost palaeotsunami deposit was possibly derived from both onshore and nearshore materials while the lower palaeotsunami deposits showed no clear evidence of their sediment sources. Such complexity raises questions about the origin of the sediments in the tsunami and storm deposits and strongly suggests that local context and palaeogeography are important aspects that cannot be ignored in tsunami provenance studies.

Key words: tsunami deposit, storm deposit, provenance, trace elements, mineral compositions, grain size parameters, cluster analysis, principal component analysis, bootstrap analysis, discriminant function analysis.

1. Introduction

Coastal areas offer favourable conditions to support dense human populations and critical infrastructure (Syvitski et al., 2009). These areas, however, are also vulnerable to coastal hazards, of which tsunamis and storms are the most disastrous (e.g. Switzer et al., 2014). A series of such disasters have occurred in the last decade, including the 2004 Indian Ocean Tsunami (IOT), Hurricane Katrina (2005), Cyclone Nargis (2008), the Tohoku-oki earthquake-induced tsunami (2011), Hurricane Sandy (2012), Typhoon Haiyan (2013) and Hurricane Patricia (2015). These disasters highlight the need for accurate coastal vulnerability assessments

including the examination of the recurrence interval of such events. Understanding the recurrence interval of these events is crucial for future risk assessment (e.g., Switzer et al., 2014). Due to the inadequate and short historical records (i.e. frequently less than 100 years) in many affected areas, the geological record preserved along coasts may capture a much longer timeframe and provide evidence for historical occurrences and allow the determination of the recurrence intervals of tsunamis (e.g. Minoura et al., 2001; [Jankaew et al., 2008](#); [Monecke et al., 2008](#)) and storms (e.g. [Liu and Fearn, 2000](#); [Nott, 2011](#)).

Both tsunami and storm deposits are the result of overwash processes caused by high-energy events, and in many cases they exhibit very similar sedimentary signatures (e.g. [Kortekaas and Dawson, 2007](#); [Switzer and Jones, 2008](#)). Thus, in order to accurately assess how frequently catastrophic events affect coastal regions, it is necessary to know whether the identified coastal washover deposit was caused by a tsunami or a storm event (e.g. Switzer et al., 2014).

Tsunami and storm deposits have been compared in numerous studies with an expectation of developing a suite of diagnostic criteria to distinguish deposits formed by different coastal overwash processes (e.g. [Nanayama et al., 2000](#); [Goff et al., 2004](#); [Tuttle et al., 2004](#); [Kortekaas and Dawson, 2007](#); [Morton et al., 2007](#); [Switzer and Jones, 2008](#); [Phantu Wongraj and Choowong, 2012](#)). Nonetheless, criteria that have been used are still problematic and site specific or only valid for known events (Gouramanis et al., 2014b). Many of these studies have relied on

sedimentological and stratigraphic signatures that can be found in both tsunamigenic and cyclonic deposits. For example, Shanmugam (2012) reviewed 15 sedimentological criteria that had been found in both tsunami and storm deposits and drew the conclusion that “there are no reliable sedimentological criteria for distinguishing paleo-tsunami deposits in various environments” (p.23). Gouramanis et al. (2014b) used a multi-proxy approach (granulometric, loss on ignition, heavy minerals and microfossils) to statistically compare the 2004 IOT deposit and 2011 Cyclone Thane deposit superimposed at the same location along the southern coast of India. The Gouramanis et al. (2014b) study indicated that tsunami and storm deposits from the same site could not be distinguished using the standard sedimentological parameters typically used to identify coastal hazard deposits.

Thus, the difficulty of using conventional diagnostic criteria in differentiating coastal washover deposits requires the development of new and novel proxies.

In this study, we seek to test two hypotheses:

1. that the mineral composition, element geochemistry and grain size parameters of modern onshore, nearshore and offshore environments can be used to determine the provenance of the 2004 IOT and paleo-tsunami deposits, and the 2007 storm surge deposit preserved on Phra Thong Island, Thailand (Fig. 1); and

2. that the 2004 IOT, paleo-tsunami and the 2007 storm surge deposits can be distinguished using mineral composition, element geochemistry and grain size parameters.

To investigate these hypotheses, we apply several novel and seldom-used (for coastal hazard deposits) statistical techniques to gain insight into the provenance of the washover deposits and compare the deposits from different events and causal mechanisms (i.e. storm, recent and paleo-tsunami).

To date, little attention has focused on the mineralogy and geochemistry of overwash deposits (Chagué-Goff, 2010 and references therein). It is believed that the geochemical signature and mineral composition of tsunami sediments are source-dependent (Chagué-Goff et al., 2011; [Goff et al., 2012](#)), and are expected to reflect the origin of coastal overwash deposits ([Font et al., 2013](#); Chagué-Goff et al., 2015). Addressing these issues will contribute a greater understanding of the sedimentation and hydrodynamic processes (i.e. erosion and deposition) occurring during coastal overwash sediment deposition (e.g. [Switzer et al., 2012](#); Goff and Dominey-Howes, 2013; [Sugawara et al., 2014](#)).

2. Site description

Phra Thong Island is approximately 125 km north of Phuket on the west coast of southern Thailand in the Andaman Sea (Fig. 1). Phra Thong Island is characterized by a series of north-south trending, sandy Holocene beach ridges and marshy swales

on the western side, and dense tidal mangroves on Pleistocene sand dunes on the eastern side ([Jankaew et al., 2008](#); [Brill et al., 2012a](#); [Scheffers et al., 2012](#); [Brill et al., 2015](#)).

The offshore area is characterized by a shallow-gradient shelf dominated by quartz, and minor carbonates (aragonite and calcite), feldspars (microcline, orthoclase, labradorite), heavy minerals (cassiterite, zircon, garnet), muscovite, monazite and kaolinite (Fig. 2 and Supp. Info Figs.S1-S2). The grainsize varies from medium- to fine-sand in the nearshore and medium- to coarse-sand in water deeper than 15 m (Fig. 2). This grain size distribution is similar to the offshore sediment grain size described from offshore Pakarang Cape approximately 40 km south of Phra Thong Island ([Feldens et al., 2012](#)). From the early 1900s to the 1970s and sporadically since, tin and other heavy metals were mined both from the onshore and offshore environments of Phra Thong Island ([Jankaew et al., 2011](#)). This activity would have influenced the mineral phases transported onshore in the last 120 years.

During the 2004 IOT event, the maximum observed tsunami wave height was 20 m - the highest recorded wave height along the Thai coast ([Tsuji et al., 2006](#)). More importantly, on Phra Thong Island, the sedimentary signatures of the 2004 IOT and at least three different past tsunami events (preserved as 5 to 20 cm thick sand sheets in coastal swales) were identified by [Jankaew et al. \(2008\)](#).

Since Jankaew et al. (2008)'s study, the 2004 IOT tsunami and paleo-tsunami deposits on Phra Thong Island have been extensively studied to determine the chronology and potential tsunami recurrence interval ([Fujino et al., 2009](#); Brill et al., 2012a; [Prendergast et al., 2012](#)), micropaleontology (Sawai et al., 2009), sedimentology and stratigraphy (Fujino et al., 2008; [Fujino et al., 2009](#); Brill et al., 2012a; Brill et al., 2012b; Brill et al., 2015), flow conditions ([Choowong et al., 2008](#); Sawai et al., 2009; Brill et al., 2014) and a ground penetrating radar survey to image the thin tsunami beds ([Gouramanis et al., 2014a](#); Gouramanis et al., 2015).

Phra Thong Island is rarely impacted by storms ([Jankaew et al., 2008](#); Brill et al., 2014) but in early May 2007 an unusual tropical depression that formed in the upper part of Gulf of Thailand moved across southern Thailand (Thai Meteorological Department, 2007). As the tropical depression moved into the Andaman Sea, the depression interacted with the southwest monsoon resulting in heavy rain (200 to 400 mm) and intense onshore waves along the north-western coast of Thailand (Thai Meteorological Department, 2007). The resultant storm surge deposited sands upon the youngest berm of Phra Thong Island.

Although the shallow marine environment is considered to be the source of the sediments comprising the 2004 IOT deposit on Phra Thong Island based on evidence from diatom assemblages (Sawai et al., 2009) and grain size distribution (Fujino et al., 2008; [Fujino et al., 2010](#)), the provenance of the older deposits has not been identified. Thus, we aim to identify the provenance and compare the

granulometry, mineralogy and geochemistry of the 2004 IOT tsunami, paleo-tsunami and 2007 storm deposits.

3. Methods

3.1. Sample collection

Sediment samples were collected in March 2012 and May 2013 from the offshore and nearshore marine environment, the modern beach and beach ridges inland, pits that contained the 2004 IOT and three palaeotsunami deposits (e.g., [Jankaew et al., 2008](#)), and pits through the 2007 storm deposit. Fourteen offshore samples were collected using a Van Veen grab from water depths ranging from 3 to 25 m and up to 10 km away from the modern shoreline. Eight onshore samples were collected from the modern beach and from 5 to 12 cm deep pits in locations where the 2004 IOT capped the ridges and swales. Four samples each of the 2004 IOT (Sand A) and the most recent prehistoric tsunami (Sand B) deposits were collected from a trench Swale Y ([Jankaew et al., 2008](#)). Three sediment samples of the third oldest palaeotsunami sandsheet (Sand C) was sampled from a pit 8.5 m south of the trench and two samples of the oldest palaeotsunami sandsheet (Sand D) from auger 10 (Fig. 1; Gouramanis et al., 2015).

3.2. Sediment analyses

Grain size analysis was performed at the Asian School of the Environment, Nanyang Technological University, Singapore, and X-ray diffraction (XRD) and X-

Ray fluorescence (XRF) analyses were carried out at the X-ray laboratory, University of Wollongong, Australia.

3.2.1 Grain size analysis

Prior to grain size analysis, all of the sediment samples were treated in hydrochloric acid (HCl) to eliminate carbonate, and hydrogen peroxide (H₂O₂) to remove organic matter. The analysis of grain size parameters (i.e. mean, sorting, skewness and kurtosis) followed 60 s of ultrasonic dispersion, and grain size measured in triplicate using a Malvern Mastersizer 2000 (size range 0.02 μ m to 2 mm). Granulometric parameters were obtained and described based on the logarithmic graphical method of Folk and [Ward \(1957\)](#) using the GRADISTAT package (Blott and Pye, 2001). The grain size was not measured for two offshore samples (PT-OS 07 and PT-OS 22) due to insufficient sample material and these two samples were excluded from further examination.

