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Variation of chemical composition in Australasian tektites from different localities in Vietnam

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Abstract–One hundred and thirteen Australasian tektites from Vietnam (Hanoi, Vinh, Dalat, and Saigon areas) were analyzed for their major and trace element contents. The tektites are either of splash form or Muong Nong-type. The splash-form tektites have SiO_2 contents ranging from 69.7 to 76.8 wt%, whereas Muong Nong-type tektites, which are considerably larger than splash-form tektites and have a blocky and chunky appearance, have slightly higher silica contents in the range of 74–81 wt%. Major-element relationships, such as FeO versus major oxides, Na_2O versus K_2O, and oxide ratio plots, were used to distinguish the different groups of the tektites. In addition, correlation coefficients have been calculated for each tektite group of this study. Many chemical similarities are noted between Hanoi and Vinh tektites from the north of Vietnam, except that the Hanoi tektites contain higher contents of CaO than Vinh; the higher content of CaO might be due to some carbonate parent material. Both Dalat and Saigon tektites have nearly similar composition, whereas the bulk chemistries of the tektites from Hanoi and Vinh appear different from those of Saigon and Dalat. There are differences, especially in the lower CaO and Na_2O and higher MgO, FeO, for the tektites of Dalat and Saigon in comparison to that of Hanoi tektites. Furthermore, the Dalat and Saigon tektites show enrichments by factors of 3 and 2 for the Ni and Cr contents, respectively, compared to those of Hanoi and Vinh. The difference in chemistry between the North Vietnam tektites (Hanoi, Vinh) to that of South Vietnam tektites (Saigon, Dalat) of this study indicate that the parent material was heterogeneous and possibly mixing between different source rocks took place.

Muong Nong-type tektites are enriched in the volatile elements such as Br, Zn, As, and Sb compared to the average splash-form tektites of this study. The chemical compositions of the average splash-form and Muong Nong-type tektites of this study closely resemble published data for average splash-form and Muong Nong-type indochinites, indicating that they have the same source. The trace element ratios Ba/Rb (2.7), Th/U (5.2), Th/Sc (1.3), Th/Sm (2.2), and the rare earth element (REE) abundances of this study show close similarities to those of average upper continental crust.

INTRODUCTION

Tektites are natural glasses that are millimeter- to centimeter-sized and occur in four major geographically extended strewn fields (e.g., Barnes 1963, 1964, 1990; Chao 1963): North American ~35 Ma old (Storzer and Wagner 1971; Glass et al. 1985, 1995); Central European (moldavites) 14.4 Ma old (Staudacher et al. 1982; Laurenzi et al. 2003); Ivory Coast, 1.07 Ma old (Koeberl et al. 1997); and Australasian 0.8 Ma old (Izett and Obradovich 1992). Despite some earlier hypotheses regarding their origin (O'Keefe 1976, 1994), most workers now agree that the bulk of the physical and chemical data on tektites is consistent with their formation by impact melting of terrestrial rocks (probably sediments) caused by the hypervelocity impact of an asteroid or cometary nucleus (e.g., Glass 1990; Koeberl 1986, 1990, 1992, 1994; Blum et al. 1992). The chemical and isotopic composition of tektites is similar to that of the upper continental crust (e.g., Taylor 1973; Koeberl 1986, 1994). Tektite glasses are not only found on land, but microtektites also occur in deep-sea sediments in three of the four strewn fields (e.g., Glass 1969, 1990; Koeberl and Glass 1988), where they are important to define the extent of the strewn fields, to constrain the stratigraphic age of tektites, and to provide evidence for the possible location of the source craters. Apart from the microtektites, tektites (on land) occur

Fig. 1. Schematic map of Vietnam and the neighboring countries of Indochina. Tektites analyzed in the present study were collected by E. Izokh (deceased; formerly Academy of Sciences of the USSR, Novosibirsk) in the 1970s from locations near the locations marked with stars. Precise finding coordinates are not available.

