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The Middle Pleistocene to Holocene tephrostratigraphy of the Takashima-oki core from Lake Biwa, central Japan

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Abstract

Thick sequences of sediments have been deposited in the Lake Biwa basin for the last 400,000 years providing useful data for Quaternary stratigraphical and paleo-environmental studies. As the Takashima-oki core taken from Lake Biwa contains a large number of key tephra beds, it is one of the types of stratigraphical cores for the Middle Pleistocene to Holocene period in the Kinki district. Previously, the tephras in this core were studied for their tephro-stratigraphical and chronological values, but the refractive indices of their heavy minerals were not measured until this study. To do this we used a temperature variation type refractometer and correlated the refractive index of volcanic glass shards with heavy minerals in each tephra. Their correlation coefficients are not so high, thus each refractive index is a useful value as an independent variable parameter for the correlation with tephra in other areas.

Key-words : widespread tephra, refractive index, heavy minerals, chronology, Lake Biwa

Introduction

Lake Biwa is situated in central Japan, with an area of 670 km^2 and a maximum depth of 103.6 m and is the largest lake in Japan. Investigation of three sediment cores, called the '200m', '1400m' and 'Takashima-oki' cores, taken from the lake have indicated that it has existed for the past 400,000 years. Therefore the sediments preserve a high quality and continuous record of environmental changes from the Middle Pleistocene to the present.

The 200m and 1400m cores were bored in 1971 and 1981, respectively. and detailed investigations of the core on the view points of sedimentology, mineralogy, physical properties, geochemistry, and floral and faunal contents have been carried out (*e. g.* Horie, 1984).

The third core, the Takashima-oki core, was bored in 1986. Compared with the other two cores, this core has many time markers because of the intercalation of 75 tephra beds. The stratigraphy and chronology of this core have been examined based on these tephra beds and their correlation with widespread tephras in other areas (Yoshikawa and Inouchi, 1991, 1993; Nagahashi *et al.*, 2004). Other investigations on this core include the total carbon content (Inouchi *et al.*, 1995), the eolian and fluvial quartz content (Xiao *et al.*, 1997a, c), biogenic silica (Xiao *et al.*, 1997b), and the diatom flora (Kuwae *et al.*, 1997, 2002). Using eolian quartz concentrations, Xiao *et al.* (1999) was able to correlate variations in the East Asian monsoons with oxygen isotope stages. Diatom concentrations have been correlated with oxygen isotopic events (Kuwae *et al.*, 2002), and these correlations and widespread tephra correlations have established a detailed chronology (Yoshikawa and Kuwae, 2001; Nagahashi *et al.*, 2004). Thus the sediments of Lake Biwa, especially the tephra-rich Takashima-oki core, are important for the study of the period from the Middle Pleistocene to the present.

The tephras of the Takashima-oki core are important time markers, but many are not described as widespread tephras in the list of Quaternary tephras of Japan by Machida and Arai (2003). Tephrostratigraphy of the Takashima-oki core is one type for this age in the Kinki district at least, and some studies have estimated the ages of sediments in other areas by correlations with tephras in the Takashima-oki core (*e.g.* Uchiyama, 1997). Thus, it is necessary to describe more properties of each tephra in this core to extend the correlations. To do this, we measured the refractive index of glass shards and heavy minerals in each tephra to supplement with the previous descriptions. The results of the measurements, and the relation between the refractive indexes of the glass shards and heavy minerals in each tephra are examined in this study.

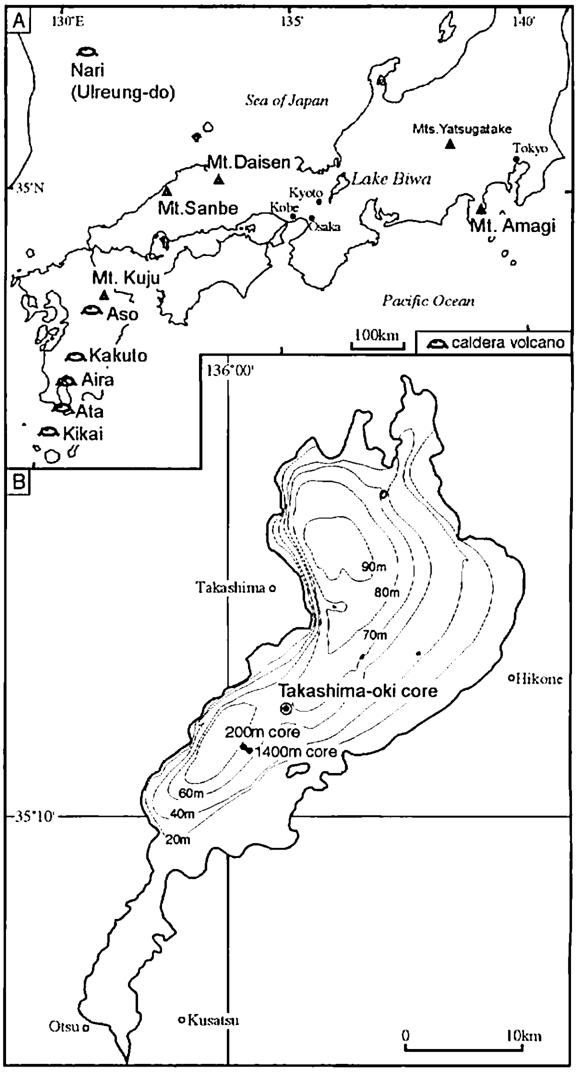

Fig. 1 Locality maps of volcanoes, Lake Biwa and drilling sites. Volcanoes are a related source of tephras in the Takashima-oki core.

Stratigraphy of the Takashima-oki core

The Takashima-oki core was bored in a water depth of 63m in the north basin of Lake Biwa (Fig. 1). Length and sediment recovery factor of the core are 141.49m and 89.7%, respectively. The core is divided into two members: above 137.28m the core is composed of massive silty clay, and below 137.28m, it is dominated by sand (Yoshikawa and Inouchi, 1991; Fig. 2).

The core intercalates 44 tephra beds and 31 tephra horizons. A tephra horizon is defined as a sediment layer that contains tephra material. Mineral compositions, heavy mineral compositions, shape of glass shards and their refractive indices and chemical composition have been investigated for these tephras (Yoshikawa and Inouchi, 1991; Nagahashi *et al.*, 2004); their data are shown in Table 1. Some of these tephras have been correlated with widespread tephras and/or in other areas based on these properties (Yoshikawa and Inouchi, 1991, 1993; Nagahashi *et al.*, 2004) as shown in Table 2.

For almost all these widespread tephras their fall-out age has been examined in detail, as shown in Fig. 2. The age of other tephras have been estimated from tephrostratigraphy based on widespread tephras and their relationships with the number of fossilized diatoms (Yoshikawa and Kuwae, 2001; Nagahashi *et al.*, 2004). The age of the lowest-most massive silty clay layer in the core has been estimated to be 390ka by Nagahashi *et al.* (2004), but Miyoshi *et al.* (1999) estimated the age of the lowest-most massive silty clay layer in the 1400m core to be 430ka.

Table 1 Lithofacies and petrographic properties of tephra in the Takashima-oki core. This table is compiled from descriptions by Yoshikawa and Inouchi (1991, 1993).