3.2.2 X-ray Diffraction (XRD)

The XRD analysis was conducted using a Philips PW 1771/00 diffractometer with Cu K α radiation, X-tube at 1 kW and a Spellman DF3 generator (the angle of two theta ranged from 4 to 70°, with a step size of 0.02°). The raw XRD profiles derived from the diffractometer were analyzed using the TRACES 4.0 software. The corrected profiles were then processed in SIROQUANT software, which calculated the weight % (wt. %) of each mineral phase present ([Williams et al., 2012](#)).

Bulk mineral contents for the Deep-Offshore, Nearshore, Onshore, Sand A and Sand B samples were analysed using quantitative XRD. Unfortunately, the very high concentration of quartz (>80 wt. %) in the bulk analyses would dampen the influence of the lower concentration minerals in the statistical analyses. Sand C, Sand D and 2007 Storm samples were not analysed but the dominance of quartz in these samples suggests a similar composition across the data set. So to investigate the role of the non-quartz component, the finer sediment fraction (63 to 125 μm) was analysed using XRD. The finer fraction XRD mineral composition was used in the statistical analyses.

3.2.3 X-ray Fluorescence (XRF)

Trace element contents were determined using a SPECTRO XEPOS energy dispersive polarization XRF spectrometer with a 50 Watt Pd end-window tube for excitation. It utilises a range of polarization and secondary targets to optimise excitation conditions for different elements. Samples for trace element analysis were prepared by pressing approximately 5 gm of powdered sample into an aluminium cup with a few drops of PVA binder and dried overnight at 70°C. Deconvolution of the spectra and conversion of X-ray intensities are performed using proprietary software developed by the manufacturer. Calibration of the instrument is made against a wide range of natural rock standards and synthetic materials.

3.3. Statistical methods

To determine the provenance of the sediments deposited by the 2004 IOT, paleo-tsunami and 2007 storm and to compare the overwash deposits, three multivariate statistical techniques (Partitioning Around Medoids (PAM), Principal Component Analysis (PCA) and Discriminant Function Analysis (DFA)) were employed. Each technique was applied separately to grain size characteristics, mineral contents and trace element data. All statistical analyses were executed in *R* (R Core Team, 2014) by using the *cluster* (Maechler et al., 2014), *vegan* (Oksanen et al., 2016) and *boot* (Canty and Ripley, 2016) packages.

3.3.1. Partitioning Around Medoids - PAM

PAM is a type of cluster analysis that can be used to identify potential groups without prior knowledge of groups in a population ([Kaufman and Rousseeuw, 2005](#)). PAM chooses representative object(s) for group(s) from the data set and then forms cluster(s) by locating other objects to the predefined closest representative object (the medoids). The medoid minimises the sum of the Euclidean dissimilarity and clusters similar objects ([Rousseeuw, 1987](#); [Kaufman and Rousseeuw, 2005](#)). The number of clusters (k) is defined *a-priori* to obtain the optimal k and PAM is run with k varying from 2 (smallest possible number of groups) to 8 (maximum number of groups) to compare the average silhouette widths and the largest average silhouette width value ([Kaufman and Rousseeuw, 2005](#)).

3.3.2. Principal Component Analysis – PCA

PCA simplifies multivariate data sets by transforming the original data to a new lower-dimensional (principal components) data set to simplify interpretations (Everitt and Hothorn, 2011). In addition, PCA can investigate the relationships between variables and the relationships among observations in a data set.

PCA was employed to study the interaction of all variables and the distribution of samples using granulometric data, mineralogy and geochemistry. All data sets were standardized prior to analysis and the correlation matrix was used to extract components due to different units and large variances in the data sets (Everitt and Hothorn, 2011). To retain the significant components from PCA analysis, the broken stick method and Kaiser-Guttman criteria applied was applied (e.g., Legendre and Legendre, 2012).

As the sample size ($n = 36$) and the number of variables (p) varies depending on the PCA performed ($p_{\text{Grain size}} = 4$, $p_{\text{Mineralogy}} = 10$ and $p_{\text{Geochemistry}} = 22$), we test the significance, and hence stability, of each significant principal component (PC; (e.g., [Jackson, 1993](#)). To test for stability in each significant PC, the individual eigenvalues ($\hat{\lambda}$) were bootstrapped using an ordinary non-parametric bootstrap technique (e.g., Efron and Tibshirani, 1993) with 10,000 iterations and individual histograms investigated. Depending if the histogram resembles a normal-family distribution or skewed distribution, then the 95% confidence intervals on the

resampled eigenvalues ($\hat{\lambda}^*$) are calculated using the percentile or the bias-corrected methods (Efron and Tibshirani, 1993; Canty, 2002).

3.3.3. Discriminant Function Analysis - DFA

DFA is a classification technique that seeks the greatest separation between well-defined or known groups of a population using linear discriminant functions (Davis, 2002). Discriminant functions are linear combinations of a set of standardised independent variables that create scores used to allocate group membership. DFA concentrates on discriminating groups and the regression coefficients of the discriminant functions maximize the ratio of between-group mean differences and within-groups variance differences (Tabachnick and Fidell, 2013). The DFA groupings were then graphically compared based on the *a priori* sedimentary environment groupings.

4. Results

4.1. Analytical results

4.1.1. Grain size analysis

The Offshore group presents a wide range of grain size characteristics and can be divided into two sub-groups: the Deep-Offshore group (>10m water depth; samples include: PT-OS 03, PT-OS 05, PT-OS 13, PT-OS 15 and PT-OS 17) and the Nearshore group (<10m water depth; samples include: PT-OS 24, PT-OS 26, PT-OS 28, PT-OS 32, PT-OS 33, PT-OS 34; Fig. 1, Supp. Figs. 1-2, Table 1).

The Deep-Offshore group is characterized by coarse to medium, poorly to moderately sorted, very fine to finely skewed and mesokurtic to very leptokurtic sand (Fig. 2, Supp. Figs. 1-2, Table 1). The Nearshore group, in contrast, is composed of very fine to fine, moderately to moderately well sorted, very finely skewed to symmetrical and mesokurtic to very leptokurtic sand (Fig. 2, Supp. Figs. 1-2, Table 1). Sample PT-OS 21, which lies between the Deep-Offshore and the Nearshore group (Fig. 1), is characterized by very coarse very poorly sorted, finely skewed and leptokurtic silt (Fig. 2, Supp. Figs. 1-2, Table 1).

The Onshore group consists of predominantly medium, moderately well sorted, symmetrical and mesokurtic sand, except PT-04, which is classified as a fine sand (Supp. Figs. 1-2, Table 1). The Sand A and Sand B groups are very similar and composed of very fine, moderately to moderately well sorted, coarsely skewed to symmetrical and mesokurtic to leptokurtic sand (Supp. Figs. 1-2, Table 1). The Sand C group is a fine, poorly sorted, finely skewed to symmetrical and very leptokurtic sand (Supp. Figs. 1-2, Table 1). The Sand D and the Storm groups are both medium, moderately sorted to moderately well sorted, mesokurtic sands, but they differ slightly in skewness, with Sand D samples finely skewed and the Storm samples typically symmetrical (Supp. Figs. 1-2, Table 1).

4.1.2. Mineralogy

The bulk sediment mineralogy suggests a relative homogeneity of the medium to coarse sands with quartz dominating (>80 wt. %) and minor aragonite, calcite and garnet being present. The fine sediment fraction mineralogy is still dominated by quartz (*ca.* 52 wt. % on average), though a range of other minerals are present including orthoclase, microcline, aragonite, zircon, cassiterite, monazite, kaolinite, muscovite and labradorite (Table 2). Calcite and garnet were not present in the finer fraction suggesting that these minerals are only present as coarse grains. The XRD results of the bulk sediment analyses show that quartz dominates the marine sediments with minor contributions of calcite, aragonite, zircon and garnet (Supp. Info. Fig. S3). Notably, aragonite has high concentrations in the nearshore environment south of the onshore sampling locations (~15 wt. %) and deeper offshore (~12 wt. %) but persists in most samples at very low concentrations (Supp. Info. Fig. S3).

For the fine mineralogical fractions, quartz dominates (>45 wt. %) the nearshore environment to depths of 15 to 20 m, but other minerals have locally high concentrations demonstrating the mineralogical heterogeneity of the marine environment in the northern part of Phra Thong Island (Fig. 2 and Supp. Info. Figs S4-S5). In the fine fraction, aragonite and muscovite are present throughout the marine environment but have locally high concentrations (aragonite: 12-15 wt. %, muscovite: 10 wt. %) in deeper environments (Supp. Info. Fig. S4). The northern nearshore environment and deep offshore environments contain high zircon (8 and 6 wt. %), orthoclase (16 wt. % in both environments) and microcline (9 and 12 wt. %), suggesting a similar mineral assemblage (Supp. Info. Fig. S5). Microcline also

occurs in high concentrations in the nearshore zone south of the onshore sampling sites and between 10 and 20 m water depth to the north (Supp. Info. Fig. S5). Cassiterite, which has been extensively mined for tin (Jankaew et al., 2011), is found adjacent to the sampled overwash deposits in the nearshore environment (~1.5 wt. %) and in water depths ranging from 10 to 20 m (Supp. Info. Fig. S4).

4.1.3. Trace element geochemistry

The results from the 34 trace elements analysed show significant heterogeneity across the marine environment and in the onshore and overwash deposits (Fig. 2, Supp. Info. Figs S6-S8, Table 3). Several of the analysed elements are excluded from further discussion including:

- sulfur (S), chlorine (Cl) and bromine (Br) because they are typically marine elements with very high concentrations in the offshore samples and low in the other samples, and, therefore, they were likely to saturate the results;
- zinc (Zn), germanium (Ge), molybdenum (Mo), cadmium (Cd), antimony (Sb) and mercury (Hg) because they showed no variation between the groups and contribute little to dissimilarity tests; and,
- cobalt (Co), tantalum (T) and tungsten (W) because the high values of these elements were caused by contamination during the grinding process.

