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Geochemical Classification and Determination of Maturity Source Weathering in Beach Sands of Eastern San' in Coast, Tango Peninsula, and Wakasa Bay, Japan

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Abstract

Geochemistry of beach sand sediments collected from the Eastern San'in coast (n=17), Tango Peninsula (n=14) and Wakasa Bay (n=7) shorelines were investigated using XRF analyses for major and trace elements to characterize their composition, classification, maturity, provenance, tectonic setting and degree of weathering in source areas. Investigated sands from all sites were very similar showing depletion in all elements except SiO_2, K_2O and As relative to the UCCN and JUCN, suggesting a moderate geochemical maturation. Beach sand sediments from these locations can be classified as arkose, subarkose and litharenite that are chemically immature and formed under arid/semi-arid conditions with a tendency towards increasing chemical maturity suggesting that they are from multiple sources. The relatively low to moderate values of weathering indices of Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA) and Chemical Index of Weathering (CIW), the beach sands from all sites in the source area have undergone low to moderate degree of chemical weathering. A-CN-K and A-CNK-FM plots, which suggest a granitic source composition, also confirm that the sand samples from these sites have undergone low to moderate degree of chemical weathering in consistent with CIA, PIA and CIW values. A plot of the analyzed beach sands data on the provenance discriminating function F1/F2 showed that most of the investigated beach sand sediments in all locations fall within mafic to intermediate ocean island arc source; similar to the tectonic setting discrimination diagrams based on major elements suggesting a passive margin.

Keywords: beach sands, provenance, weathering, geochemistry, chemical maturity

1. Introduction

The composition of coastal sediments is influenced by numerous components and processes, which contain important information about geochemical composition, weathering conditions and tectonic settings of the provenance and associated depositional basins. Beach sands are composed mainly of quartz, feldspar and other minerals resistant to wave abrasion and are products of a combination of weathering, fragmentation and degradation (Pettijohn et al., 1987). The geochemistry of clastic sediments can be effectively utilized for the evaluation of tectonic setting and provenance determination (Bhatia, 1983; Roser & Korsch, 1986, 1988; Condie et al., 1992). Tectonic setting discrimination diagrams based on major elements proposed by Roser & Korsch (1988, 1988) has been applied to this study to estimate the provenance and its tectonic setting. Chemical weathering indices such as Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA) and Chemical Index of Weathering (CIW) are commonly used for characterizing weathering profiles. These indices incorporate the bulk of major element oxide chemistry into a single value for each sample. In order to evaluate the chemical weathering intensity, the investigated beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay were subjected to weathering indexes such as CIA, PIA and CIW. For further interpretation, a variety of triangular and scatter plots were also constructed from the geochemical data obtained. Other important reference compositions such as average Upper Continental Crust (UCC) (Rudnick & Gao, 2005) and average

Japan arc Upper Crust (JUC) (Togashi & Imai, 2000) estimated from the representative surface rocks were also included for comparison.

The present study examines the geochemistry of sand samples collected from beaches on the Eastern San'in coast, Tango Peninsula and Wakasa Bay. The main purpose of the present is to determine their classification, maturity, sediment source area weathering, provenance and tectonic settings and to shed light on the source area paleo-weathering conditions in these sites. These factors were evaluated using elemental abundances, weathering indices and elemental ratios in comparison to the average Upper Continental Crust (UCC) and average Japan arc Upper Crust (JUC) as estimated from the representative surface rocks. This study summarizes the results of an investigation on beach sand samples from Eastern San'in coast (Hyogo and Kyoto Prefecture), Tango Peninsula (Kyoto Prefecture) and Wakasa Bay (Fukui Prefecture), southwest Japan.

2. Sampling and Analytical Methods

Locations of sampled sites are given in Figure 1.

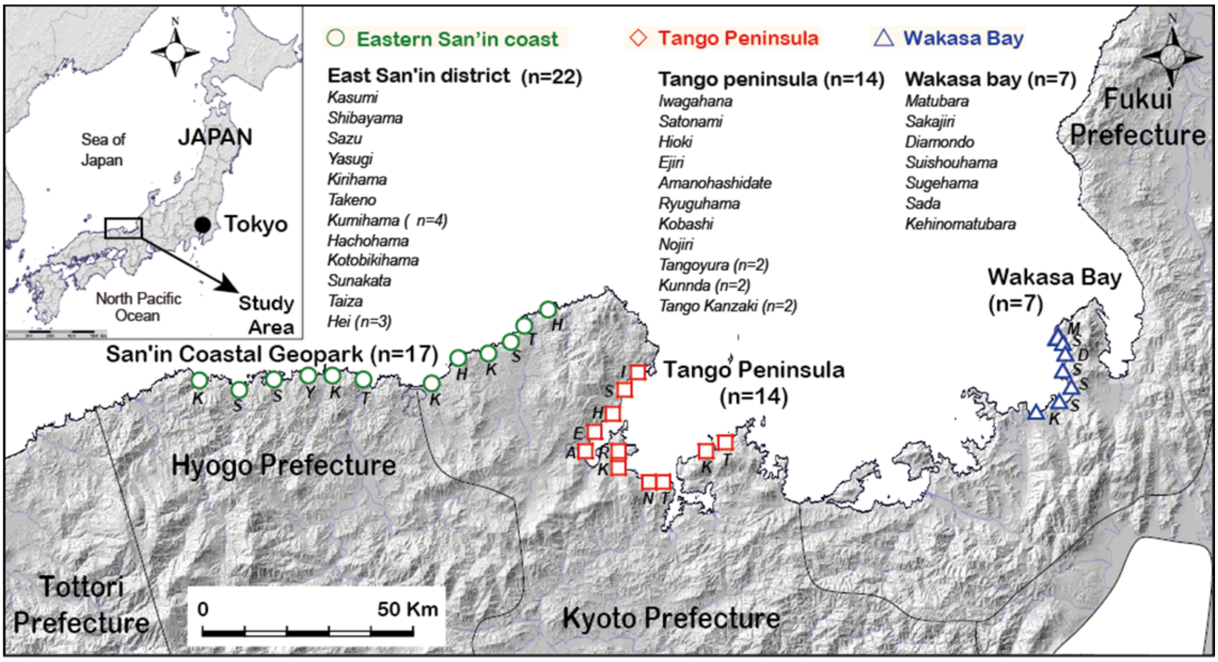

Figure 1. Location of sampled beaches on the Eastern San'in coast, Tango Peninsula, and Wakasa Bay shorelines, Japan