Unit	Lithofacies	Depth	**	***	Grain component (%)					Glass Shape (%)				Heavy mineral composition (%)						
Name		(m)	(cm)	(mm)	Gl	Fl	Qz	Hm	Oth	H	C	T	Oth	Bt	Am	Opx	Cpx	Zr	Ap	Opq
BT 1	(not to be observed as a bed)	1.52m		0.28	93	5	1	1	*	2	39	50	9	8	29	32	4	0	3	24
BT 2	(not to be observed as a bed)	1.72m		0.25	2	17	3	7	71			+		7	77	3	0	0	2	11
BT 3	lens, whi. med. vit.	2.23m	2.5	0.66	99	1	0	*	*	71	24	5	0	0	*	37	24	0	4	35
BT 4	wh-grawhi, fin-med, grading	2.65m	2.5	0.27	82	15	1	*	2	*	20	80	0	52	18	*	7	0	10	13
BT 5	lens, whi, vfi-fin	3.18m	3.0	0.20	39	45	3	1	12	8	14	74	4	3	15	11	7	2	5	57
BT 6	(not to be observed as a bed)	4.76m		0.33	58	23	2	8	9	2	38	39	21	16	75	0	0	0	*	8
BT 7	yelwhi-ligpin, fin-cor, cbg(L), grading	7.90m	1.0	0.87	49	33	*	11	7	0	30	63	7	6	69	14	0	0	3	8
BT 8	lens, whi, vfi-fin	8.35m	0.3	0.92	21	36	2	11	30	1	6	91	2	5	55	32	0	0	1	7
BT 9	lens, whi, fin-med, cbg, grading	8.37m	1.0	1.18	20	38	1	8	33	0	24	67	9	6	59	27	0	0	0	8
BT 10	whi-grawhi, vfi-med, grading	8.62m	10.0	0.95	95	2	*	*	0	63	34	3	0	0	10	44	11	0	3	32
BT 11	whi-yelwhi, med, vit	8.72m	2.5	0.84	95	4	0	1	0	63	29	8	*	5	5	33	11	0	3	43
BT 12	lens, whi-yelwhi, med, vit	8.84m	2.0	0.73	98	2	0	*	0	62	31	6	1	0	7	46	13	*	2	32
BT 14	(not to be observed as a bed)	14.59m		0.40	29	35	*	18	18	1	16	73	10	1	6	60	13	0	0	20
BT 15	(not to be observed as a bed)	14.69m		0.43	55	26	3	14	2	1	11	88	*	23	66	*	0	0	2	9
BT 16	whi, pum, cbg	26.70m	2+	1.83	10	42	*	46	2	0	18	82	0	0	65	31	0	0	0	4
BT 17	whi, pum, cbg	27.15m	8.5	1.80	27	38	2	30	3	*	18	82	0	*	60	28	0	0	*	12
BT 18	lens, whi, pum	27.20m	2.0	2.55	22	45	2	31	*	0	7	93	0	*	77	20	0	0	0	3
BT 19	whi, pum, cbg	28.24m	5.0	1.90	20	31	1	48	*	0	10	90	0	1	72	20	0	0	0	7
BT 20	lsc, whi, pum	28.34m	1.5	2.53	17	42	3	29	9	2	10	88	0	2	68	26	0	0	0	4
BT 21	lens, yelwhi-whi, med-cor, cry, Pu	29.44m	1.0	1.38	5	39	3	46	7	4	18	78	0	2	80	16	0	0	*	2
BT 22	yelwhi-whi, med, vit, Pu	29.61m	2+	2.30	92	5	1	2	*	51	32	17	0	4	29	31	14	0	2	20
BT 23	lens, whi, med-cor, Pu	29.72m	1.0	2.26	75	15	1	8	1	39	40	19	2	2	31	28	13	0	5	21
BT 24	(not to be observed as a bed)	29.92m		1.10	80	14	*	5	1	52	26	20	2	3	39	34	11	0	2	11
BT 25	lens, whi, fin-med, vit	30.88m	1.0	0.78	97	1	2	*	0	57	37	5	1	*	2	40	34	0	3	21
BT 26	lens, whi-gra, fin-med, vit	30.94m	0.5	0.52	93	3	3	1	0	59	38	1	2	1	11	34	22	0	1	31
BT 27	whi-grawhi, fin, vit	32.27m	2.0	0.48	93	5	1	1	*	22	49	28	1	5	0	54	8	0	16	17
BT 28	lens, whi, med-cor, cbg, Pu	32.76m	1.5	2.06	87	9	*	3	1	30	42	26	2	7	36	31	9	0	4	13
BT 29	whi-grawhi, fin, vit	32.89m	2.0	0.60	84	11	1	1	3	2	12	86	0	11	3	37	13	0	10	26
BT 30	(not to be observed as a bed)	33.00m		0.30	86	5	1	2	6	2	9	69	20	52	22	11	1	0	3	11
BT 31	(not to be observed as a bed)	34.35m		0.45	30	26	2	11	31	0	10	68	22	3	54	37	0	0	0	6
BT 32	(not to be observed as a bed)	34.45m		0.40	82	10	2	4	2	2	19	49	30	8	30	38	11	0	1	12
BT 33	(not to be observed as a bed)	34.90m		0.60	86	10	1	1	2	*	52	32	16	2	0	57	23	0	0	18
BT 34	liqred-liqpin, fin-med, cbq, qradinq, Pu	38.60m	3.0	0.60	78	15	1	3	3	*	26	74	0	0	0	29	35	0	0	36
BT 35	(not to be observed as a bed)	39.07m		0.38	93	5	1	1	*	0	7	85	8	8	0	34	31	0	0	27
BT 36	ligred-ligpin, vfi-med, grading, Pu	39.45m	4.5	1.18	79	13	*	2	6	*	8	89	3	0	*	38	31	0	*	31
BT 37	whi, med-cor, cbg, cry	41.34m	1.0	0.83	49	27	1	23	*	0	11	89	0	4	62	13	2	0	*	17