From this, 22 trace elements (V, Cr, Ni, Cu, As, Se, Rb, Sr, Zr, Nb, Sn, Ba, La, Ce, Hf, Pb, Th, U, Y, Cs, Ga, Bi) were included in the statistical analyses (Table 3).

Of these 22 trace elements, distinct elemental zones exist in the marine environment west of Phra Thong Island (Fig. 2 and Supp. Info. Figs S6-S8). Notably, the

nearshore zone contains a high degree of trace element heterogeneity which mirrors the mineralogical heterogeneity. Immediately offshore from the onshore sampling sites the trace elements have high concentrations of Sr, Nb, Sn, La, Rb, Th, U, Y and Zr (Fig. 2 and Supp. Info. Fig. S6). Farther offshore in intermediate depth waters (10 to 20 m) As, Cr, Pb, V, Ba and Sr have high elemental concentrations (Fig. 2 and Supp. Info. Fig. S7). In the northern nearshore zone Ce, La, Th, U, Y and Zr have higher elemental concentrations than to the south, but also have high concentrations of Bi, Hf, Nb and Se (Fig. 2 and Supp. Info. Figs S6, S8). The nearshore environment south of the onshore sampling sites has high concentrations of Ba, Cr, Cu, Cs, Ga, Ni, Rb, Pb and V (Supp. Info. Figs S6-S8). The trace elemental concentrations in water deeper than 20 m have high Sr concentrations and, in the northern section, high Sn (Fig. 2).

4.2. Statistical results

In this section, the terms denoted by a subscript *GS*, *MIN* and *CHEM* are statistical analyses (i.e. PAM, PCA and DFA) for the grain size parameters, mineral contents and trace elements, respectively.

4.2.1 Grain size parameters

Four granulometric parameters (mean, sorting, skewness and kurtosis) were examined using PAM_{GS}. The PAM_{GS} (Fig. 3) indicates that eight clusters can be identified (overall average silhouette is 0.53). Cluster 1 includes one Sand A and one Sand B sample (Fig. 3). Cluster 3 comprises all of Sand C and one Nearshore

sample. Cluster 4 incorporates most of the Sand A, Sand B (three samples for each group) and four Nearshore samples (Fig. 3). Cluster 6 is composed of three Deep-Offshore samples and all of Sand D samples. Cluster 7 is the largest cluster and is made up of all of Onshore and Storm samples. Clusters 2, 5 and 8 contain only a single sample for each group and their silhouette widths are zero (Fig. 3). The zero silhouette width of these clusters implies a “neutral case” and samples in these clusters can be also equally assigned to either neighboring cluster (e.g. the second-best choice; [Kaufman and Rousseeuw, 2005](#)).

The PCA_{GS} result is consistent with the PAM_{GS} analysis (Fig. 4a). The broken stick model (Fig. 4b) and Kaiser-Guttman criteria (Supp. Info Table S1) suggest that only the first two principal components ($PC1_{GS}$ and $PC2_{GS}$) are necessary to explain 82% of the variance in the grain size data set. The ordinary non-parametric bootstrap analysis of $\hat{\lambda}^*$ does not differ significantly from the $\hat{\lambda}$ determined from the PCA for either $PC1_{GS}$ or $PC2_{GS}$ indicating the stability of each principal component using the available data. Histograms and quantile-quantile plots for $PC1_{GS}$ (Supp. Info. Fig. S9) and $PC2_{GS}$ (Supp. Info. Fig. S9) demonstrate the relative normality of the distributions of $\hat{\lambda}^*$, and that $\hat{\lambda}$ ($PC1_{GS} = 2.08$ and $PC2_{GS} = 1.206$) resides within the percentile 95% confidence interval of $\hat{\lambda}^*$ ($PC1_{GS} = (1.803, 2.616)$; and $PC2_{GS} = (0.94, 1.395)$).

$PC1_{GS}$ and $PC2_{GS}$ explain 52% and 30% of the variance, respectively. $PC1_{GS}$ is defined by sorting, skewness and kurtosis and shows very little difference between

the Sand A, Sand B, Onshore and Storm deposits that overlap with the Nearshore sediments (Fig. 4a). $PC1_{GS}$, also results in significant overlap between the grain size parameters of the Nearshore, Deep Offshore, Sand C and Sand D (Fig. 4a). $PC2_{GS}$ is defined by the mean sediment grain size and shows extensive overlap between each of the overwash deposits and environments with the mean grain size of the Deep Offshore environment (Fig. 4a). However, $PC2_{GS}$ does separate Sands A, B and C that are situated within the Nearshore sediments, from the Storm deposits that are very similar to the Onshore deposits (Fig. 4a).

Both $PC1_{GS}$ and $PC2_{GS}$ show a large scatter in the distribution of Deep-Offshore and Nearshore sediments as seen in the Folk-Ward Classification (Table 1). In both principal components, Sand A and Sand B samples, and the Onshore and Storm samples overlap. There is a gradation in mean grain size from the Sand A and Sand B samples to the Onshore and Storm samples with the Nearshore sediments interspersed between these deposits. The Deep-Offshore sediments show a wide distribution in $PC1_{GS}$ and $PC2_{GS}$ that reflects a high diversity of grain size characteristics.

In the DFA_{GS} , discriminant function 1 ($DF1_{GS}$) is highly significant (percentage separation is 75%) and separates Sand D and the Deep-Offshore groups from Sand A, Sand B and most Nearshore samples (Fig. 5). Discriminant function 2 ($DF2_{GS}$; accounts for 17% separation) discriminates Sand C from the remaining sediment samples (Fig. 5). The similarity of Sand A and Sand B is demonstrated in the

DFA_{GS}, and these two groups are situated close to the three Nearshore samples (Fig. 5) as observed in the PCA_{GS} (Fig. 4a). The Storm and Onshore groups agree with the PCA_{GS} results (Fig. 4a) and are defined by DF2_{GS}, which separates these samples from Sand C.

4.2.2. Mineral content

Prior to the statistical analyses of the mineralogical data, we replaced the missing value of muscovite in sample PT-OS 33 with the mean of muscovite contents in samples from other Nearshore samples. Similarly, the mean of the labradorite content for Onshore samples was substituted in sample PT-09.

The PAM_{MIN} determined only two clusters with an average silhouette width of 0.4. The first large cluster includes all of the Onshore, Sand A, Sand B and Nearshore samples and half of the Deep-Offshore group, while the second cluster comprises the rest of the Deep-Offshore group (Fig. 6).

The PCA_{MIN} result (Fig. 7a) is consistent with the PAM_{MIN} (Fig. 6) analysis showing a broad mineralogical transition from the Nearshore and Onshore deposits to the two most recent tsunami deposits (Sand A and Sand B). The broken stick model (Fig. 7d) and Kaiser-Guttman criteria (Supp. Info. Table 2) suggest that the first three principal components are necessary to explain most of the variance in the mineralogy data set. The first three principal components (PC1_{MIN}, PC2_{MIN} and

$PC3_{MIN}$) are sufficient to explain the mineralogy dataset and account for 81% of the explained variance (Fig. 7d and Supp. Info. Table 1).

The ordinary non-parametric bootstrap analysis of $\hat{\lambda}^*$ does not differ significantly from the $\hat{\lambda}$ determined from the PCA_{MIN} for either $PC1_{MIN}$, $PC2_{MIN}$ or $PC3_{MIN}$ indicating the stability of each principal component using the available data. Histograms and quantile-quantile plots for $PC1_{MIN}$ (Supp. Info. Fig. S10) and $PC2_{MIN}$ (Supp. Info. Fig. S10) are relatively normally distributions of $\hat{\lambda}^*$, and that $\hat{\lambda}$ ($PC1_{MIN} = 3.58$ and $PC2_{MIN} = 2.69$) resides within the percentile 95% confidence interval of $\hat{\lambda}^*$ ($PC1_{MIN} = (3.259, 4.98)$ and $PC2_{MIN} = (2.01, 3.31)$). The histogram and quantile-quantile plot of $PC3_{MIN}$ (Supp. Info. Fig. S11) is skewed and a normal distribution cannot be assumed. However, $\hat{\lambda}$ ($PC3_{MIN} = 1.83$) resides within the bias-corrected percentile 95% confidence interval of $\hat{\lambda}^*$ ($PC3_{MIN} = (1.27, 2.61)$).

$PC1_{MIN}$ (~36% of the variance) is only positively correlated with quartz content and is negatively correlated with labradorite, monazite, kaolinite and muscovite (Fig. 7a). Conversely, quartz does not significantly contribute to variations in $PC2_{MIN}$ (~27% of the variance) but zircon, orthoclase, microcline and cassiterite positively contribute to $PC2_{MIN}$. Labradorite, monazite, kaolinite and muscovite are also weakly negatively correlated with $PC2_{MIN}$ (Fig. 7a). $PC3_{MIN}$ (18% of the variance) is positively correlated with orthoclase, monazite and aragonite, and negatively correlated with muscovite, kaolinite, zircon and cassiterite when compared with $PC1_{MIN}$ (Fig. 7b). However, comparison between $PC2_{MIN}$ and $PC3_{MIN}$ (Fig. 7c)

shows that orthoclase and aragonite are orthogonal to monazite, and muscovite and kaolin are orthogonal to zircon and cassiterite. Of note, aragonite appears to influence a single Deep Offshore sample and a single Sand B sample, likely due to the presence of coral rubble, which is not present in any other sample.

The first three principal components show that Sand A and Sand B are mineralogically indistinguishable (Fig. 7a-c) and that most of the Nearshore and Onshore sediments cluster around the origin of the three principal component plots highlighting the relative mineralogical homogeneity (Fig. 7a-c). Even after the removal of coarse-grained quartz, the Nearshore samples are influenced by increasing concentrations of fine-grained quartz, whereas the Onshore sediments have relative higher concentrations of zircon, orthoclase, microcline and cassiterite (Fig. 7a-c). The Deep Offshore samples have elevated labradorite, muscovite, monazite and kaolinite concentrations relative to other minerals (Fig. 7a-c).