Sampling sites were selected based on accessibility and the character of the beach.Sampling was carried out at moderate to low tides, based on tidal information available from the Japan Meteorological Agency and beach sand samples were collected using a stainless steel scoop from the uppermost centimeters in selected locations. Approximately 200 g of sand samples was collected from the foreshore of thirty-eight beaches along the Japan Sea coast. These included Eastern San'in coast (n=17), Tango Peninsula (n=14) and Wakasa Bay (n=7) (Figure 1). The sand samples were oven-dried at 110°C for 24 hours then crushed in an automatic agate mortar and pestle grinder. Contents of major (SiO_2, TiO_2, Al_2O_3, $Fe_2O_3^*$, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5) and trace (As, Pb, Zn, Cu, Ni, Cr, V, Sc, Y, Nb, Zr, Th, and Sr) elements were determined by X-ray fluorescence (XRF) at Shimane University using RIX-2000 Spectrometer (Rigaku Denki Co. Ltd) following the Ogasawara (1987) method. Contents of major elements were obtained on fused glass discs by the pre-ignited materials with an alkali flux involving 80% lithium tetraborate ($Li_2B_4O_7$) and 20% lithium metaborate ($LiBO_2$). Trace element abundances were determined by pressing prior powdered sand samples into a 40 mm diameter plastic rings using 200 kN force for one minute in an automatic pellet press (E-30 T.M Maekawa) Average errors for the analyzed elements are less than ±10%).

3. Results and Discussion

3.1 Major and Trace Elements Geochemistry

Data on geochemical composition of sand samples from the studied sites is shown in Table 1.

For comparison with the Upper Continental Crust (UCC) (Rudnick & Gao, 2005) and Japan arc Upper Crust (JUC) (Togashi & Imai, 2000) estimated from the representative surface rocks, means of major elements (Table 2a) and trace elements (Table 2b) are also shown.

Table 1. Major (wt%) and trace element (ppm) composition of beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay, Japan

Sample/	Major Elements (wt%)										CIA	CIW	PIA	Trace Elements (ppm)												
Location	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^*$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5				As	Pb	Zn	Cu	Ni	Sc	V	Sr	Y	Nb	Zr	Th	Cr
East San'in coasts (n=17)																										
Kasumi	84.67	0.24	7.42	1.70	0.04	0.54	2.08	1.42	1.87	0.04	48	55	47	3	15	9	5	-	1	9	172	17	2	45	1	2
Shibayama	66.82	0.34	11.86	3.31	0.04	1.27	11.21	2.50	2.56	0.08	51	58	52	4	13	8	3	2	4	21	157	15	3	48	1	27
Sazu	87.86	0.11	6.83	0.75	0.02	0.17	0.33	1.25	2.67	0.01	55	72	60	8	14	16	4	5	10	55	181	15	4	53	2	90
Yasugi	80.11	0.14	10.31	1.02	0.02	0.25	1.70	1.65	4.78	0.02	49	64	47	3	13	3	3	-	-	-	117	15	3	44	2	3
Kirihama	69.06	0.27	8.76	1.99	0.03	0.90	13.77	1.62	3.55	0.06	48	62	47	22	11	20	2	8	5	21	222	13	3	63	3	34
Takeno	41.89	0.31	5.30	2.45	0.06	2.22	43.35	1.53	2.78	0.10	40	51	31	16	12	8	3	2	-	-	142	12	2	48	3	20
Kumihama 1	74.35	0.24	9.74	2.22	0.05	1.00	7.45	1.63	3.27	0.04	52	64	53	12	11	12	4	1	13	5	350	12	2	51	2	4
Kumihama 2	72.58	0.69	9.78	3.89	0.08	1.35	7.34	1.44	2.82	0.04	55	67	58	26	14	34	4	17	15	38	473	19	2	55	3	33
Kumihama 3	83.53	0.12	7.64	1.18	0.02	0.41	2.77	1.35	2.94	0.02	49	62	49	27	15	45	6	21	14	89	472	19	5	91	4	139
Kumihama 4	81.07	0.18	8.50	1.72	0.03	0.64	3.53	1.49	2.81	0.02	51	62	52	19	13	17	1	7	6	9	221	17	3	66	2	12
Hachohama	84.24	0.09	6.35	0.85	0.02	0.31	4.79	1.14	2.19	0.02	50	62	51	22	14	28	2	14	7	28	266	17	3	66	3	31
Kotobikihama	88.19	0.07	6.17	0.65	0.01	0.16	1.51	0.99	2.25	0.01	48	59	46	9	9	25	4	-	46	19	1315	16	-	-	2	3
Sunakata	83.80	0.19	7.27	1.73	0.03	0.56	3.17	1.16	2.06	0.02	54	65	56	15	12	24	5	-	25	19	826	19	1	76	4	2
Taiza	86.04	0.07	7.92	0.43	0.02	0.14	0.61	1.34	3.42	0.01	53	71	56	11	16	17	2	-	2	9	168	26	4	71	4	-
Hei 1	81.09	0.12	10.46	0.97	0.02	0.32	1.30	2.05	3.65	0.02	52	65	53	4	14	16	1	-	-	3	66	18	4	61	3	-
Hei 2	82.38	0.16	9.27	1.43	0.03	0.47	1.55	1.92	2.78	0.02	51	61	51	13	18	68	10	3	24	43	670	17	2	39	5	15
Hei 3	78.64	0.26	10.06	2.51	0.04	1.16	2.66	2.07	2.58	0.03	48	55	47	5	13	20	5	3	4	27	186	12	3	84	3	14
Tango peninsula (n=14)																										
Iwagahana	78.13	0.12	12.44	1.04	0.02	0.34	1.23	2.89	3.78	0.02	53	64	55	4	15	21	3	1	2	15	170	19	2	67	2	10
Satonami	81.01	0.06	10.85	0.54	0.01	0.20	1.17	2.45	3.70	0.01	52	64	53	3	15	8	5	11	-	-	149	18	2	47	1	12
Hioki	81.19	0.09	11.54	0.78	0.02	0.28	0.87	2.54	2.67	0.01	57	67	60	4	14	17	2	-	-	22	151	17	3	64	3	19
Ejiri	82.00	0.09	10.07	0.70	0.02	0.38	1.43	2.50	2.80	0.01	51	60	51	3	13	10	2	11	2	2	153	15	3	52	3	56
Amanohashidate	80.93	0.11	11.18	0.85	0.02	0.27	1.11	2.39	3.12	0.01	55	65	57	4	15	17	3	3	-	1	153	16	3	58	2	29
Ryuguhama	83.21	0.03	9.06	0.36	0.01	0.17	2.21	1.78	3.17	0.01	49	60	48	6	12	7	1	-	5	-	198	18	2	45	2	18
Kobashi	74.28	0.05	11.29	0.63	0.02	0.30	7.20	2.42	3.79	0.02	48	58	46	7	12	13	-	-	12	-	456	18	2	41	2	8
Nojiri	73.16	0.21	12.11	2.18	0.04	1.18	5.16	2.75	3.18	0.03	48	56	48	10	13	35	5	52	11	31	358	17	3	72	4	227
Tangoyura a	77.19	1.46	9.09	5.35	0.12	1.48	2.94	1.11	1.21	0.04	52	56	52	14	12	60	13	33	15	193	165	16	9	127	6	220
Tangoyura b	84.60	0.35	8.03	2.72	0.05	0.80	0.74	1.20	1.47	0.03	62	71	67	12	11	48	11	26	3	73	88	14	6	83	4	68
Kunnda a	86.61	0.12	7.65	0.78	0.02	0.29	0.64	1.44	2.45	0.01	55	69	59	3	12	16	4	3	1	8	102	15	4	65	3	36
Kunnda b	84.14	0.09	9.21	0.72	0.02	0.18	0.77	1.53	3.34	0.01	55	70	59	2	15	19	8	-	-	2	117	16	3	59	3	22
Tango Kanzaki a	82.53	0.45	8.71	3.42	0.06	1.05	0.91	1.33	1.51	0.04	62	70	65	18	12	58	12	31	7	112	93	15	7	93	4	66
Tango Kanzaki b	85.26	0.31	7.60	2.53	0.05	0.73	0.70	1.29	1.49	0.03	61	70	64	20	11	42	8	23	3	62	87	13	5	79	3	41
Wakasa bay (n=7)																										
Matubara	84.17	0.43	7.58	3.20	0.06	0.88	0.86	1.08	1.65	0.09	61	71	65	7	12	42	14	20	7	59	61	18	5	77	5	44
Sakajiri	82.15	0.31	9.58	2.07	0.06	0.52	1.04	1.61	2.59	0.06	57	69	61	9	17	50	6	12	3	26	118	21	5	96	8	39
Diamondo	90.31	0.02	5.55	0.25	0.01	0.04	0.12	0.63	3.06	0.00	55	82	64	-	-	-	-	-	-	-	-	-	-	-	-	-
Suishou	87.81	0.03	6.79	0.44	0.01	0.05	0.17	0.96	3.74	0.01	54	79	60	9	16	5	1	7	-	-	18	28	4	41	4	42
Sugehama	80.75	0.13	10.27	1.31	0.03	0.22	0.79	1.46	5.02	0.02	53	73	56	7	19	42	4	8	-	-	63	35	8	62	6	26
Sada	83.24	0.18	7.71	1.46	0.04	0.36	2.99	1.39	2.59	0.04	51	62	51	11	16	33	3	8	5	2	185	19	3	87	5	32
Kehinomatubara	85.36	0.09	8.18	0.96	0.03	0.17	0.26	1.51	3.42	0.02	55	74	61	4	17	18	3	11	-	-	39	28	4	54	8	28