BT 38	(not to be observed as a bed)	42.82m		0.33	88	10	0	2	*	1	44	51	4	11	20	32	5	0	0	32
BT 39	(not to be observed as a bed)	43.49m		0.50	83	14	1	2	*	21	40	35	4	7	22	15	27	0	0	29
BT 40	lens, yelwhi, fin-med, vit	43.78m	0.5	0.32	94	4	1	*	1	8	53	39	0	2	1	48	6	0	22	21
BT 41	yelwhi-ora, fin-med, vit	43.94m	0.5	0.50	92	6	1	1	*	9	55	35	1	*	5	47	5	0	22	21
BT 42	(not to be observed as a bed)	46.81m		1.00	52	24	2	4	18	18	41	40	1	16	26	36	7	0	1	14
BT 43	(not to be observed as a bed)	47.41m		0.60	86	4	1	2	7	12	56	20	12	3	2	42	43	0	2	8
BT 44	whi, pum, inverse grading	63.03m	2.5	1.86	26	33	3	38	*	0	2	97	1	*	80	16	0	0	1	3
BT 45	yelwhi, pum, Pu	68.29m	0.7	0.65	24	39	3	33	1	0	4	96	0	7	74	14	0	0	*	5
BT 46	(not to be observed as a bed)	68.72m		0.23	98	2	0	*	*	20	51	29	0	11	52	11	0	0	11	15
BT 47	whi, pum, Pu	70.26m	0.8	1.87	15	31	2	50	2	0	7	93	0	2	88	2	0	0	0	8
BT 48	whi, pum, Pu	70.37m	3.0	1.97	14	41	2	43	*	0	5	95	*	2	86	*	0	0	3	9
BT 49	lsc, whi, pum, Pu	70.65m	1.5	1.77	13	47	4	34	2	0	4	96	0	1	90	1	0	0	1	7
BT 50	(not to be observed as a bed)	73.37m		0.70	90	9	0	1	*	74	24	0	2	5	11	49	3	0	0	32
BT 51	lsc, cry, Pu	73.58m	2.0	1.55	95	4	1	*	*	74	21	5	*	0	4	44	3	0	3	46
BT 52	(not to be observed as a bed)	76.97m		0.28	1	30	1	5	64				+	0	74	16	*	0	*	10
BT 53	(not to be observed as a bed)	79.17m		0.40	3	22	1	10	64			+	+	3	64	21	0	0	*	12
BT 54	(not to be observed as a bed)	83.57m		0.33	40	23	1	4	32	19	39	30	12	10	67	0	0	0	0	23
BT 55	(not to be observed as a bed)	84.72m		0.38	90	3	0	5	2	58	32	8	2	3	92	0	0	0	0	5
BT 56	(not to be observed as a bed)	84.87m		0.28	8	26	2	28	36			+		*	98	0	0	0	1	1
BT 57	whi, fin	85.56m	0.5	0.24	73	22	3	1	1	*	14	86	0	2	8	75	*	0	2	13
BT 58	yelbro, fin-cor, vit, Pu	86.49m	11.0	1.60	95	3	1	1	*	64	29	7	0	10	59	11	3	0	1	16
BT 59	lens, whi-ligpin, fin-med, vit, grading, para(U)	92.57m	5.0	0.28	80	17	1	*	2	12	46	40	2	1	0	53	15	0	14	17
BT 60	ligpin-redpur, fin-med, vit, para	93.18m	1.5	0.48	93	4	2	*	1	8	44	42	6	1	1	44	1	0	17	36
BT 61	liqht redpur, fin-cor, qradinq, vit, cbq(L	94.37m	41.0	0.59	99	*	0	*	0	48	38	14	*	*	9	49	9	0	10	23
BT 62	ligpin, fin-med, vit	94.45m	1.5	0.95	98	2	0	*	*	5	54	36	5	*	2	57	9	0	6	26
BT 63	(not to be observed as a bed)	94.82m		0.35	8	29	3	11	49			+		9	89	*	0	0	*	2
BT 64	(not to be observed as a bed)	95.17m		0.22	1	39	5	6	49				+	2	90	1	0	0	2	5
BT 65	(not to be observed as a bed)	99.18m		0.35	44	34	*	6	16	1	43	42	14	24	21	39	*	6	0	10
BT 66	ligpin, vfi-fin	101.68m	0.5+	0.10	92	7	*	1	0	7	75	18	0	56	28	8	0	0	0	8
BT 67	lens, yelwhi, fin-med	102.54m	2.0	0.40	60	24	1	14	1	*	3	96	1	*	86	10	0	*	2	2
BT 68	(not to be observed as a bed)	105.08m		0.80	7	32	2	19	40		+	+		23	69	1	0	0	0	7
BT 69	(not to be observed as a bed)	108.33m		0.33	3	56	8	8	25			+	+	2	91	1	0	0	2	4
BT 70	(not to be observed as a bed)	114.63m		0.40	99	1	0	*	*	84	13	3	*	31	32	9	0	0	0	28
BT 71	(not to be observed as a bed)	119.93m		0.50	2	22	1	6	69			+	+	2	80	10	*	0	*	8
BT 72	whi-ora, ligpin-redpur(U), fin-med, vit, Pu	120.72m	7.5	1.14	93	5	1	*	1	13	62	24	1	*	2	56	26	0	*	16
BT 73	(not to be observed as a bed)	121.94m		0.20	78	17	0	3	2	0	4	94	2	15	76	7	0	0	0	2
BT 74	whi-grawhi, fin-med, cbg(L), Pu	122.17m	5.0	1.06	45	31	2	17	5	*	6	92	2	3	70	15	0	0	3	9
BT 75	(not to be observed as a bed)	132.78m		0.30	37	31	1	16	15	0	11	78	11	0	87	3	0	0	3	7
BT 76	yelwhi, med-cor, cbg, cry	135.46m	3.0	0.69	22	35	2	40	1	0	5	94	1	1	72	19	0	0	1	7