The DFA_{MIN} shows that the Deep-Offshore group is distinct and dispersed from other groups, especially along the $DF2_{MIN}$ (Fig. 8). $DF1_{MIN}$ (52% of the separation) discriminates the Deep-Offshore, Nearshore and Sand A from Sand B and Onshore group very well (Fig. 8). In contrast, $DF2_{MIN}$ (39% of the separation) only separates Sand A group from Sand B samples, but that these two deposits overlap with the Nearshore and Onshore sediments (Fig. 8). Combined, both $DF1_{MIN}$ and $DF2_{MIN}$ show that Sand A sediments are mineralogically similar to the Nearshore sediments, and that Sand B and the Onshore sediments have a similar mineralogy (Fig. 8).

4.2.3. Trace elements

Twenty-two trace elements were used to investigate the relationship between the environments and overwash deposits using PAM, PCA and DFA analyses. Prior to PAM, PCA and DFA analyses of the geochemistry data, three samples (one Sand D and two Onshore samples) were removed due to their very high Zr concentrations that heavily influenced the analysis (not shown).

The PAM_{CHEM} analysis identified two clusters (average silhouette width of 0.36). The first cluster contained all of the Sand B samples, one Nearshore sample, one Deep-Offshore and one Sand D sample (Fig. 9). Based upon the PAM_{CHEM} analysis the two latter samples are misclassified, suggesting that these two samples would have been assigned to the second cluster (i.e. the second best choice, e.g. [Kaufman and Rousseeuw \(2005\)](#)). The large second cluster comprises all of the remaining samples (Fig. 9) indicating a similarity in the chemical composition between the Onshore, Sand A, Sand C, Sand D, Nearshore and Storm samples.

The first two principal components of the PCA_{CHEM} are shown in Figure 10a, although the broken stick model (Fig. 10d) suggests that four principal components are necessary to explain the variance in the geochemistry data. The Kaiser-Guttman criteria (Supp. Info. Table 3) suggest that the first five principal components ($PC1_{CHEM} = 37\%$, $PC2_{CHEM} = 27\%$, $PC3_{CHEM} = 10\%$, $PC4_{CHEM} = 9\%$ and $PC5_{CHEM} = 5\%$) are necessary to explain the variance in the geochemistry data set (88%).

$PC3_{CHEM}$ and $PC4_{CHEM}$ are very close to the cut-off for significance and $PC5_{CHEM}$ is well below the broken stick cut-off. Thus, for the simplicity of interpretation, $PC3_{CHEM}$, $PC4_{CHEM}$ and $PC5_{CHEM}$ are not discussed further.

As with the grain size and mineralogical data, the ordinary non-parametric bootstrap analysis of $\hat{\lambda}^*$ does not differ significantly from the $\hat{\lambda}$ determined from the PCA_{CHEM} for either $PC1_{CHEM}$ or $PC2_{CHEM}$ indicating the stability of each principal component using the available data. Histograms and quantile-quantile plots for $PC1_{CHEM}$ (Supp. Info. Fig. S12) and $PC2_{CHEM}$ (Supp. Info. Fig. S12) are skewed and a normal distribution cannot be assumed. However, $\hat{\lambda}$ ($PC1_{CHEM} = 8.23$ and $PC2_{CHEM} = 5.95$) resides within the bias-corrected percentile 95% confidence interval of $\hat{\lambda}^*$ ($PC1_{CHEM} = (7.23, 9.46)$ and $PC2_{CHEM} = (3.79, 7.62)$).

The $PC1_{CHEM}$ shows positive correlations with Sand B, Sand D and most of the Nearshore samples (Fig. 10a), whereas most of the Deep-Offshore, Onshore and all of the Sand C and Storm sediments are negatively correlated to $PC1_{CHEM}$ (Fig. 10a). $PC1_{CHEM}$ is positively correlated with a cluster of variables including La, Ce, Th, Zr, Y, U and Hf. This cluster strongly drives variations along the $PC1_{CHEM}$ and thus separates Sand B from the other groups (Fig. 10a). The Deep Offshore, Onshore, Sand C and the Storm deposits are depleted in all of the analysed elements (Fig. 10a). $PC2_{CHEM}$ is characterized by strong positive correlations with As, V and Sr that separate two of the Deep offshore samples from the other samples (Fig. 10a),

and negative correlations with Nb, Sn. Nb and Sn that are only found in high concentrations in Sand D (Fig. 10a).

$PC1_{CHEM}$ and $PC2_{CHEM}$ show that most of the sediment samples cluster around the origin of the axes (i.e. from -1 to 1 standard deviation), and only two Deep Offshore samples, one Nearshore sample, Sand B and Sand D contribute most of the variation in the PCA_{CHEM} . The PCA_{CHEM} shows that many of the elements are highly correlated suggesting that many elements can be excluded from the DFA, but still explain most of the variance of the data set. Here, elements that have high correlation coefficients (i.e. $r \geq 0.9$) with other elements were eliminated to avoid significant loss of information. Thus, from the cluster of highly correlated variables La, Ce, Y, Hf, Zr, U and Th (Supp. Info. Table S4), La, Ce and Y were excluded as they are rare earth elements and are less reliably determined when analyzed by XRF. Hf was also eliminated due to a smaller loading value (0.86) in $PCA1_{CHEM}$ compared to U (0.9) and Th (0.94). Zr was retained since this element has been attributed to high-energy environments (Chagué-Goff et al., 2011) and is present in high concentrations in zircon.

Rb is also highly correlated with Ba ($r = 0.94$, Supp. Info. Table S4) but Ba was selected because it occurs in carbonate minerals. Similarly, the correlation coefficient between Sn and Nb is very high, $r = 0.98$, but Sn was used in DFA_{CHEM} because it is associated with cassiterite and is important to the island's historical mining activities.

The results of the DFA_{CHEM} analysis show that the first two discriminant functions highlight a complex arrangement of each environment and sediment group's relationship to the other groups (Fig. 11). DFA1_{CHEM} accounts for 32% of the separation and is a gradation between three pairs of indistinguishable and overlapping groups: Sand C-Storm, Nearshore-Sand B and Sand A-Onshore (Fig. 11). The DFA1_{CHEM} separates the three pairs of groups and also discriminates the Deep-Offshore group. Sand D has one sample overlapping with the Nearshore-Sand B and another sample located close to the Sand C-Storm groups along DFA1_{CHEM} (Fig. 11).

DFA2_{CHEM} (24% of the separation) cannot separate the Deep-Offshore from the Nearshore group and there is a little overlap in their scores with the Sand C group's score (Fig. 11). These three groups are well discriminated from the Storm, Sand A and Onshore group in which the Storm and Sand A are almost identical. The DFA2_{CHEM} also discriminates Sand B and Sand D from other groups (Fig. 11).

5. Discussion

5.1. Proxies and impact factors in the study site

5.1.1. Geochemical signatures

The use of sediment geochemistry as a tool for studying coastal overwash deposits is still in its early stages even though an increasing number of studies have utilized geochemical signatures (see Chagué-Goff, 2010 for a review). For example, Chagué-Goff et al. (2012a) traced the maximum inundation of the 2011 Tohoku-oki

event by using marine-derived salts in mud deposits (i.e. S and Cl) and suggested these as potential identifiers for paleo-tsunamis. Font et al. (2013) combined geochemical signatures with other proxies to identify the sediment source of the 1755 Lisbon tsunami deposits. Geochemical signatures (e.g. water-soluble salts and metalloids) also have been used for environment impact assessments in the short time after tsunami events in both tropical settings (e.g. Szczuciński et al., 2005) and temperate environments (e.g. Chagué-Goff et al., 2012b).

The major challenge comes from the impact of post-depositional changes (e.g. dilution or weathering processes) that may alter the concentration of elements after events have occurred ([Szczuciński et al., 2007](#); [Chagué-Goff, 2010](#); [Shanmugam, 2012](#); [Font et al., 2013](#)). For instance, a cyclone-related event normally causes heavy rainfall that can quickly dilute concentration of marine salts in storm deposits and therefore might bias the interpretation. Similarly, [Szczuciński et al. \(2007\)](#) also reported a major decrease of water-soluble salts in the 2004 tsunami deposits due to rainy season in several locations in Thailand, south of Phra Thong Island. These studies reveal that saltwater signatures (i.e. salt) are very sensitive to environmental changes (e.g. dilution or leaching processes). And as Phra Thong Island is also affected by heavy precipitation (the rainy season is from April to November with approximately 1900 mm of rainfall, based on the 1971-2000 data period (Thai Meteorological Department (2012), that causes significant vertical movement of the fresh watertable resulting in remobilization of the marine-derived salts in both tsunami and storm deposits. [Szczuciński et al. \(2007\)](#) concluded that other elements, such as heavy metals and metalloids, were not affected by rainfall and

therefore could be used to study the provenance of sediments deposited during tsunami inundation (e.g. Chile; Chagué-Goff et al., 2015). Thus, taking that into account, the present study focused on using a wide range of metalloid and heavy metals.

In the modern marine environment trace elements vary spatially and can provide insights into the sediment source of coastal overwash deposits. Understanding the depth at which elements and minerals are concentrated in the modern environment may shed light on the depth at which the elements and minerals were mobilized prior to deposition as overwash deposits. This is akin to the analysis of microfauna and microflora to determine depths of scour during coastal overwash (e.g. [Tanaka et al., 2012](#)).

5.1.2. Grain size parameters

Granulometric characteristics can provide useful information about sediment origin, sedimentation and hydrodynamic processes and have been extensively used in comparing tsunami and storm deposits (e.g. [Nanayama et al., 2000](#); [Goff et al., 2004](#); [Tuttle et al., 2004](#); [Kortekaas and Dawson, 2007](#); [Morton et al., 2007](#); [Gouramanis et al., 2014b](#)) or in interpreting tsunami or storm events (e.g., [Switzer and Jones, 2008](#)).

The spatial distribution of mean grain size from offshore Phra Thong Island shows that the shallow marine samples are generally finer than those from deeper water

(Fig. 2). In addition, the mean grain size and selected trace elements are highly positively correlated (Supp. Info. Table S2.5). This correlation reflects that most trace elements are found in heavy minerals that are finer and possibly concentrated nearshore over time.