Results showed that SiO_2, dominated the analyzed sand samples averaging 78.02wt% (Eastern San'in coast sands), 81.02wt% (Tango Peninsula sands) and 84.83wt% (Wakasa Bay sands) (Table 2a). Except for the samples from the Shibayama, Kirihama, and Takeno beaches with (66.82wt%; 69.06wt%; and 41.89wt %) respectively, SiO_2 contentswere relatively high in other sites. Contrary to their lower SiO_2 contents, the beach sands from Shibayama, Kirihama and Takeno had distinctively high CaO contents of 11.21wt%; 13.77wt% and 43.35wt% respectively (Table 1). The high SiO_2 concentrations result in low contents of other elements, with Al_2O_3 contents of between 5.30 to 11.86wt% in Eastern San'in coast sands, 7.60 to 12.44wt% in the Tango Peninsula and 5.55to 10.27wt% Wakasa Bay sands (Table 2a). Average Al_2O_3 contents are 8.45wt% in the Eastern San'in coast sands, 9.92wt% for the Tango Peninsula sands and 7.95wt% in the Wakasa Bay sands (Table 2a). Concentrations of the remaining major elements that are present in abundant amounts (TiO_2, $Fe_2O_3^*$, MnO, MgO, Na_2O, K_2O and P_2O_5) were generally <5wt% and often <1wt% (Table 2a). Among the trace elements, the contents of ferromagnesian elements (Ni, Cr, V and Sc) and large cations (Y, Nb, Zr, Th and Sr) tended to be less abundant in contrast with average values of the Upper Continental Crust (UCC) and the Japan arc Upper Crust (JUC) (Table 2b). Box plots for major elements composition in beach sand samples of Eastern San'in coast, Tango Peninsula and Wakasa Bay are illustrated in Figure 2. Sand samples from Wakasa Bay have the highest mean SiO_2 content and the highest median K_2O content, but contained the lowest mean and median concentrations of Al_2O_3, MnO, MgO, CaO, and Na_2O.

Table 2a. Summary statistics of major element abundances in beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay, Japan compared to UCC (Rudnick & Gao, 2005) and JUC (Togashi & Imai, 2000)

Sample/	Major Elements (wt%)												
Location	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^*$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CIA	CIW	PIA
East San'in coasts (n=17)													
Average	78.02	0.21	8.45	1.69	0.03	0.70	6.42	1.56	2.88	0.03	50	62	50
Max	88.19	0.69	11.86	3.89	0.08	2.22	43.35	2.50	4.78	0.10	55	72	60
Min	41.89	0.07	5.30	0.43	0.01	0.14	0.33	0.99	1.87	0.01	40	51	31
Tango peninsula (n=14)													
Average	81.02	0.25	9.92	1.61	0.03	0.55	1.93	1.97	2.69	0.02	54	64	56
Max	86.61	1.46	12.44	5.35	0.12	1.48	7.20	2.89	3.79	0.04	62	71	67
Min	73.16	0.03	7.60	0.36	0.01	0.17	0.64	1.11	1.21	0.01	48	56	46
Wakasa bay (n=7)													
Average	84.83	0.17	7.95	1.38	0.03	0.32	0.89	1.24	3.15	0.03	55	73	60
Max	90.31	0.43	10.27	3.20	0.06	0.88	2.99	1.61	5.02	0.09	61	82	65
Min	80.75	0.02	5.55	0.25	0.01	0.04	0.12	0.63	1.65	0.00	51	62	51
UCC	66.62	0.64	15.40	5.04	0.10	2.48	3.59	3.27	2.80	0.15	51	57	52
JUC	67.53	0.62	14.67	5.39	0.11	2.53	3.90	2.72	2.42	0.12	51	56	52