lens: lenticular bed, lsc: lie scattered in clay bed, whi: white, grawhi: gray-white, gra: gray, yelwhi: yellowish white, yelbro: yellowish brown, redpur: reddish purple, ligred: light red, ligpin: light pink, ora: orange, cbg: conspicuous black grain, pum: pumiceous, para: parallel lamina, (L): lower part, (U): upper part, vfi: clay size, fin: silt size, med: very fine sand to fine sand size, cor: medium sand to coarse sand size, vit: vitric tephra, cry: crystal tephra, Pu: including pumice(over 0.5mm about diameter), **:thickness, ***: max diameter of tephra grain, Gl: volcanic glass, Fl: feldspar, Qz: quartz, Hm: heavy minerals, Oth: others, H, C and T: shape type of volcanic glass after Yoshikawa(1976), Bt: biotite, Am: amphiboles, Opx: orthopyroxene, Cpx: clinopyroxene, Zr: Zircon, Ap: apatite, Opq: opaque minerals, +: common, *: less than 1%,

Table 2 Widespread correlations of tephras in the Takashima-oki core. Their ages are shown on Fig. 2.

	widespread tephra	volcano or caldera	correlations	References
BT1	Amagi-Kawagodaira (Kg)	Amagi volcano (Izu Peninsula)	BB7(Lake Biwa), Matsukawado(Osaka)	Yoshikawa and Inouchi(1991), Nishida *et al.*(1993), Machida and Arai (2003)
BT3	Kikai-Akahoya (K-Ah)	Kikai caldera (south of Kyushu)	Yokooji(Osaka), KR21(Lake Biwa), and many places	Yoshikawa and Inouchi(1991), Machida and Arai(1978), Yoshikawa(1999)
BT4	Utsuryo-Oki (U-Oki)	Nari caldera (Ulreung-do; Korea)	Minato(Osaka) and many places	Machida *et al.*(1981), Yoshikawa and Inouchi(1991)
BT5	Sanbe-Ukinuno(SUk)	Sanbe volcano (Sanin district)?	BB37(Lake Biwa), Sakate(Nara)	Yoshikawa and Inouchi(1991), Machida and Arai(2003)
BT7		Daisen volcano (Sanin district)?	BB51(Lake Biwa), Daisen-Hoki or Daisen-Odori(Daisen)	Yoshikawa and Inouchi(1991), Ishida *et al.*(1984), Machida *et al.*(1991)
BT9			Kitoragawa(Osaka), KR39D(Lake Biwa)	Yoshikawa and Inouchi(1991), Yoshikawa(1999)
BT10	Aira-Tn (AT)	Aira caldera (southern part of Kyushu)	Heianjingu(Kyoto), BB55(Lake Biwa), KR39E(Lake Biwa) and many places	Machida and Arai(1976), Yoshikawa and Inouchi(1991), Yoshikawa(1999)
BT14			BB85a(Lake Biwa)	Yoshikawa and Inouchi(1991)
BT15	Sanbe-Ikeda(SI) or Kuju-dai1(Kj-P1)	Sanbe volcano or Kuju volcano	BB85(Lake Biwa)	Yoshikawa and Inouchi(1991), Machida *et al.*(1991)
BT16-BT21			BB151,152,153,163,164(Lake Biwa)	Yoshikawa and Inouchi(1991)
BT22	Aso-4	Aso caldera(middle part of Kyushu)	BB165(Lake Biwa), Abiko(Osaka) and many places	Machida *et al.*(1985), Yoshikawa and Inouchi(1991)
BT25	Kikai-Tozurahara (K-Tz)	Kikai caldera (south of Kyushu)	BB173(Lake Biwa) , Kitahanada (Osaka) and many places	Machida and Arai(1983), Yoshikawa and Inouchi(1991)
BT28			BB179(Lake Biwa)	Yoshikawa and Inouchi(1991)
BT34			BB207(Lake Biwa)	Yoshikawa and Inouchi(1991)
BT39			Ky-II(Kobe), P4(Kobe)	Nagahashi *et al.*(2004)
BT43	Aso-2	Aso caldera (middle part of Kyushu)		Nagahashi *et al.*(2004)
BT44, 45,47, 48,49			BB323,337(Lake Biwa), KS80,78,77(Osaka)	Yoshiakawa and Inouchi (1991, 1993)
BT51			Koshienhama I(Osaka Bay), P7 (Kobe), Blueglass (Yatsugatake)	Yoshikawa *et al.*(1993), Miyakawa *et al.*(1996), Uchiyama(1998)
BT58	Ata-Toihama(At-Th)	Ata caldera (southern part of Kyushu)	BB395U(Lake Biwa), ks108(Osaka), Nsm(Osaka), Kt-6 (Yatsugatake), P8(Kobe)	Machida *et al.*(1991), Yoshikawa and Inouchi(1991), Ogura *et al.* (1992), Yoshikawa *et al.*(1993), Uchiyama(1998), Nagahashi *et al.*(2004)
BT59			Terabayashi II(around Lake Biwa)	Satoguchi and Yamakawa(2006)
BT60			Terabayashi I(around Lake Biwa)	Satoguchi and Yamakawa(2006)
BT61	Aso-1	Aso caldera(middle part of Kyushu)	BB425(Lake Biwa), KR229(Lake Biwa), Kt-3(Yatsugatake)	Yoshikawa and Inouchi(1993), Yoshikawa(1999), Nagahashi *et al.*(2004)
BT62			Kt-2(Yatsugatake)	Nagahashi et al.(2004)
BT66	Ng-1		BB435(Lake Biwa), Handa(Osaka), Kt-1(Yatsugatake) and many places	Mizuno and Kikkawa(1991), Yoshikawa and Inouchi(1991, 1993), Uchiyama(1998)
BT70	Kakuto(Kkt)	Kakuto caldera(southern part of Kyushu)	K1-171(Osaka Bay), P9(Kobe), B236cc(Lake Biwa) and many places	Machida and Arai(1992), Yoshika-wa *et al.*(2000), Nagahashi *et al.* (2004), Yamashita *et al.*(2005)
BT72			K1-175(Kobe), B244cc(Lake Biwa)	Yoshikawa *et al.*(2000), Yamashita *et al.*(2005)
BT74			B249(Lake Biwa)	Yamashita *et al.*(2005)

Descriptions of tephras

The stratigraphy, lithofacies, petrographic properties (Yoshikawa and Inouchi, 1991, 1993; Table 1) and chemical composition of glass shards (Nagahashi *et al.*, 2004) of the tephras have been described. Samples were treated before analyses (Yoshikawa and Inouchi, 1991). We measured the refractive indices of glass shards (nd), amphiboles (n2) and orthopyroxenes (γ) in those same samples by using the MAIOT manufactured by the Furusawa Geological Survey. The device is a refractometer that uses a method of measuring actual immersion oil temperatures, and has a measurement error of 0.00012 (Furusawa, 1995). Refractive indices of glass shards were previously measured by Yoshikawa and Inouchi (1991) via the dispersion coloration technique using a set of standard glass and a technique of phase microscopy (Yoshikawa, 1984). Their data are shown in Table 3.

Refractive indices of volcanic glass shards (nd) range from 1.497 to 1.547, with some individual glass shards

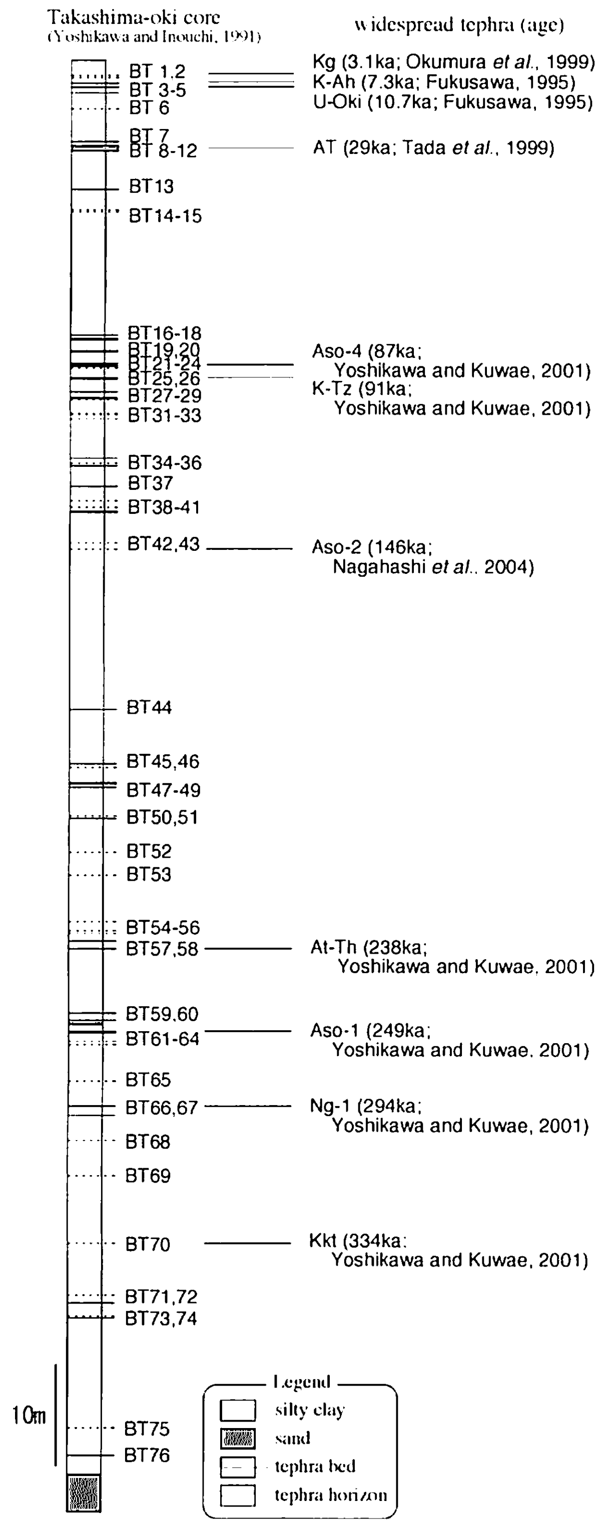

Fig. 2 Geologic column of the Takashima-oki core and correlations with widespread tephras (Yoshikawa and Inouchi, 1991, 1993; Nagahashi *et al.*, 2004). Solid lines are tephra beds. Dotted lines are tephra horizons. Tephra horizons are defined as sediment beds that contain tephra materials.

showing unusual features, such as a wide range or two peaks. Tephras that have relatively wide ranges of indices are BT20, 29, 37, 39, 42 and 43 (Fig. 3). These tephras are intercalated over small sections of the strata, and their ages range from about 85ka to 146ka. The origin of the BT43 is the Kyushu district in south-western Japan (Nagahashi *et al.*, 2004).