In regard to temporal variability, [Szczuciński et al. \(2007\)](#) reported the effect of rainfall on the mean grain size of the 2004 IOT deposits after one year and found a coarsening in half of the sandy tsunami samples. This change was ascribed to heavy rain that had removed the finer fraction from sandy tsunami deposits during the rainy season and, therefore, the effect of rainfall over time should be taken into account in paleo-tsunami studies in tropical climates (e.g. Thailand; [Szczuciński et al., 2007](#)). In contrast to tropical regions, fine-grained deposits are more likely to be eroded quickly by aeolian forces in arid regions (e.g. Peru; [Spiske et al., 2013](#)).

5.1.3. Mineral contents

Mineral compositions have recently been used as a useful tool (mostly with the focus on heavy mineral assemblages) in washover deposit studies (e.g. [Switzer et al., 2005](#); [Szczuciński et al., 2005](#); [Szczuciński et al., 2006](#); [Jagodziński et al., 2009](#); [Jagodziński et al., 2012](#); [Switzer et al., 2012](#); [Cuven et al., 2013](#); [Font et al., 2013](#); [Gouramanis et al., 2014b](#)). The mineral content of the bulk samples from Phra Thong Island is dominated by quartz (>80 wt %). This result is consistent with mineral compositions reported by [Jankaew et al. \(2011\)](#) who noted a very high concentration of quartz (*ca.* 85 to 90 wt %) and a very small concentration of heavy

minerals (*ca.* 1.7 to 2 wt % mostly of small cassiterite grains) in both the 2004 IOT deposits and paleo-tsunamis deposits on Phra Thong Island.

Our analytical analysis of the finer sand fraction (0.063 to 0.125 mm) considerably reduced the concentration of quartz and more minor minerals were detected implying that the finer sediment mineralogical fraction provides more meaningful information on the mineralogical variability of the overwash deposits. Unfortunately, due to the coarse grain size of Sand C, Sand D and the Storm samples, insufficient material prevented mineral analysis of these fine fractions. This difficulty prevented contrasting the older tsunami deposits and the storm deposit, but with the dominance of quartz across our sample set, we suggest that the use of mineral composition in this case is unlikely to be useful. Likewise, [Jagodziński et al. \(2012\)](#) could not use heavy mineral assemblages as a proxy to distinguish Tohoku-oki tsunami deposits from onshore sediments but noted that the result might differ when using a smaller size fraction (e.g. mud fraction). Similarly, Gouramanis et al. (2014b) also highlighted the difficulty of using heavy minerals in conjunction with key grain size parameters to discriminate tsunami and storm deposits due to the significant variations between and within pits on the southern Indian coastline.

5.2. Implications for studying coastal overwash deposits

5.2.1. Discrimination of modern tsunami and storm deposits

Due to a lack of mineral content data for the storm deposit and oldest paleo-tsunami deposits, we only use the statistical results from the elemental concentrations and granulometric parameters to investigate whether the Storm and Sand A can be discriminated.

In the PAM_{CHEM} (Fig. 9), our results show that both the Sand A deposits and those of the 2007 Storm cannot be discriminated using geochemistry. This result implies that the Storm and Sand A deposits are likely composed of the same minerals, the geochemical data are inadequate for distinguishing the two deposits and that the mechanism in which the sediments were deposited cannot be defined (Fig. 9).

The PCA_{CHEM} shows that the Sand A deposit is similar to the Storm deposit but that these deposits cluster around the origin of the two first principal components (within 1 standard deviation; Fig. 10) suggesting that none of the trace metals contribute significantly to discriminating the two deposits. However, the DF_{CHEM} discriminates Sand A from the Storm deposit due to the subtle loadings of each trace element (most likely Sr, As and V) on $DF1_{CHEM}$ (Fig. 11). The granulometric data (PAM_{GS} , PCA_{GS} , DFA_{GS}) suggest that the 2007 Storm and Sand A deposits can be discriminated. In the PAM_{GS} , these two groups occur in different clusters (Fig. 3) indicating a significant difference in grain size parameters between the two recent overwash deposits. The PCA_{GS} reveals that the mean grain size is the only key

feature to distinguish the 2007 Storm deposits (medium sand) from those of the Sand A (very fine sand; Fig. 4, Supp. Figs. 1-2, and Table 1). This result is mirrored in the DFA_{GS} analysis (Fig. 5). The results of other granulometric parameters (sorting, skewness and kurtosis) show very little difference between the deposits of the Storm and Sand A.

5.2.2. Provenance of the tsunami deposits

Sand A

The results for trace element (PCA_{CHEM}), mineralogy (PCA_{MIN} , DFA_{MIN}) and grain size (PAM_{GS} , PCA_{GS} and DFA_{GS}) analyses suggest that most of the Sand A deposit is predominantly derived from the shallow nearshore environment, although some contribution from onshore beach sediment cannot be discounted (e.g. DFA_{CHEM}). This conclusion agrees with Sawai et al.'s (2009) examination of the diatoms preserved in Sand A on Phra Thong Island from the same sites examined here, and Jagodziński et al. (2009) who suggested that the heavy mineral suite of the seafloor sediments, beach sediment and local soils combined to form the tsunami deposits on Kho Khao Island (~20 km south of Phra Thong Island).

Paleo-tsunami

While the provenance of Sand A deposits has been identified, the provenance of prehistoric tsunami deposits is less clear. Our statistical results show that all three paleo-tsunami deposits differ from each other and the Sand A deposit, and thus suggest variable sources of the paleo-tsunami sediments or potential diagenetic alteration.

The grain size, mineralogical and trace element analysis of Sand B presents a complex history. The grain size analysis (PAM_{GS} , PCA_{GS} , and DFA_{GS}) indicates a strong similarity between Sand A and Sand B, which are both similar to the Nearshore sediments. Mineralogically, Sand B and Sand A are very similar in (PAM_{MIN} and PCA_{MIN}) with overlap with the Nearshore sediment. However, DFA_{MIN} suggests that Sand B is closely related to the Onshore sediments. Geochemically, Sand B contains high concentrations of Th, Ce, La, Y and U similar to the Nearshore (PCA_{CHEM}) and these elements define DFI_{CHEM} . Thus Sand B is very likely a mixture of Onshore and Nearshore sediments.

Prendergast et al. (2012) beach ridge plain evolution model suggested that the formation of a new beach ridge complex occurs every 500 years, so Sand B, which was deposited between *ca.* 350 to 430 years ago (from optically stimulated luminescence (OSL), Prendergast et al., 2012) and *ca.* 550-700 years ago (from ^{14}C Accelerator Mass Spectrometry, Jankaew et al., 2008) may have been affected by the presence of a new beach ridge. However, the significant difference in the trace metal composition between Sand B and Sand A deposits may indicate that either post-depositional processes could have modified the deposit and/or the offshore sediment geochemistry has been strongly modified since Sand B was deposited.

The interpretations of the provenance of the Sand C and Sand D deposits are also complex. The grain size (PAM_{GS} , PCA_{GS} and DFA_{GS}) and geochemical (PAM_{CHEM} ,

PCA_{CHEM} and DFA_{CHEM}) analyses demonstrate that these two tsunami deposits differ substantially from each other and Sands A and B. PCA_{GS} and DFA_{GS} analyses show Sand D is similar to the Deep-Offshore sediments, while Sand C differs significantly from all of the other groups (Figs 4 and 5). The difference in grain size between the tsunami deposits may be due to changes in the source sediment grain size between each tsunami event. Unfortunately, our results cannot validate or refute this potentiality. The PCA_{CHEM} shows that Sand D is geochemically dissimilar to the other tsunami and storm deposits (Fig. 10), but Sand D shares similarities with Sand B in the DFA_{CHEM} (Fig. 11). For Sand C, multivariate techniques reveal that both Sand C and the Storm group appear to be similar in their geochemical composition (Figs 10 and 11).

This suggests that Sand C and Sand D were possibly derived from sediment sources different from Sand A and Sand B. Nevertheless, the complexity of results and the lack of historical and geological evidence prevent us from determining exactly where the deposits originated. For example, the similarity of Sand C and the Storm deposits in their geochemistry might lead to a suggestion that Sand C was deposited by a paleo-storm and not by a paleo-tsunami (c.f. [Jankaew et al., 2008](#)). However, Sand C is the thickest and most far-ranging paleo-overwash deposit preserved on Phra Thong Island, and Phra Thong Island is not impacted by storms capable of distributing sediments on this scale due to its geographical setting ([Jankaew et al., 2008](#)). Thus, the use of geochemical information in deriving a cause for such deposits is difficult to reconcile. In such cases, the term “large marine overwash

event” proposed by Switzer et al. (2014) should be used when the causes and provenance remain unknown.

5.2.3. Provenance of the storm deposit

The provenance of the Storm deposit is most likely from the onshore sediments preserved on the modern beach and beach berm based on the grain size (PAM_{GS} , PCA_{GS} , and DFA_{GS}) and trace element (PCA_{CHEM}) analysis. The DFA_{CHEM} analysis indicates separation of the Storm and Onshore deposits, but that the Storm deposits are very similar to the Sand C deposits.

5.2.4. Temporal geochemical variations – insights into post-depositional changes

It is important to study the temporal variations of elemental concentrations in order to understand the impacts of post-depositional changes and to validate the usefulness of sediment chemistry in paleo-tsunami deposits. However, only a few publications have investigated how tsunami deposits have become geochemically altered across different time scales and climate regions (e.g. [Szczuciński et al., 2006](#); [Szczuciński et al., 2007](#); Chagué-Goff et al., 2012a; Chagué-Goff et al., 2012b). Geological evidence on Phra Thong Island offers a unique opportunity to compare the modern tsunami deposits with three other paleo-tsunamis that, in turn, could provide more detail on geochemical signatures with more elements compared to previous works.

The concentration of 22 trace elements that have significant variations were plotted to compare between all of the tsunami deposits (Fig. 12). The results show that there is no consistent variability in the different tsunami deposits. In general, the trace elements can be divided into three sub-groups that have the same trends based on the elements' relative concentrations in each tsunami deposit. The first sub-group includes Sr, V and Cu that have high or very high concentrations in Sand A but are low or very low in the older tsunami deposits (Fig. 12); the second sub-group consists of elements that have the highest concentration in Sand B (Ni, La, Ce, Pb, Th, U, Y, Ba and Rb; Fig. 12); and, the third sub-group consist of elements that have the highest value in Sand D (Zr, Nb, Sn and Hf; Fig. 12). In two-thirds of the elements, Sand C deposits contain the lowest concentrations compared to the other three tsunami deposits (Fig. 12).