Table 2b. Summary statistics of trace element abundances in beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay, Japan compared to UCC (Rudnick & Gao, 2005) and JUC (Togashi & Imai, 2000)

Sample/	Trace Elements (ppm)												
Location	As	Pb	Zn	Cu	Ni	Cr	V	Sc	Y	Nb	Zr	Th	Sr
East San'in coasts (n=17)													
Average	13	13	22	4	8	29	26	13	16	3	60	3	353
Max	27	18	68	10	21	139	89	46	26	5	91	5	1315
Min	3	9	3	1	1	2	3	1	12	1	39	1	66
Tango peninsula (n=14)													
Average	8	13	27	6	19	59	47	6	16	4	68	3	174
Max	20	15	60	13	52	227	193	15	19	9	127	6	456
Min	2	11	7	1	1	8	1	1	13	2	41	1	87
Wakasa bay (n=7)													
Average	8	16	32	5	11	35	29	5	25	5	70	6	81
Max	11	19	50	14	20	44	59	7	35	8	96	8	185
Min	4	12	5	1	7	26	2	3	18	3	41	4	18
UCC	5	17	67	28	47	92	97	10	21	12	193	10	320
JUC	7	17	74	25	38	84	110	16	26	9	135	8	225

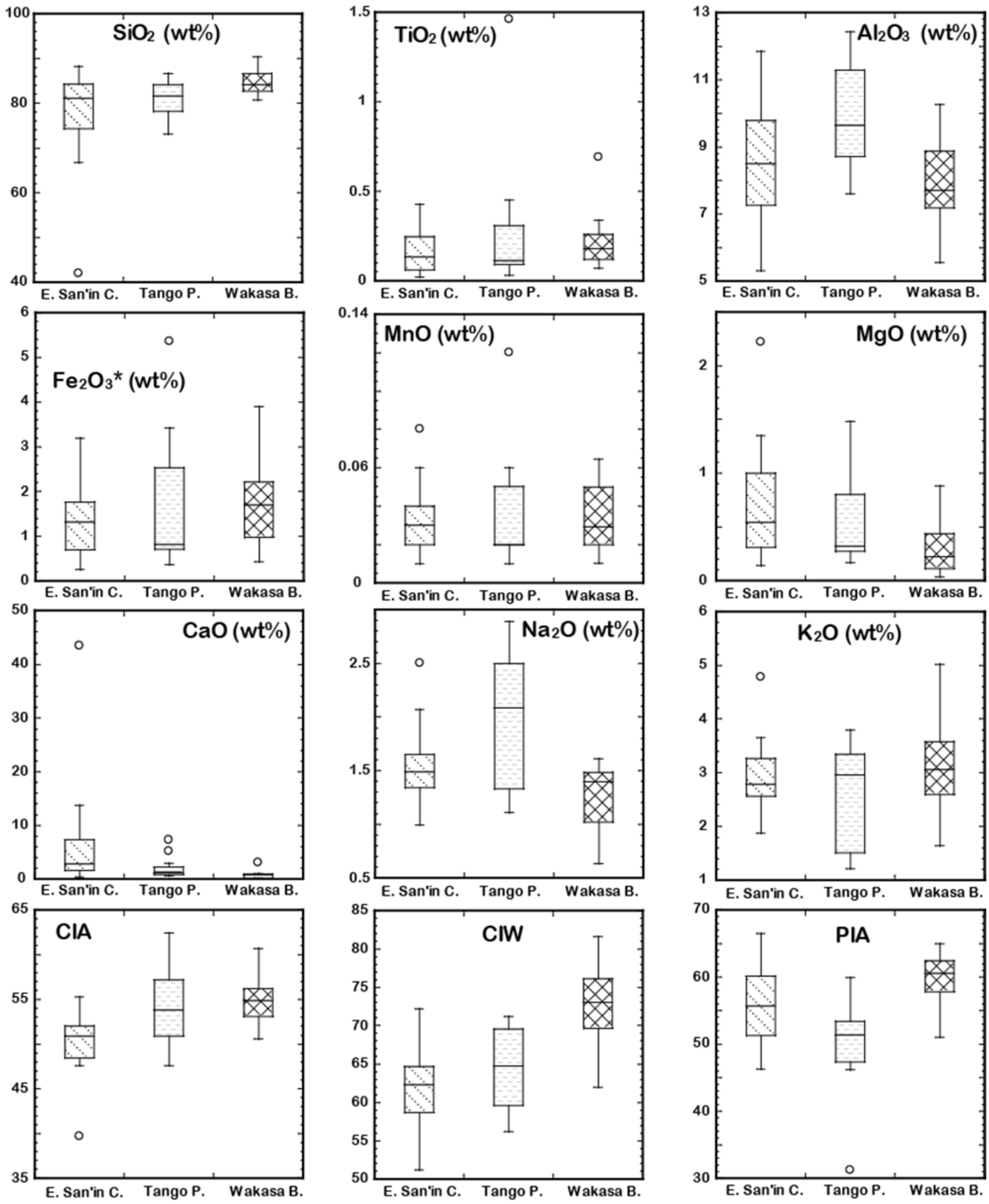

Figure 2. Boxplots showing the summary of geochemical compositions of beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay, Japan

Note. Vertical lines give the range, excluding outliers (circles); boxes enclose 50% of the data and illustrate the 25% quartile, median (horizontal bar), and 75% quartile. Outliers are defined as the upper or lower quartile ±1.5 times the interquartile difference.

3.2 Geochemical Classification

The geochemical classification of beach sand samples of Eastern San'in coast, Tango Peninsula and Wakasa Bay was investigated using the log ratios of Na_2O/K_2O plotted against the log ratios of SiO_2/Al_2O_3 (Pettijohn & Potter, 1972) and the log ratios of $Fe_2O_3^*/K_2O$ plotted against the log ratios of SiO_2/Al_2O_3 (Herron, 1988). The SiO_2 content and SiO_2/Al_2O_3 ratio are the most commonly used geochemical criteria for differentiating mature and immature sediments (Potter, 1978); which also reflect the abundance of quartz, feldspar and clay contents. Herron, (1988) modified the diagram of Pettijohn & Potter, (1972) using log Fe_2O_3/K_2O along the Y-axis instead of log Na_2O/K_2O. The Na_2O/K_2O ratio characterize an index of chemical maturity whereas the ratio of $Fe_2O_3^*/K_2O$ allows a better classification of arkoses (Herron, 1988) (**1-**quartz arenite: log (SiO_2/Al_2O_3) ≥ 1.5; **2-**greywacke: log (SiO_2/Al_2O_3) < 1 and log (K_2O/Na_2O) < 0; **3-**arkose (includes subarkose): log (SiO_2/Al_2O_3) < 1.5 and log (K_2O/Na_2O) ≥ 0 and log ($Fe_2O_3^*$+MgO) / (K_2O+Na_2O) < 0; **4-**Lithic arenite: log (SiO_2/Al_2O_3) < 1.5 and either log (K_2O/Na_2O) < 0 or log ($Fe_2O_3^*$+MgO) / (K_2O+Na_2O) ≥ 0. If log (K_2O/Na_2O) < 0, lithicarenite can be confused with greywacke). The most peculiar characteristic in the geochemical classification of the beach sands from Eastern San'in coast, Tango Peninsula and Wakasa Bay is in their corresponding compositions and all these samples are scattered mostly around arkose, subarkose and litharenite (Figures 3a and b). Arkoses are immature sandstones with abundant feldspars; both potassic feldspar and plagioclasean indication ofrelatively immature beach sand sediments with low to moderate weathering.