Indices of amphiboles (n2) range from 1.6610 to 1.7493, mainly from 1.665 to 1.690 (Fig. 4). Among these the BT4 tephra has an especially large value (n2=1.7301-1.7493). The tephra was correlated with the widespread Utsuryo-Oki (U-Oki) tephra by Yoshikawa and Inouchi (1991), which erupted at Ulreung-do island in the Sea of Japan.

The orthopyroxene indices (γ) range from 1.6925 to 1.7377, with the majority ranging between 1.695 to 1.710. Tephras that have indices of wide ranges are BT10, 11, 12, 29, 65, 66 (Fig. 4).

Data for each tephra is available to the public on the Lake Biwa Museum in Japanese website (Fig. 5). The address is "http://www.lbm.go.jp/emuseum/zukan/tephra/takashima/ takashimatop.html".

Correlation between refractive index of volcanic glass shards and heavy minerals

Tephras containing volcanic glass and amphiboles or orthopyroxenes are common. Each correlation about refractive index was made using volcanic glass, amphibole and orthopyroxene. Figures showing a combination of the highest value, lowest value, and the mean value were conducted (Fig. 6). Their correlation coefficients (R^2: Fig. 6) are calculated by the least square method.

Two trends in their data can be recognized. There is a positive correlation between volcanic glass and amphibole, and an inverse correlation is recognized for orthopyroxene and amphibole. Even the highest correlation coefficient of the latter, which is 0.274, is relatively low. These correlations are weak, so each refractive index can be available as an important autonomous variable and can be useful as an independent variable for the tephra correlation in other areas in future studies.

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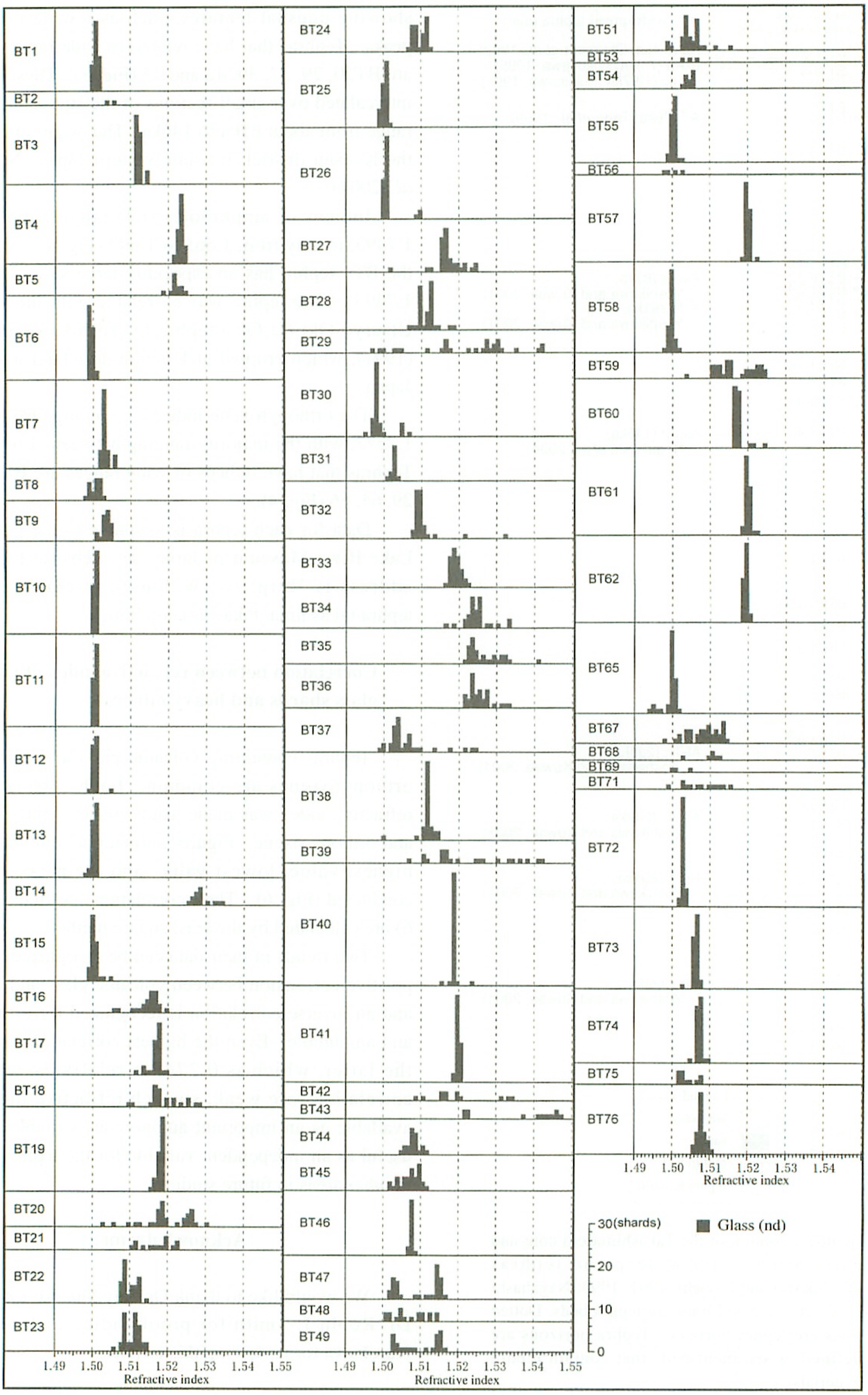

Fig. 3 Refractive indices of volcanic glass shards (nd) in each tephra. Each tephra is measured for some shards so that a graph has a range and a peak.