All observations in Sand A and paleo-tsunami deposits reveal that there is no simple trend in the temporal variation of the trace element chemistry on Phra Thong Island. This complexity might not be fully explained due to the lack of knowledge about how heavy-metal elements spatially vary in the marine system over time. In addition, local settings and depositional environment also play an important role in chemical alterations (Chagué-Goff et al., 2011). For example, based on the variations of Sr in our data set, we observe that Sr concentration is much higher in the modern deposits and very low in the three other prehistoric tsunami deposits (Fig. 12). The low Sr concentration in the deeper and older sand layers possibly corresponds to the lack of inorganic and biogenic carbonate microfossils in the deposits, which are rapidly dissolved due to elevated ambient temperatures and high

volumes of precipitation causing significant groundwater fluctuation through acidic peat-rich environments ([Jankaew et al., 2008](#); [Sawai et al., 2009](#)). In contrast to our results, [Chagué-Goff et al. \(2012a\)](#) reported very little difference in Sr concentration between the 2011 Tohoku-oki tsunami deposits and the 869 A.D. Jogan tsunami deposits in Japan highlighting the site-specific feature of geochemical signatures.

The evidence presented here from Phra Thong Island raises questions about the reliability of using geochemical signatures for studying paleo-tsunami deposits (e.g. sediment provenance). This differs from the recent study of [Kuwatani et al. \(2014\)](#) in which a set of chemical elements was proposed that could be used to identify tsunami deposits from surrounding sediments following the 2011 Tohoku-Oki earthquake. The method used in this study suggested that elements such as Na, Ca and Mg could be useful in discriminating tsunami deposits from other sediments, but this study lacks validation using the paleo-tsunami deposits. Ca and Sr have very similar chemical behaviour and our data show that Sr is strongly depleted in prehistoric deposits in Thailand (Fig. 12). Similarly, other metals that are easily transported as salts and carbonates (i.e. Na and Mg) also can be very quickly remobilized in short time periods. [Kuwatani et al. \(2014\)](#) also proposed other heavy metal elements (e.g. Cr, Cu, Pb) are useful to identify tsunami deposits, but our data show that these elements vary considerably between overwash deposits recorded at the same site. Hence, there is no guarantee that this set of elements can be widely applied.

5.2.5. Comparison of the statistical analyses

The use of three different statistical techniques allows us to compare between the techniques.

PAM analysis is based on simple Euclidean distance to assign samples, but both PCA and DFA have to solve more complicated matrices within and between groups. Our PAM results showed significant differences in the environments and overwash deposits with eight groups identified when the grain size parameters were examined. However, for the mineralogy and geochemistry, there was insufficient separation between the deposits and environments and in each case only two groups with samples from multiple environments and deposits were recognized. The mineralogical and geochemical analyses using PAM therefore were of little use in discriminating the deposits and identifying the provenance of the sediments in each deposit.

The PCA analysis proved to be a significant improvement on gaining insight into the complexity and inter-relationship between each of the grain size, mineralogical and geochemical parameters investigated. Applying bootstrap analysis to the eigenvalues to test for stability in the derivation of principal components has not been applied previously in coastal hazard studies and is a necessary step in evaluating the significance of each principal component. Achieving stability in the principal components indicates that the principal components derived from the data are not significantly different from random resampling of the data. This validation

of the principal components demonstrates that the sample size used in each PCA is sufficient to provide meaningful and accurate results on the relationship between parameters and sampling sites.

The results of the DFA analysis differed from the PCA analysis and were expected to do so. The PCA analysis seeks to define axes which maximize the variance of each variable to compare variables and individual samples in multivariate space, whereas the DFA seeks to identify a model of all of the variables to extract the maximum separation in multidimensional space. Thus the two methods can be used simultaneously and different information gleaned. Where the two methods agree further credence is added to identifying the provenance of overwash deposits or comparing between deposits. Where the two methods disagree, both methods can provide valuable insight into the nature of the sedimentary deposits.

6. Conclusions

In this study, we examined the use of grain size parameters, mineral composition and trace element geochemistry in determining the provenance of tsunami (the 2004 IOT and three paleo-tsunami) deposits and the 2007 storm surge deposit on Phra Thong Island, Thailand. We also evaluated whether the 2004 tsunami and 2007 storm deposits could be discriminated using grain size and geochemistry. Our statistical analyses, including cluster analysis, PCA and DFA, suggest that the two modern washover deposits are geochemically indistinguishable whereas the mean grain size of the sediment appears to be the only good discriminator of the storm

and the 2004 tsunami deposits. Therefore, the trace element composition cannot be used as diagnostic criteria to distinguish known tsunami and storm deposits from Phra Thong Island. If known storm and tsunami deposits cannot be distinguished using these criteria, can these criteria be used to distinguish unknown or hypothesised overwash processes?

Regarding the provenance of coastal overwash deposits, our statistical results reaffirm that the 2004 IOT deposits were mainly generated from the shallow nearshore environment, which is consistent with previous studies. Meanwhile, the provenance of palaeotsunami deposits is rather complicated and might not be fully explained by the data sets used in this study. Sand B is very likely a mixture of onshore and nearshore sediments but the sources of Sand C and Sand D are unclear. The difficulty in accurately identifying the provenance of the palaeotsunami deposits is probably compounded by past long-term offshore mining activities (for Sand B) and/or diagenetic alteration (for Sand C and Sand D). Thus, our findings cast doubt on the utility of performing sediment chemistry to discriminate overwash deposits, and to characterize the sediment source and source environment of overwash sediments. However, the statistics-based approach in this study is capable of providing meaningful insights into studies of coastal overwash deposits and shows promise for other locations where overwash deposits are preserved.

Acknowledgements

This research is supported by National Research Foundation Singapore (National Research Fellow Award No. NRF-RF2010-04) and the Singapore Ministry of

Education under the Research Centres of Excellence initiative. KJ thanks A1B1-2 grant (RES-A1B1-34) from the Faculty of Science, Chulalongkorn University for financial support to collect storm deposit samples. We thank Joshua Kartik for the finer fraction assistance, Ronnakrit Rattanasriampaipong for fieldwork assistance and Chuoi Tongjin for his hospitality. We also thank Asst. Prof. Jessica Pilarczyk for the editorial handling, Shigehiro Fujino and one anonymous reviewer for their constructive feedback on the manuscript. This work comprises Earth Observatory of Singapore contribution No. 88.

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Figure captions:

Figure 1: a) The regional map shows the location of Phra Thong Island (Ko Phra Thong - KPT), Thailand (red square); b) the detailed map shows the locations of the offshore samples, onshore samples and the local bathymetry; c) A close-up view of the pre-2004 onshore samples (yellow dots), storm samples (red triangle), Sand C (green square, samples were collected from 40-43 cm depth from a pit), Sand D (orange square, samples were collected from 75-77 cm depth from an auger core

(A10)) and the Jankaew et al. (2008)'s trench where Sand A and Sand B were taken; d) The stacked tsunami sand sheets from Jankaew et al. (2008)

Figure 2: Surface interpolation maps of the offshore sediment sample grain size parameters (the mean and sorting), quartz mineral (finer fraction) and selected trace elements. Sample labels are shown in Figure 1.

Figure 3: The PAM analysis for grain size parameters. (a) The number of groups and equivalent silhouette width. (b) The clustering structure of sample set, different colours differentiate clusters

Figure 4: The PCA analysis for grain size parameters. (a) The first two principal components (PCA1 versus PCA2); (b) The screeplot shows the ordination analysis (black line) versus the broken stick rule (red line).

Figure 5: The DFA analysis for grain size parameters. The graph shows the first two discriminant function analysis (DF1 versus DF2). The stacked histograms show the scores and power of separation of each group relative to the other groups.

Figure 6: The PAM analysis for mineral contents. (a) The number of groups and equivalent silhouette width. (b) The clustering structure of sample set, different colours differentiate the clusters.

Figure 7: The PCA analysis for mineral contents. (a) The first two principal components PCA1 versus PCA2; (b) PCA1 versus PCA3; (c) PCA2 versus PCA3; (d) The screeplot shows the ordination analysis (black line) versus the broken stick rule (red line).

Figure 8: The DFA analysis for mineral contents. The graph shows the first two discriminant function analysis (DF1 versus DF2). The stacked histograms show the scores and power of separation of each group relative to the other groups.

Figure 9: The PAM analysis for trace elements. (a) The number of groups and equivalent silhouette width. (b) The clustering structure of the sample set, different colours differentiate the clusters.

Figure 10: The PCA analysis for trace elements. (a) The first two principal components PCA1 versus PCA2; (b) PCA1 versus PCA3; (c) PCA2 versus PCA3; (d) The screeplot shows the ordination analysis (black line) versus the broken stick rule (red line).

Figure 11: The DFA analysis for trace elements. The graph shows the first two discriminant function analysis (DF1 versus DF2). The stacked histograms show the scores and power of separation of each group relative to the other groups.

Figure 12: The mean temporal variations of 22 trace elements (in ppm) between the 2004 IOT and the three paleo-tsunami deposits.

Table captions:

Table 1: Grain size parameters (mean, sorting, skewness and kurtosis) of sediment samples performed using the Malvern Mastersizer 2000.

Table 2: Mineral contents of finer fraction (in wt. %).

Table 3: Trace element concentrations of bulk samples (in ppm).