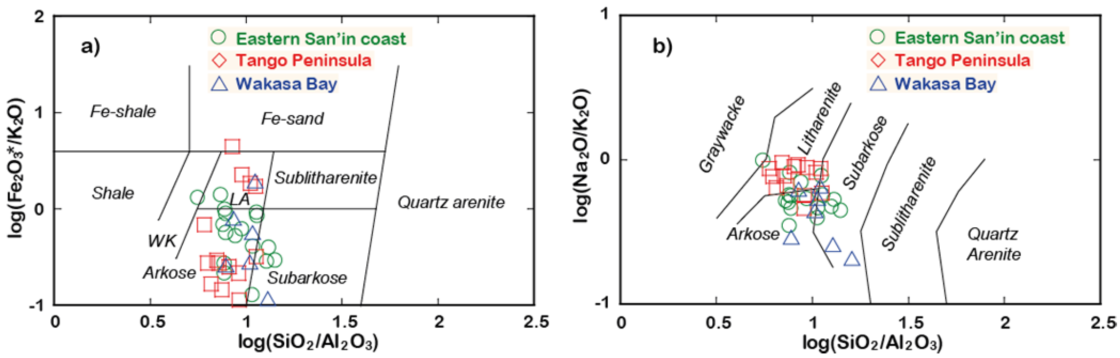

Figure 3. Geochemical classification schemes of beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay, Japan. **a)** Classification after Herron, (1988). LA. Litharenite, and WK. Wacke. **b)** Geochemical classification using log (SiO_2/Al_2O_3) -log (Na_2O/K_2O) diagram after Pettijohn & Potter (1972)

3.3 Normalized Compositions

Average compositions of sands from Eastern San'in coast, Tango Peninsula and Wakasa Bay beaches were compared by normalization against average UCC and JUC. Results showed that the Eastern San'in coastal sands are strongly depleted in all elements except SiO_2, CaO, As and Sr relative to both UCC_N and JUC_N (Figure 4). The enrichment of CaO relative to the UCC_N and JUC_N, is in consistent with the variable enrichment of carbonate compositions in the beach sands from Shibayama, Kirihama, and Takeno (Table 1). The similarity in normalized patterns observed in UCC_N, JUC_N as well as the patterns for the sands from Eastern San'in coast, Tango Peninsula and Wakasa Bay beaches further suggest moderate geochemical maturation.

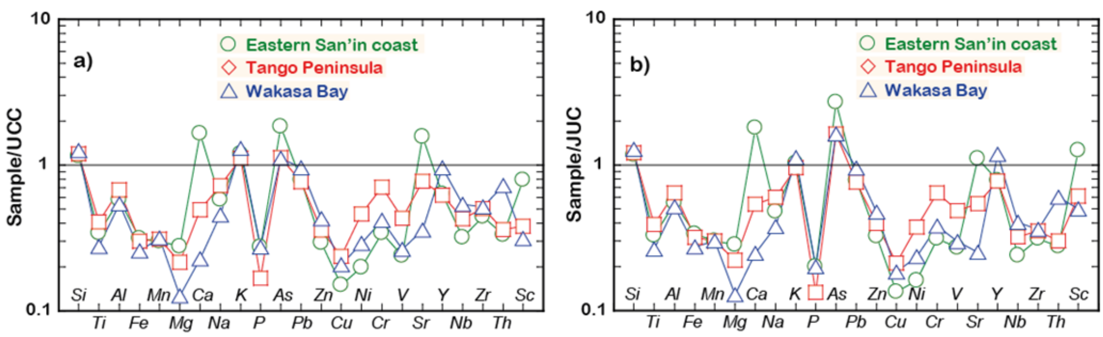

Figure 4. Average normalized major and trace element plots of beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay, Japan. **a)** Average normalized samples compared to average Upper Continental Crust (UCC) estimated from the representative surface rocks by Togashi & Imai, (2000). **b)** Average normalized samples compared to average Japan arc Upper Crust (JUC) normalized values from Rudnick & Gao, (2005). The major element values were normalized as wt% and trace elements as ppm

3.4 Weathering Intensity and Chemical Maturity

As the degree of chemical weathering is a function of climate and rates of tectonic uplift (Wronkiewicz & Condie, 1987), the raising chemical weathering intensity suggests the decrease in tectonic activity and/or the change of climate towards warm and humid conditions which are more favorable to chemical weathering in the source region (Jacobson et al., 2003). Weathering indices of sedimentary rocks can therefore provide useful information of tectonic activity and climatic conditions in the source area.

3.4.1 Chemical Index of Alteration

The Chemical Index of Alteration (CIA) of Nesbitt and Young (1982, 1984) was used to evaluate the degree of weathering. This index measures the extent to which feldspar has been converted to aluminous weathering products. CIA ratios in feldspar and fresh source rocks are typically ~50, whereas those in residual weathering products such as kaolinite and gibbsite can reach 100. This index can be calculated using molecular proportions, from the formula:

$$CIA = [Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)] \times 100 \qquad \textit{Equation 1}$$

Where CaO^* represents the amount in silicates only.

In this study, CaO was corrected with subsequent methodology proposed by McLennan et al., (1993), in which CaO values are accepted only if $CaO<Na_2O$ and when $CaO>Na_2O$, it is assumed that the concentration of CaO equals that of Na_2O. High CIA values reflect the removal of mobile or unstable cations (Ca, Na, K) relative to highly immobile or stable residual constituents (Al, Ti) during weathering (Nesbitt and Young, 1982). Conversely, low CIA values indicate near absence of chemical alteration and consequently may reflect cold and/or arid conditions (Nesbitt & Young, 1982, 1989). CIA=50-60 indicates an incipient weathering, CIA = 60-80 an intermediate weathering and CIA>80 extreme weathering (Nesbitt & Young, 1982).