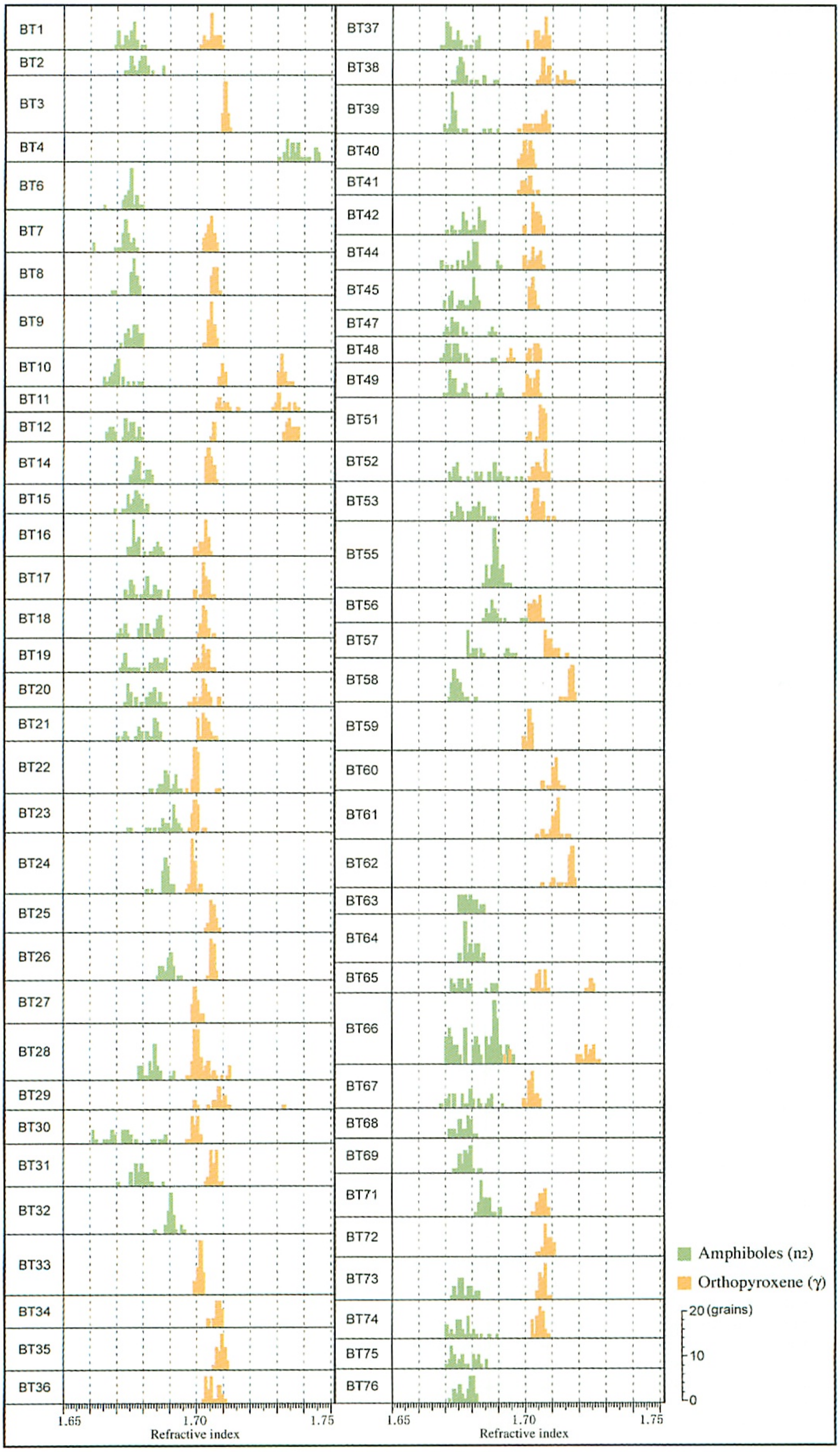

Fig. 4 Refractive indices of amphiboles (n2) and orthopyroxenes (γ) in each tephra. Each tephra is measured for some grains.

Table 3 Refractive indices of volcanic glass shards (nd), amphiboles (n2) and orthopyroxenes (γ) in tephras of the Takashima-oki core.