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Table 1

Groups	Sample codes	Mean (phi)	Sorting	Skewness	Kurtosis	Description
Deep-Offshore	PT-OS 03	1.577	1.601	0.465	1.59	Medium Sand, Poorly Sorted, Very Fine Skewed, Very Leptokurtic
Deep-Offshore	PT-OS 05	1.218	0.782	0.105	0.962	Medium Sand, Moderately Sorted, Fine Skewed, Mesokurtic
Deep-Offshore	PT-OS 13	0.999	0.89	0.242	1.246	Coarse Sand, Moderately Sorted, Fine Skewed, Leptokurtic
Deep-Offshore	PT-OS 15	1.275	0.994	0.228	1.398	Medium Sand, Moderately Sorted, Fine Skewed, Leptokurtic
Deep-Offshore	PT-OS 17	0.842	0.951	0.318	1.293	Coarse Sand, Moderately Sorted, Very Fine Skewed, Leptokurtic
Deep-Offshore	PT-OS 21	4.153	2.01	0.176	1.223	Very Coarse Silt, Very Poorly Sorted, Fine Skewed, Leptokurtic
Mean		1.67	1.2	0.25	1.28	
Nearshore	PT-OS 24	3.458	0.613	0.134	1.161	Very Fine Sand, Moderately Well Sorted, Fine Skewed, Leptokurtic
Nearshore	PT-OS 26	3.448	0.874	0.311	1.997	Very Fine Sand, Moderately Sorted, Very Fine Skewed, Very Leptokurtic
Nearshore	PT-OS 28	3.021	0.527	0.014	0.935	Very Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Nearshore	PT-OS 32	2.798	0.527	0.002	0.935	Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Nearshore	PT-OS 33	2.843	0.541	0.006	0.931	Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Nearshore	PT-OS 34	2.202	1.164	0.044	0.784	Fine Sand, Poorly Sorted, Symmetrical, Platykurtic
Mean		2.96	0.7	0.085	1.12	
Onshore	PT-02	1.971	0.557	0.01	0.938	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Onshore	PT-04	2.17	0.62	0.003	0.924	Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Onshore	PT-05	1.856	0.57	0.004	0.937	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Onshore	PT-07	1.996	0.671	-0.012	0.94	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Onshore	PT-07(S)	1.24	0.639	0.027	0.921	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic

Onshore	PT-08	1.75	0.667	0.035	0.933	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Onshore	PT-09	1.692	0.62	0.021	0.932	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Onshore	PT-11	1.848	0.674	0.015	0.936	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Mean		1.81	0.63	0.01	0.93	
Sand A	PT-CT04 19	3.157	0.707	-0.068	1.061	Very Fine Sand, Moderately Sorted, Symmetrical, Mesokurtic
Sand A	PT-CT04 18	3.205	0.639	-0.064	0.989	Very Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Sand A	PT-CT04 11	3.052	0.812	-0.196	1.16	Very Fine Sand, Moderately Sorted, Coarse Skewed, Leptokurtic
Sand A	PT-CT04 09	3.09	0.624	0.04	1.046	Very Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Mean		3.126	0.7	0.072	1.064	
SandB	PT-CTpaleo06	3.061	0.858	-0.239	1.247	Very Fine Sand, Moderately Sorted, Coarse Skewed, Leptokurtic
SandB	PT-CTplaeo07	3.152	0.567	0.063	1.049	Very Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
SandB	PT-CTpaleo11	3.165	0.585	-0.017	0.937	Very Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
SandB	PT-CTpaleo10	3.028	0.657	-0.077	0.991	Very Fine Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Mean		3.1	0.67	0.067	1.056	
SandC	SandC 1	2.696	1.188	0.008	1.63	Fine Sand, Poorly Sorted, Symmetrical, Very Leptokurtic
SandC	SandC 2	2.818	1.074	0.165	1.675	Fine Sand, Poorly Sorted, Fine Skewed, Very Leptokurtic
SandC	SandC 3	2.839	1.039	0.18	1.706	Fine Sand, Poorly Sorted, Fine Skewed, Very Leptokurtic
Mean		2.78	1.1	0.12	1.67	
SandD	SandD 1	1.315	0.961	0.24	1.092	Medium Sand, Moderately Sorted, Fine Skewed, Mesokurtic
SandD	SandD 2	1.557	1.164	0.287	1.115	Medium Sand, Poorly Sorted, Fine Skewed, Leptokurtic
Mean		1.44	1.06	0.26	1.1	
Storm	Storm 1	1.554	0.552	0.01	0.934	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic
Storm	Storm 2	1.588	0.605	0.016	0.926	Medium Sand, Moderately Well Sorted, Symmetrical, Mesokurtic

Storm	Storm 3	1.583	0.559	0.002	0.934	Medium Sand,Moderately Well Sorted,Symmetrical,Mesokurtic
Mean		1.57	0.57	0.01	0.93	

Table 2

Groups	Sample codes	Quartz (%)	Labradorite (%)	Orthoclase (%)	Microcline (%)	Aragonite (%)	Zircon (%)	Cassiterite (%)	Monazite (%)	Kaolin (%)	Muscovite (%)
Deep-Offshore	PT-OS 03	38.8	2.2	9.6	4.8	12.6	1.4	0.5	3.5	2.6	7.8
Deep-Offshore	PT-OS 05	44	2	16.1	10.1	13.7	5.3	0.7	3	0.9	3.8
Deep-Offshore	PT-OS 07	38.7	1.8	12	1.3	9.7	1.2	0.2	2.9	1.3	9.3
Deep-Offshore	PT-OS 13	59.9	0.5	10.5	5.7	6.4	3.1	0.7	2.2	1.7	6.2
Deep-Offshore	PT-OS 15	42.1	3.2	7.4	7.8	8.7	2.2	0.8	3.5	3.5	9.4
Deep-Offshore	PT-OS 17	40.1	2.9	10.5	10.5	10.1	4.5	1.7	4.2	1.8	6.7
Deep-Offshore	PT-OS 21	63.3	0.6	7.8	9.1	5.3	2.1	0.6	1.9	1.5	3.9
Deep-Offshore	PT-OS 22	64.7	1.6	9.1	8.2	5.3	2.4	0.6	1.5	1.9	2
Nearshore	PT-OS 24	65.5	0.8	9.3	6.7	9.2	3.4	1.1	1.4	0.8	1.6
Nearshore	PT-OS 26	56.3	0.5	12.5	8.4	11.4	4.2	1.1	2.3	0.6	2.7
Nearshore	PT-OS 28	46.5	1.1	14.5	9.5	11.1	6.6	0.9	2.6	1.7	4.8
Nearshore	PT-OS 32	61.1	0.7	12.4	7.6	7.4	4.1	1	1.9	1.1	2.8
Nearshore	PT-OS 33	78.4	0.3	7.5	5.2	3.3	2.4	0.4	1.5	0.6	3.1*
Nearshore	PT-OS 34	58.7	1	11.1	8	9.6	3.4	1.6	1.7	0.9	3.9
Onshore	PT-02	53.4	1.7	14.3	8.7	8.2	5.6	1.2	2	1	3.9
Onshore	PT-04	56.3	0.9	13.6	8.4	7.8	4.6	1.6	2.2	1	3.5
Onshore	PT-05	45.7	1.6	14.9	10.6	10	7.3	0.8	2.4	1.2	4.4

Onshore	PT-07	57.1	1	12.5	8.5	7.3	5.3	1.1	2.4	1	2.6
Onshore	PT-07 (s)	37.6	1	14.9	13.1	12.3	8.3	1	1.8	1.7	6.6
Onshore	PT-08	49.6	1.7	14	9.4	8.9	7.7	1.1	2.2	0.9	4.4
Onshore	PT-09	37.3	1.2*	12.7	9.4	9.2	13.5	3.8	1.3	2.6	6.6
Onshore	PT-11	47.8	0.5	10.7	8.2	6.7	12.3	3.1	1.4	1.4	5.7
SandA	PT CT 04										
	09	52.1	1.4	13.8	9	12	4.6	1	2.4	0.9	2.9
SandA	PT-CT 04										
	11	57	0.3	11.8	8.7	10.1	3.7	1.4	1.8	1.2	3.9
SandA	PT-CT 04										
	18	51.2	1.5	14	9	12.4	4.8	0.9	2.5	0.9	2.8
SandA	PT-CT 04										
	19	53.8	1.1	12.9	9.8	11	4.7	1.1	2.2	0.5	2.8
SandB	PT-CT 06										
	pal	44.6	2.6	13.6	10.8	11	6.3	0.6	2.9	1.3	4.9
SandB	PT-CT 07										
	pal	48.5	1.4	14.5	9.9	8.9	6.2	1	2.6	1.3	4.8
SandB	PT-CT 10										
	pal	53.2	1.4	13.3	8.5	9.2	6.7	1	2.4	1.2	3.1
SandB	PT-CT 11										
	pal	53.9	1.5	11.7	9.6	8.1	6.4	1.2	2.1	1.2	4.1

*: missing values, replaced by the mean of group

Table 3

Groups	Sample codes	V (ppm)	Cr (ppm)	Ni (ppm)	Cu (ppm)	As (ppm)	Se (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Nb (ppm)	Sn (ppm)	Ba (ppm)	La (ppm)	Ce (ppm)	Hf (ppm)	Pb (ppm)	Th (ppm)	U (ppm)	Y (ppm)	Cs (ppm)	Ga (ppm)	Bi (ppm)
Deep-Offshore	PT-OS 03	18.7	22.2	12	7.5	0.5	3.3	20.4	50.1.7	91.7	5.8	23	31.5	5.9	8.1	0.4	6.2	9.6	0.5	9.2	7.3	5	2.1
Deep-Offshore	PT-OS 05	7	13.2	5.5	5.8	0.5	2.9	19.8	35.6.2	50.1	3	7.2	24.8	6.7	0.7	0.5	3.3	5.4	0.5	5.6	2	2.4	2.1
Deep-Offshore	PT-OS 07	15.5	17.8	5.9	7.8	0.5	3.1	32.1	59.2.6	32.8.3	11.2	206	48.8	8.6	35.3	4.5	6.3	14	1.6	13.9	2	4.6	2.1
Deep-Offshore	PT-OS 13	9.7	8.4	5.6	6.1	3.2	3.4	10.3	18.4.8	11.9.5	8.4	35.6	22.3	7.1	10.9	3.6	3.4	9.2	0.5	8.6	2	3	2.2
Deep-Offshore	PT-OS 15	12.8	12.9	5.4	7.2	9	2.9	11.8	23.5.7	60	3.4	12.6	17.8	4.5	4.5	0.3	4.4	9.8	0.5	7.5	2	2.9	2.3
Deep-Offshore	PT-OS 17	10.3	12.3	7	6.8	3	3.9	11.1	20.4.2	57.4	4.5	35.2	10.1.5	8	13.1	1.7	3	7.7	0.5	6.8	2	3	2.9
Deep-Offshore	PT-OS 21	46.9	36.6	16.7	12.5	8.6	2.6	160.8	56.3.8	43.8.7	24.3	47.9	111.6	41.9	108.3	8.8	35.2	49.2	0.5	35.2	18.8	15.7	2.9
Deep-Offshore	PT-OS 22	44	39.8	12.5	10.1	17.2	1.4	100.7	72.9.6	30.6.6	17.5	45.9	84.9	12.5	66.3	7.6	28.8	33.6	4.8	27.2	2	10.3	1.9