The computed CIA values of the Eastern San'in coast sands ranged between 40 and 55 with an average of 50 an indication that no weathering has virtually occurred. The average CIA values for Tango Peninsula and Wakasa Bay sands were 54 and 55; ranging from 48 to 62 and 51 to 61 respectively. However, the values are moderately high relative to the ranges of Eastern San'in coast sands (Table 2a). These CIA values indicate that the Tango Peninsula and Wakasa Bay sands have undergone weak to intermediate chemical weathering. Overall, the relatively low to intermediate CIA beach sand values across the three study areas indicate low degree of chemical weathering, which may reflect cold and/or arid climate conditions in the source area (Nesbitt & Young, 1982).

3.4.2 Chemical Index of Weathering

Weathering effects can also be evaluated using the Chemical Index of Weathering (CIW) in molecular proportions) identical to the CIA, from the formula:

$$CIW = Al_2O_3/(Al_2O_3+CaO^*+Na_2O)] \times 100 \qquad \textit{Equation 2}$$

Where CaO* is the CaO residing only in the silicate fraction.

This equation is more appropriate in understanding the extent of plagioclase alteration alone since K_2O is subtracted from Al_2O_3 in the numerator and denominator of the CIA equation. However, Fedo et al., (1995) argued that the use of CIW calculation to quantify chemical weathering intensity is inappropriate and should be used with caution since the equation provides values of 80 for unweathered potassic granite and values close to 100 for clay minerals such as kaolinite, illite and gibbsite, similar to values found for residual products of CIW for smectite, 80; kaolinite, illite and gibbsite, 100. The CIA and CIW are interpreted in similar way with a value of 50 for unweathered upper continental crust and about 100 for highly weathered materials with complete removal of alkali and alkaline-earth elements (McLennan et al., 1983; McLennan, 1993; Mongelli et al., 1996).

CIW values of beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay ranged from 51 to 72, 56 to 71 and from 62 to 82 respectively. The average CIW for Wakasa Bay and Tango Peninsula sands (60 and 56) were slightly higher compared to those of the Eastern San'in coast (50) (Table 2a). The CIW index values are higher than CIA values for the analyzed samples, due to the exclusion of K_2O from the index. On the basis of CIW, the weathering intensity of the investigated beach sands from Eastern San'in coast, Tango Peninsula and Wakasa Bay maybe interpreted to show low to moderate weathering.

3.4.3 Plagioclase Index of Alteration

The degree of the chemical weathering can be estimated using the Plagioclase Index of Alteration modified from the CIA equation to monitor plagioclase (Fedo et al., 1995). The plagioclase index of alteration (PIA) is calculated according to the following equation in molecular proportions:

$$PIA = 100 \times (Al_2O_3\text{-}K_2O) / (Al_2O_3+CaO^*+Na_2O\text{-}K_2O) \quad \textit{Equation 3}$$

Where CaO* is the CaO residing only in the silicate fraction.

High PIA values (>84) would indicate intense chemical weathering while lower values (~50) is characteristic of unweathered or fresh rock samples. Post-Archean Australian Shales (PAAS) have PIA value of 79. The PIA values of beach sands from the Eastern San'in coast ranged from 31 to 60 with a mean of 50. The mean PIA values were 56 for Tango Peninsula beach sands and 60 for Wakasa Bay sands. The PIA values ranged from 46 to 67 and from 51 to 65 in Tango Peninsula and Wakasa Bay (Table 2a).

3.4.4 A-CN-K Diagram

The geochemical compositions of investigated beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay were plotted on a ternary Al_2O_3, CaO^*+Na_2O, and K_2O, (A-CN-K) diagram as shown in Figure 5a. Generally, Al_2O_3 (A) is plotted at the top apex, CaO^*+Na_2O (CN) at the bottom left and K_2O (K) at the bottom right and helps in understanding their weathering trends and mineralogical compositions (Nesbitt & Young (1984, 1989). Plagioclase and K-feldspar plot at 50% Al_2O_3 on the left and right boundaries, respectively to form the (feldspar join). The clay mineral groups, kaolin, chlorites and gibbsite plot at the A apex (100% Al_2O_3). The initial weathering trends of igneous rocks are sub-parallel to CN-A. Calcite plots at the CN apex. Illite and smectites plot on the diagram at 70% and 85% Al_2O_3. As weathering progresses, clay minerals are produced at the expense of feldspars and bulk composition of soil/sediments samples evolve up the diagram towards A apex, along the weathering trend. The most intensely weathered samples will therefore, plot highest on the diagram, reflecting the preponderance of aluminous clay minerals. The weathering trend intersects then A-K boundary once all plagioclase is weathered and then is redirected towards the A apex because K is extracted from the residues in preference to Al (Nesbitt et al., 1996).

As shown in the ternary A–CN–K plot in Figure 5a, the CIA ratios of investigated beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay are generally low (<60), indicating minimal weathering. In A-CN-K ternary plot (Figure 5a), majority of the investigated beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay occupy the central part of triangle, more towards the A-CN line and plot close to the plagioclase and K-feldspar lines, suggesting poor weathering conditions. Most of beach sands from the Eastern San'in coast group are around the weathering trend of granites and felsic volcanic rock near the plagioclase-K-feldspar line. Some beach sand samples from the Eastern San'in coast and Tango Peninsula scattering below the feldspar line but close to the A-CN side of the diagram, attest to the fact that due to high contents of CaO they possess low CIA values.

3.4.5 A-CNK-FM Diagram

Weathering trends can also be observed in molar proportions of Al_2O_3 - $CaO^*+Na_2O+K_2O$ - FeO^*+MgO (A-CNK-FM) (Nesbitt & Young, 1984, 1989). CaO^*, Na_2O and K_2O (CNK) are plotted at the lower apex, Al_2O_3 (A apex) at the top and FeO* (total iron as FeO^*) and MgO are summed to form the third variable (Figure 5b). Plagioclase plus K-feldspar (Fel) plot on the left hand boundary at 50% Al_2O_3. Illite plots on the left boundary at approximately 75% (and greater) Al_2O_3 and kaolin and gibbsite plot at the A apex. Biotite plots three quarters of the way along the line between feldspars and FM apex. Chlorite plots on the right hand boundary as a solid solution ranging from approximately 15% to 25% Al_2O_3. Most of the investigated beach sands as well as average Upper Continental Crust (UCC) and Japan arc Upper Crust (JUC) plot close to the feldspar composition on the line joining Fel point on the A-CNK boundary to the FM apex.