	Refractive index of volcanic glass shards (mode)		Refractive index of amphiboles(mode)	Refractive index of orthopyroxene (mode)
	This study	Yoshikawa and Inouchi(1991)		
BT1	1.499-1.502	1.497-1.503(1.499-1.502)	1.6698-1.6802(1.677)	1.7018-1.7091(1.706)
BT2	1.504-1.506		1.6734-1.6876(1.676-1.681)	
BT3	1.511-1.515(1.511-1.513)	1.508-1.515(1.510-1.513)		1.7095-1.7124(1.711)
BT4	1.522-1.525	1.519-1.525	1.7301-1.7493(1.734)	
BT5	1.518-1.525	1.519-1.526(1.520-1.524)		
BT6	1.498-1.501	1.498-1.501(1.498-1.500)	1.6656-1.6792(1.676)	
BT7	1.501-1.506(1.501-1.503)	1.501-1.506(1.502-1.504)	1.6617-1.6778(1.679)	1.7021-1.7077(1.706)
BT8	1.498-1.503	1.498-1.503(1.499-1.501)	1.6689-1.6785(1.676-1.677)	1.7054-1.7089(1.707)
BT9	1.500-1.505	1.502-1.506(1.503-1.505)	1.6714-1.6797(1.677-1.678)	1.7025-1.7074(1.705-1.706)
BT10	1.499-1.501	1.498-1.501(1.499-1.500)	1.6652-1.6795(1.670-1.671)	1.7082-1.7352(Group1:1.710 Group2:1.732)
BT11	1.500-1.501	1.498-1.501(1.499-1.500)		1.7071-1.7377(Group1:1.708-1.710 Group2:1.731)
BT12	1.499-1.504(1.499-1.501)	1.498-1.501(1.499-1.501)	1.6667-1.6790(1.674-1.679	1.7057-1.7377(Group1:1.707 Group2:1.735)
BT13				
BT14	1.525-1.534(included lower 1.519)	1.524-1.534	1.6753-1.6837(1.678)	1.7033-1.7074(1.704)
BT15	1.499-1.504(1.499-1.502)	1.499-1.506(1.499-1.501)	1.6692-1.6815(1.675-1.678)	
BT16	1.506-1.520(1.511-1.517)	1.507-1.523(1.512-1.518)	1.6743-1.6871(1.677)	1.6997-1.7051(1.704)
BT17	1.512-1.519(1.516-1.518)	1.511-1.520(1.515-1.518)	1.6733-1.6896(1.676-1.682)	1.6998-1.7062(1.703)
BT18	1.509-1.529(1.516-1.529)	1.512-1.521(1.515-1.518)	1.6701-1.6873(1.687)	1.7008-1.7061(1.703)
BT19	1.515-1.519	1.514-1.520(1.515-1.518)	1.6717-1.6884(1.674)	1.6980-1.7067(1.703)
BT20	1.503-1.531(1.516-1.519,1.524-1.527)	1.511-1.525(1.514-1.522)	1.6739-1.6884(1.683-1.685)	1.6974-1.7082(1.703)
BT21	1.511-1.523	1.512-1.523(1.517-1.522)	1.6701-1.6869(1.685-1.686)	1.7003-1.7072(1.700-1.705)
BT22	1.507-1.515(1.507-1.513)	1.508-1.513(1.509-1.511)	1.6823-1.6941(1.689-1.690)	1.6969-1.7085(1.700-1.701)
BT23	1.506-1.514(1.508-1.514; 2peaks)	1.508-1.513(1.510-1.511)	1.6743-1.6943(1.692)	1.6974-1.7030(1.700)
BT24	1.506-1.512(2peaks)	1.507-1.513(1.508-1.510)	1.6810-1.6917(1.689)	1.6960-1.7015(1.699)
BT25	1.498-1.501	1.497-1.503(1.499-1.501)		1.7037-1.7080(1.706-1.707)
BT26	1.499-1.510(1.499-1.501)	1.499-1.501	1.6857-1.6943(1.690-1.691)	1.7041-1.7073(1.706-1.707)
BT27	1.502-1.525(1.515-1.520)	1.512-1.519(1.513-1.516)		1.6981-1.7029(1.700)
BT28	1.507-1.519(1.509-1.513; 2peaks)	1.507-1.517(1.508-1.513)	1.6780-1.6918(1.685)	1.6965-1.7123(1.700-1.701)
BT29	1.496-1.543	1.499-1.536(1.525-1.533)		1.6993-1.7327(Group1:1.709 Group2:1.733)
BT30	1.495-1.506(1.496-1.499)	1.493-1.504(1.496-1.498)	1.6610-1.6885	1.6967-1.7010(1.699-1.701)
BT31	1.501-1.503	1.501-1.504	1.6707-1.6876(1.680)	1.7032-1.7092(1.706-1.708)
BT32	1.507-1.532(1.507-1.511)	1.505-1.512(1.508-1.510)	1.6842-1.6957(1.691)	
BT33	1.517-1.523	1.514-1.526(1.515-1.519)		1.6994-1.7028(1.702)
BT34	1.517-1.534(1.521-1.526)	1.515-1.527(1.520-1.526)		1.7042-1.7097(1.708-1.709)
BT35	1.522-1.542(1.522-1.533)	1.519-1.526(1.520-1.525)		1.7069-1.7117(1.710)
BT36	1.522-1.534(1.522-1.528)	1.518-1.525(1.520-1.523)		1.7028-1.7100(1.704-1.706)
BT37	1.499-1.524(1.501-1.509)	1.501-1.507(1.502-1.505)	1.6689-1.6824(1.671)	1.7002-1.7084(1.708)
BT38	1.499-1.514(1.509-1.514)	1.508-1.514(1.509-1.511)	1.6726-1.6894(1.676-1.677)	1.7047-1.7171(1.707)
BT39	1.506-1.542	1.500-1.527(1.513-1.519)	1.6699-1.6896(1.673)	1.6974-1.7086(1.707-1.708)
BT40	1.516-1.524(1.517-1.520)	1.517-1.523(1.518-1.520)		1.6974-1.7032(1.702)
BT41	1.519-1.521	1.517-1.521(1.518-1.520)		1.6976-1.7041(1.699-1.702)
BT42	1.508-1.534 (included lower 1.504)	1.507-1.525	1.6701-1.6846(1.688)	1.6993-1.7066(1.703)
BT43	1.521-1.547(1.541-1.547)	1.522-1.548(1.540-1.548)		1.6984-1.7090(1.703)
BT44	1.505-1.511	1.506-1.512(1.509-1.511)	1.6681-1.6907(1.681-1.682)	1.6994-1.7067(1.702-1.706)
BT45	1.501-1.512	1.501-1.514(1.507-1.514)	1.6695-1.6826(1.681)	1.7011-1.7043(1.703)
BT46	1.506-1.508	1.505-1.508		
BT47	1.502-1.517(1.508-1.517; 2peaks)	1.500-1.516(1.506-1.515)	1.6696-1.6888(Group1:1.671-1.675 Group2:1.688)	
BT48	1.500-1.515	1.501-1.518	1.6687-1.6881(1.671-1.675)	1.6935-1.7059(1.704-1.706)
BT49	1.502-1.516(2peaks)	1.501-1.515	1.6698-1.6911(1.672)	1.6999-1.7053(1.701-1.705)
BT50		1.501-1.507(1.503-1.506)		
BT51	1.499-1.516(1.502-1.508)	1.504-1.516(1.506-1.510)		1.7006-1.70778(1.706-1.707)
BT52			1.6712-1.6985	1.7018-1.7086(1.708)
BT53	1.502-1.507		1.6724-1.6880(1.675)	1.7002-1.7105(1.703-1.705)
BT54	1.503-1.506	1.499-1.507(1.504-1.506)		
BT55	1.499-1.502	1.498-1.504(1.499-1.501)	1.6848-1.6943(1.689)	
BT56	1.498-1.503		1.6847-1.7000(1.688)	1.7007-1.7060
BT57	1.519-1.522(1.519-1.521)	1.518-1.522	1.6780-1.6964(1.679)	1.7070-1.7158(1.708)
BT58	1.498-1.501	1.497-1.502(1.500-1.501)	1.6716-1.6818(1.673-1.676)	1.7133-1.7183(1.717-1.718)
BT59	1.504-1.525(1.510-1.525)	1.510-1.525(1.518-1.524)		1.6990-1.7028(1.702-1.703)
BT60	1.516-1.525(1.516-1.518)	1.514-1.524(1.515-1.518)		1.7066-1.7149(1.712)
BT61	1.518-1.522	1.518-1.522(1.519-1.521)		1.7045-1.7162(1.713)
BT62	1.519-1.520	1.517-1.521		1.7066-1.7189(1.718)
BT63			1.6753-1.6849(1.675-1.681)	
BT64			1.6756-1.6843(1.678)	

Table 3 Refractive indices of volcanic glass shards (nd), amphiboles (n2) and orthopyroxenes (γ) in tephras of the Takashima-oki core.

	Refractive index of volcanic glass shards (mode)		Refractive index of amphiboles(mode)	Refractive index of orthopyroxene (mode)
	This study	Yoshikawa and Inouchi(1991)		
BT65	1.494-1.502(1.498-1.502)	1.499-1.502(1.500-1.501)	1.6722-1.6894	1.7020-1.7252(Group1:1.705-1.706 Group2:1.725-1.726)
BT66		1.497-1.499	1.6705-1.6954(1.689)	1.6925-1.7275(Group1:1.695 Group2:1.723-1.726)
BT67	1.498-1.514(1.506-1.514)	1.500-1.514(1.506-1.512)	1.6686-1.6911	1.6991-1.705681.703)
BT68	1.499-1.505		1.6716-1.6816(1.676-1.680)	
BT69	1.503-1.513(1.510-1.513)		1.6733-1.6835(1.676-1.680)	
BT70		1.500-1.503(1.501-1.502)		
BT71	1.499-1.515		1.6813-1.6901(1.684)	1.7026-1.7087(1.705-1.708)
BT72	1.498-1.505(1.502-1.505)	1.498-1.504(1.502-1.504)		1.7041-1.7109(1.708)
BT73	1.502-1.507(1.505-1.507)	1.503-1.509(1.506-1.508)	1.6726-1.6828(1.676)	1.7043-1.7090(1.706-1.708)
BT74	1.505-1.509(1.506-1.509)	1.503-1.512(1.506-1.508)	1.6700-1.689481.679)	1.7020-1.7088(1.705-1.707)
BT75	1.502-1.508	1.500-1.506(1.502-1.505)	1.6706-1.6854(1.673)	
BT76	1.505-1.511	1.507-1.511(1.508-1.509)	1.6718-1.6815(1.679-1.681)	1.7007-1.7060(1.706)