Nears	PT-		15.					117	60	15	29.	63.	81.	101		32.	18.	105	16.	87.			
hore	OS 24	5	1	9.9	8.5	1	3.1	.8	1.8	81	4	6	2	.7	266	1	9	.5	7	9	2	7.1	2.8
Nears	PT-							113	59	11	24.	52.	75.	82.		24.	21.	80.	10.	69.			
hore	OS 26	11	16	8.8	7.8	3.7	2.3	.5	5.8	44	4	6	6	5	183	4	1	4	4	8	2	7.2	2.6
Nears	PT-		16.	11.				63.	34	26	45.	120	49.			55.	14.	152	24.	13			
hore	OS 28	5.4	9	8	8.6	0.5	3.5	7	5.9	87	4	.3	6	159	346	8	7	.7	7	9.3	2	5.1	3.3
Nears	PT-		10.					62.	37	93	18.	63.	54.	75.	131	17.	10.	54.		45.			
hore	OS 32	5.2	1	6.3	7.9	1.2	2.7	8	6.3	6.6	9	2	8	7	.3	9	6	5	6.8	5	2	5.1	2.3
Nears	PT-		11.					70.	48	12	21.	91.	58.	67.	181	23.	12.	81.		61.			
hore	OS 33	4.8	1	5.7	7.2	1.4	2.3	2	3.5	69	6	3	8	3	.4	7	1	3	9.9	6	2	4.5	2
Nears	PT-		12.					64.	40	11	65.	152	57.	38.	71.	21.	12.	44.		49.			
hore	OS 34	6.7	4	5.3	7.2	2	2.1	6	6.6	63	8	.7	3	9	4	2	4	3	7.6	3	2	5.2	1.8
Onsh		11.						11.		49		61.		15.	33.	13.		14.		15.			
ore	PT-02	1	7.5	9.7	7.8	0.5	4.8	1	3.2	7.2	18	8	1.5	2	4	1	0.8	8	1.6	9	2	3	3.3
Onsh								18.		37	14.	45.	23.	15.		10.		10.		13.	11.		
ore	PT-04	8	5.8	9.9	7.9	0.5	5.8	3	4.5	6	3	4	4	1	0.5	8	1.4	5	0.6	4	3	3.5	3.2
Onsh			11.						66.	10	48.	100		33.	63.	22.		26.					
ore	PT-05	6.6	8.5	4	8.3	0.5	5.7	11	7	62	2	.2	1.5	5	6	7	2.6	5	5.9	35	2	5	3.5
Onsh					10.			20.	10	70	34.	64.	26.	17.				12.		19.			
ore	PT-07	5.4	7.8	6.3	3	0.5	4.4	9	8.9	3.5	4	6	8	5	0.5	14	3.9	8	3.9	3	2	4.1	2.6
Onsh	PT-07				12.				12	11		164		32.	63.	25.		25.		38.			
ore	(s)	0.5	13	6.8	3	0.5	4.4	10	7.8	90	85	.9	1.5	2	3	3	5.3	6	7.8	7	2	4.4	2.8
Onsh			13.	11.				10.	11	15	116	273	21.	38.	95.	35.		34.					
ore	PT-08	7.3	4	7	8.3	0.5	7	2	6.1	36	.6	.3	6	5	6	2	5.6	1	9.5	55	2	6.7	4.2
Onsh			25.						92.	47	400	127	15.	105		94.	22.	97.	31.	17			
ore	PT-09	0.5	6	9.7	7.2	0.5	1.9	8.6	6	24	.3	6	4	.6	253	2	7	1	7	0.4	2	5.1	0.5
Onsh			23.	11.				11.	12	50	329			85.		102	18.		35.	16			
ore	PT-11	0.5	1	1	7.5	0.5	3.5	7	7.3	69	.8	952	1.5	6	230	.9	6	110	3	5.8	2	5.9	2.2
Sand	PT CT								48	83								46.					
A	04 09	16	16	11	9	0.5	6.6	81	8	1	22	64	63	48	104	20	1	1	9.2	41	3.5	8	0.5

Sand A	PT-CT 04 11	13.5	12.7	6	8.6	1.8	1.2	81.2	49.5.6	90.6.7	23.8	78.8	64	50	108.6	20.3	13.5	47.9	10.9	44.7	2	2.9	0.5
Sand A	PT-CT 04 18	13.9	14	5.9	4	0.5	2.3	83.2	46.8.4	93.7.3	79.24	62.6	46.4	103.1	17.9	13.6	51.8	11.8	46.3	11.8	6	2.2	
Sand A	PT-CT 04 19	11.7	16.1	5.7	8.8	0.5	1.4	82	5.8	0.2	8	5	1	3	.3	8	8	9	9.9	1	2	3.3	0.5
SandB	PT-CT 06									21								159	20.	11			
SandB	pal PT-CT 07	7	15	13	4	0.5	10	93	19	34	35	144	70	162	379	53	1	.7	2	7	3.5	8	0.5
SandB	pal PT-CT 10	2.1	14.6	15.4	11.4	0.5	6.8	93.8	15.9	21.92	35.6	152.8	76.1	174.6		49.1	15.8	165.8	21.7	11.8.4	10.3	7.8	4.9
SandB	pal PT-CT 11	2.9	11.5	14.1	12.6	0.5	6.2	90.5	15.3	18.18	35.1	137.2	66.2	122.1			14.1	129.6	17.5	96.6	2	8.2	4.3
SandB	pal Sand	0.5	11.7	12.6	12.2	0.5	5.5	90.2	15.1	18.95	35.3	150.3	64.7	141.9	281.7	41.2	14.5	135.4	19.1	10.0.7	8.7	7	3.8
SandC	C 1	3	9	6	6	0.3	3	37	7	6	7	28	52	15	35	4	5	8.4	1.1	10	3.5	4	2
SandC	C 2	1	6	5	5	0.3	3	29	5	1	4	9	42	1	15	3	4	6.3	1	7	3.5	3	2
SandC	C 3	4	10	6	6	0.3	3	70	20	9	13	39	67	39	72	13	12	1	4.1	30	3.5	5	2
SandD	D 1	0.5	17	7	5	0.3	3	10	30	44	191	701	23	69	129	56	10	2	4	90	3.5	4	2
SandD	D 2	0.5	15	7	4	0.3	3	11	29	79	155	443	23	71	121	53	9	4	5	86	3.5	3	0.5
Storm	Stor m 1	0.5	10.1	7.2	5.7	0.3	3.1	62.8	77.15	9.5	16	52	5	9	8	9	9	6	6.6	4	3.5	4.8	2

	Stor		14.					11.	26.	12	95.	241		22.	49.	23.		26.		41.				
Storm	m 2	0.5	5	5.6	7.2	0.3	3	5	9	40	3	.4	0.7	7	7	6	5.4	6	7.6	3	3.5	5	2.4	
	Stor							70.	16.	67	14.	42.	74.	48.	77.	13.	12.	34.		32.				
Storm	m 3	1.8	11	6.7	5.9	0.3	2.9	5	6	7.1	9	4	3	9	7	4	4	6	5.7	3	3.5	4.3	1.7	

Table 4

	V	Cr	Ni	Cu	As	Se	Rb	Sr	Zr	Nb	Sn	Ba	La	Ce	Hf	Pb	Th	U	Y	Cs	G a
V																					
C	0.71																				
r	***																				
N	0.36	0.49																			
i	*	**																			
C	0.34		0.42																		
u	*	0.25	**																		
A	0.78	0.65		0.1																	
s	***	***	0.21	9																	
S	-	-	0.54	0.0																	
e	0.21	0.27	***	7	-0.3																
R	0.45	0.37	0.43	0.4	0.3	-															
b	**	*	**	2**	1	0.04															
S	0.66	0.53		0.2	0.4	0.47	0.49														
r	***	***	0.01	8	7**	**	**														
Z	-			-	-																
r	0.40			0.0	0.2			-	0.2												
	*	0.25	0.31	2	7	0.12	0.08	5													
N				0.1	0.1	-	0.35	0.2	0.88												
b	-0.3	0.32	0.11	2	7	0.07	*	5	***												
S				0.1	0.1	-	0.34	0.2	0.87	0.98											
n	-0.3	0.32	0.1	5	8	0.08	*	4	***	***											
B	0.42	0.32	0.31	0.2	0.2	-	0.94	0.4		-	-	-									

2

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***: significant for $p < 0.001$, **: significant for $p < 0.01$ and *: significant for $p < 0.05$

Table 5

	Ni	Rb	Sr	Zr	Sn	Ba	Hf	Pb	Th	U	Ga
Ni	0.63										
Rb	*										
		0.81*									
Sr	0.55	*									
Zr	0.21	0.46	0.36								
				0.77*							
Sn	0	0.33	0.19	*							
	0.61	0.98*	0.83*								
Ba	*	**	**	0.46	0.37						
				1.00*	0.74						
Hf	0.23	0.46	0.34	**	**	0.45					
	0.74	0.97*	0.74*			0.95*					
Pb	**	**	*	0.4	0.29	**	0.4				
				0.97*	0.64		0.98*				
Th	0.34	0.58*	0.46	**	*	0.56	**	0.52			
				0.98*	0.66		0.98*		0.96*		
U	0.18	0.39	0.33	**	*	0.37	**	0.31	**		
	0.82	0.88*				0.87*		0.95*		0.0	
Ga	**	**	0.66*	0.15	0.12	**	0.16	**	0.29	6	
Me	0.61	0.96*	0.80*			0.96*		0.93*	0.74*	0.5	0.80
an	*	**	*	0.63*	0.42	**	0.62*	**	*	6	**

***: significant for $p < 0.001$, **: significant for $p < 0.01$ and *: significant for $p < 0.05$