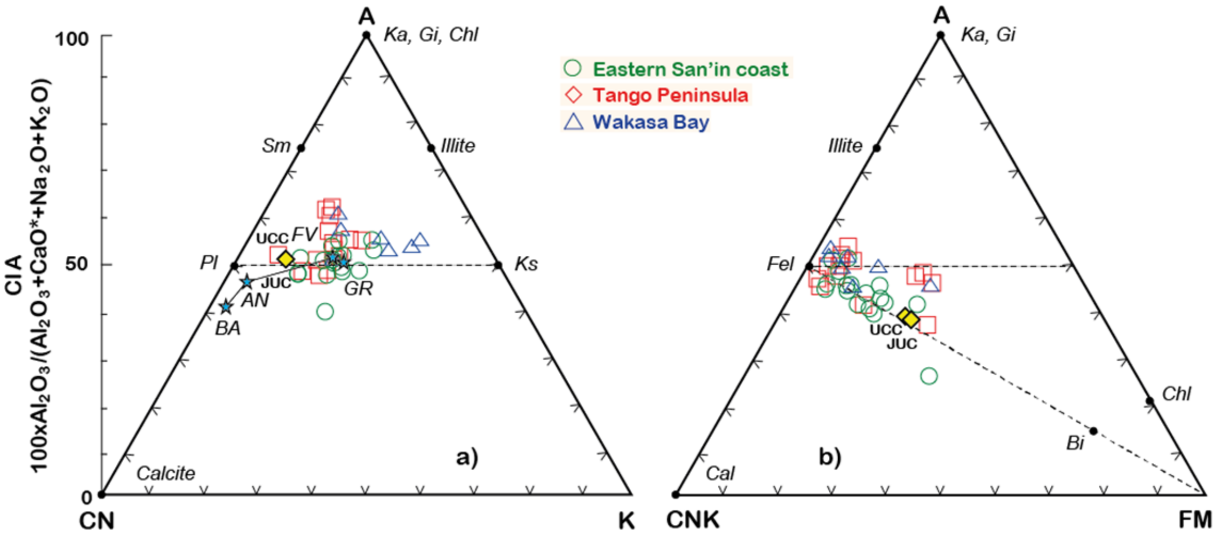

Figure 5. A-CN-K **(a)** and A-CNK-FM **(b)** plots of analyzed beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay, Japan. Ka= kaolinite; Chl= chlorite; Gi= gibbsite; Sm= smectite; Pl= plagioclase; Ks= K-feldspar; Fel= feldspar; Bi= biotite. Dotted line linking stars is the compositional trend in pristine average Phanerozoic-Cenozoic igneous rocks (Condie, 1993). Stars: BA= basalt, AN= andesite, FV= felsic volcanic rock, GR= granite. A= Al_2O_3; CN= CaO* + Na_2O; K= K_2O; CNK= CaO* + Na_2O + K_2O; FM= FeO^* + MgO

3.5 Chemical Maturity

The major element compositions of investigated beach sands from the Eastern San'in coast, Tango Peninsulaand Wakasa Bay are shown in the ternary plot Al_2O_3×5-SiO_2-CaO×2 (Figure 6). This illustration (Brumsack, 1989) is based on the assumption that marine sediments may be regarded as mixtures of alumosilicates (expressed by Al_2O_3 and SiO_2 content), biogenic silica (partly represented by the SiO_2 content) and biogenic carbonate (largely amounted to the CaO content). Apparently, the investigated beach sands present mixtures of terrigenous detrital material and biogenic silica with minor amounts of carbonate.

Figure 7a presents the bivariate plot of SiO_2 (reflective of quartz content) against $Al_2O_3^*$+K_2O+Na_2O (reflective of feldspar content) representing chemical maturity trend as function of climate as proposed by Suttner & Dutta (1986). The plotted samples revealed semi-arid to semi humid climatic conditions in the area from various sources tending towards increasing chemical maturity. Overall, the investigated beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay showed variable degrees of chemical maturity extending from low to intermediate levels. The beach sands plotted in the semi-arid region may have experienced little or no chemical weathering and are far less mature than those plotted in the semi humid area. The K_2O/Na_2O ratio discrimination diagram (Figure 7b) after Crook, (1974) and SiO_2 contents, show that the majority of the investigated beach sands are predominantly quartz-intermediate type.

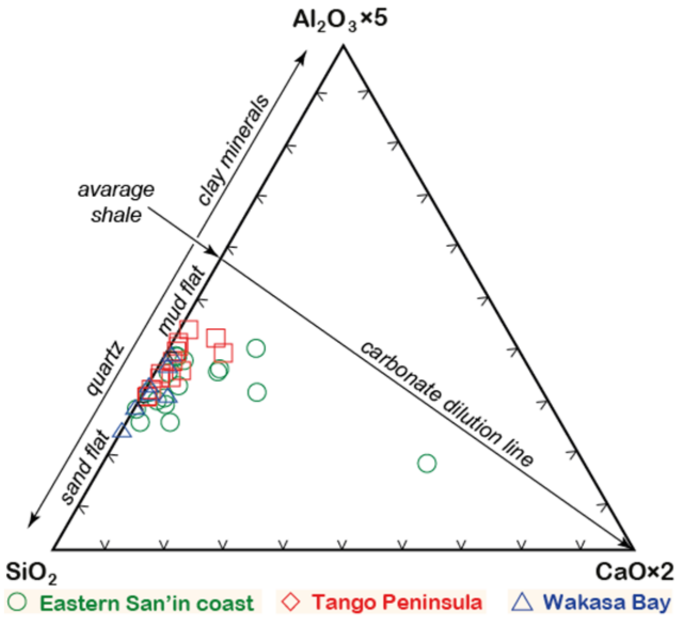

Figure 6. Ternary plot Al_2O_3×5–SiO_2–CaO×2 (Brumsack, 1989) of analyzed beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay, Japan