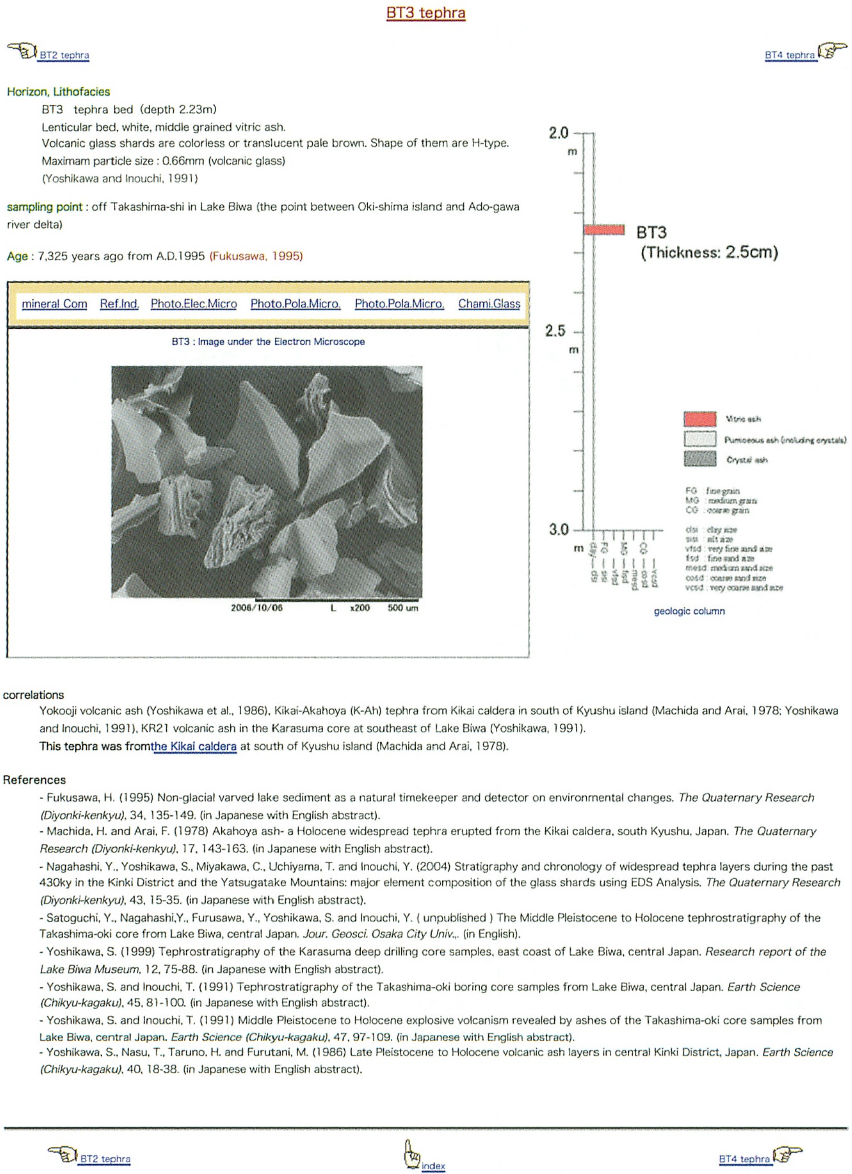

Fig. 5 The internet page of tephra intercalated in the Takashima-oki core. This figure is about the BT 3 tephra. Their pages show the data of each tephra in Japanese, but this figure is in English. Address of the top page is " http: //www.lbm.go.jp/emuseum/ zukan/tephra/takashima/takashimatop.html ".

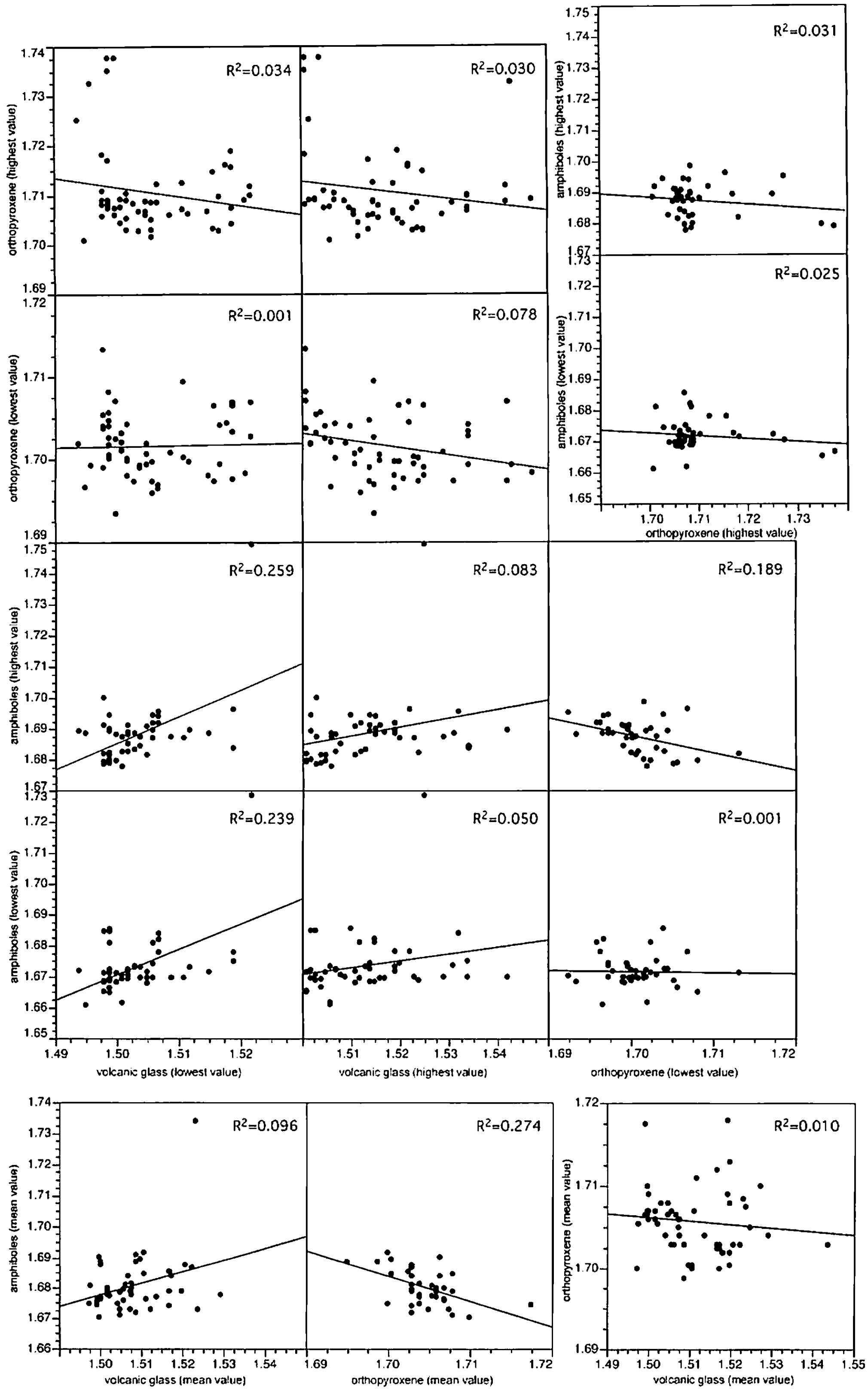

Fig. 6 Correlation between refractive indices of volcanic glass shards and heavy minerals. Their correlations coefficients are not so high (R^2=0.001 - 0.274).

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