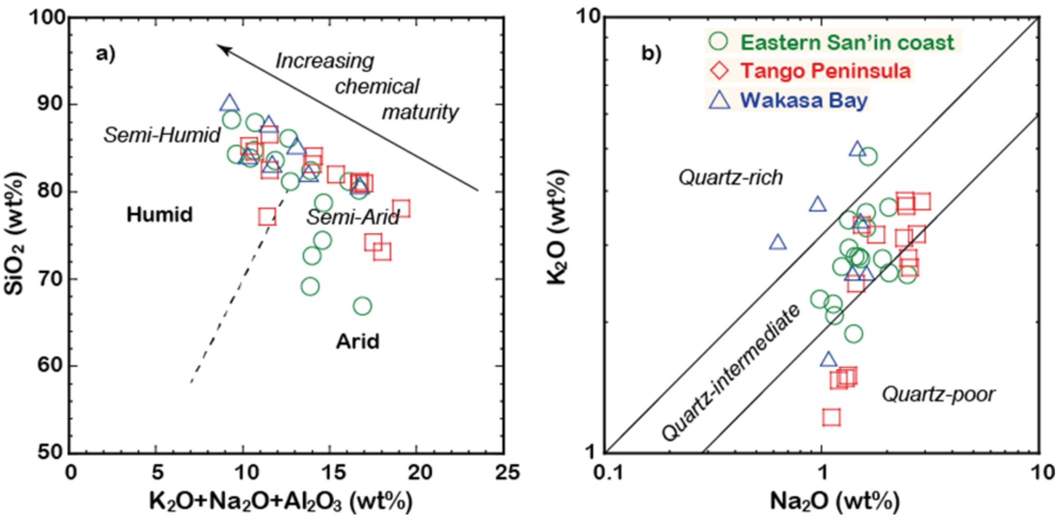

Figure 7. **a)** Plot of SiO_2 (reflective of quartz content) versus $K_2O+Na_2O+Al_2O_3$ (reflective of feldspar content), and **b)** Plot of Na_2O versus K_2O of analyzed beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay, Japan

3.6 Provenance and Tectonic Setting

The percentage weight (wt%) of major elements shown in Table 1 was used to discriminate the tectonic setting of the investigated beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay. The discriminant functions of the diagram use Al_2O_3, TiO_2, $Fe_2O_3^*$, MgO, CaO, Na_2O and K_2O contents as variables and classifies samples of unknown provenance in one of four categories (P1–P4) according to their discriminant scores (F1, F2) (Roser & Korsch, 1988). This function discriminate among four sedimentary provenances: mafic, (P1) ocean island arc; intermediate, P2; mature island arc; felsic, (P3) active continental margin; and recycled, (P4) granitic–gneissic or sedimentary source. However, provenance discrimination diagrams based only on major elements are somewhat unreliable because of the mobilization of these components during weathering and alteration (Roser & Korsch 1988). The majority of beach sand samples of East San'in district, Tango peninsula and Wakasa bay plot on the P1 and P2 fields of mafic and ocean island arc (Figure 8a).

The tectonic setting of beach sand sediments from the Eastern San'in coast, Tango Peninsula and Wakasa Bay was evaluated using the plot of SiO_2/Al_2O_3 versus K_2O/Na_2O (after Roser & Korsch, 1986). The ratio of K_2O/Na_2O versus SiO_2/Al_2O_3 is generally used for distinguishing between sediments deposited in the passive continental margin and oceanic island arc margin (Roser & Korsch, 1986). This scheme attempts to identify sediments deposited in active continental margin (ACM) and passive margin (PM) settings. From the K_2O/Na_2O–SiO_2/Al_2O_3 discrimination diagram (Roser & Korsch, 1986), most of the investigated beach sands from the Eastern San'in coast, Tango Peninsula and Wakasa Bay are plotted in the active and passive continental margin bounds (Figure 8b).

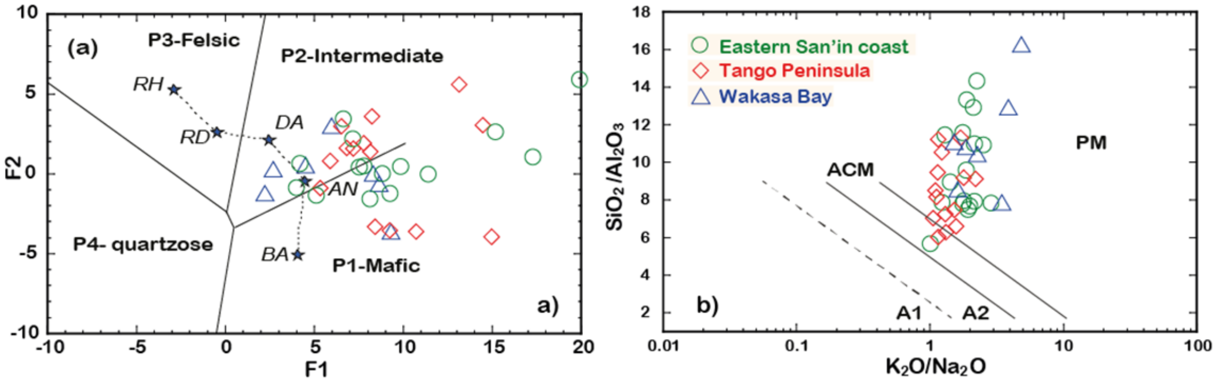

Figure 8. **a)** Discriminant function plot (Roser & Korsch 1988) of analyzed beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay. Averages BA = basalt, AN = andesite, DA = dacite, RD = rhyodacite, and RH = rhyolite are from Roser & Korsch (1988). F1 = -1.773TiO_2 +0.607Al_2O_3 +0.76$Fe_2O_3^*$ -1.5MgO +0.616CaO +0.509Na_2O -1.224K_2O -9.09; F2 = 0.445TiO_2 +0.07Al_2O_3 -0.25$Fe_2O_3^*$ -1.142MgO +0.438CaO +1.475Na_2O +1.426K_2O -6.861. **b)** K_2O/Na_2O -SiO_2/Al_2O_3 discriminant plot (Roser & Korsch1986). A1, arc setting, basaltic, and andesitic detritus; A2, evolved arc, felsic and plutonic detritus; ACM, active continental margin; PM, passive margin

4. Conclusions

Geochemical classification schemes of log (Na_2O/K_2O) versus log (SiO_2/Al_2O_3), and log ($Fe_2O_3^*/K_2O$) against log (SiO_2/Al_2O_3) show that the investigated beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay are mainly arkose, subarkose and litharenite; suggesting that the sediments are from multiple sources. The normalized UCC as well as JUC patterns for the investigated sands from both sites are very similar with both showing depletion in all elements except SiO_2, K_2O, and as, suggesting a moderate geochemical maturation. Majority of the sediments formed under semi-arid/semi-arid conditions tending towards increasing chemical maturity suggesting that the beach sands are from multiple sources. The geochemical compositions of investigated beach sands from the three locations indicate limited differences among them. Low to moderate values of the weathering indices: Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA) and Chemical Index of Weathering (CIW) suggest below average to moderate weathering conditions in the source area as well as immature to moderately mature beach sands sediment, which may reflect cold and/or arid climate conditions tending towards increasing chemical maturity in the source area. Major and trace element compositions suggest that the that the investigated beach sands from the Eastern San'in coast, Tango Peninsula, and Wakasa Bay were derived from a typical mafic to intermediate ocean island arc source in addition the tectonic setting of the beach sands sediments distinguish typical passive margin.

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