in three main forms: 1) normal or splash-form tektites, 2) aerodynamically shaped tektites, and 3) Muong Nong-type (layered) tektites. The aerodynamic ablation results from partial re-melting of the tektite glasses and is known mainly from the Australasian strewn fields, primarily as flanged-button australites. The shape of the splash-form tektites (spheres, droplets, tear drops, dumbbells, etc.) is not formed aerodynamically, but results mostly from the solidification of rotating solids (Koeberl 1990; Elkins-Tanton et al. 2003). Muong Nong-type tektites, named after a type locality in Laos (Lacroix 1935), are usually considerably larger than normal tektites and have chunky and blocky appearance. Most contain more vesicles, are more heterogeneous on a millimeter scale, and have higher volatile element contents than the splash-form tektites (e.g., Koeberl 1992; Schnetzler 1992). They are mostly found in Indochina, in the countries of Laos, Vietnam, Thailand, Cambodia, and adjacent areas of China. The purpose of the present paper is to provide precise major and trace element analyses of a large tektite sample suite, to determine the regional variation in the chemical composition, to compare their chemical variation with other Australasian tektites, and to provide further constraints on the nature of their precursor rocks. This is the first time such a large trace element data set was determined for a large sample suite from a subset of the Australasian strewn field.

SAMPLES AND ANALYTICAL METHODS

Tektites were collected from different localities in Vietnam (areas near Hanoi, Vinh, Dalat, and Saigon), as shown in Fig. 1. Our samples range from only a few millimeters to about 4 cm in diameter and belong mostly to the splash-form variety, except three samples from Dalat, two from Vinh, and one from Saigon, which are of Muong Nong-type. We analyzed 113 tektite samples from different localities of Vietnam; these are from a collection given to C. Koeberl by the late E. Izokh (Novosibirsk), which is now at the University of Vienna, Department of Geological Sciences. The weights of the tektites are in the range between 0.2 to 3.0 g for the Hanoi and Vinh area tektites, except one sample from Hanoi having 5.4 g, and tektites from Dalat weigh 0.4 to 3.5 g; the Muong Nong-type tektites ranged in weight from 1.72 to 6.83 g. The samples were split and fragments for analysis were carefully crushed into chips (20 to 60 mg) and then rinsed with clean acetone and distilled water and dried. Only clean fragments were analyzed. The tektites were analyzed for their major and trace element contents. First, the trace elements were analyzed by instrumental neutron activation analysis (INAA) at the Department of Geological Science, University of Vienna. About 20 to 60 mg of each sample and about 100 mg of international rock standards were used for irradiation. Details on analytical techniques, standards, instrumentation, correction procedures, as well as data on precision and accuracy of our method, are described by Koeberl (1993). Specific uncertainties for the elements reported here, using our current INAA procedure, are given in Son and Koeberl (2005) (their Table 3).

After a cooling period of 6 months, the irradiated tektite fragments were used for electron microprobe analysis to determine the major element contents. Polished sections were analyzed using a four-spectrometer Cameca SX-100 microprobe at the Department of Geological Sciences, University of Vienna, at 20 keV accelerating voltage, 20 nA current, and 1 μm beam diameter. Natural and synthetic standards were used for calibration and the PAP correction (Pouchou and Pichoir 1991) was applied to the data. Typical uncertainties are about 1 to 2 rel%.

RESULTS

Major Element Composition

The major and trace element composition of the 113 tektite samples as well as averages and standard deviations are presented in Table 1 (available online at http://meteoritics.org/Online%20Supplements.htm). The average major oxide compositions of this study (Tables 1 and 2) are consistent with average indochinite data (given in Table 3). All tektite samples analyzed have silica contents ranging between 70 and 81 wt%, with an average of 73.6 wt% (Tables 1 and 2). The data show an inverse relationship between the content of SiO_2 and that of the oxides of Al, Ti, Fe, and Mg; some of these correlations are shown in Fig. 2. A strong inverse relationship is apparent between SiO_2 versus TiO_2, Al_2O_3, and FeO (Fig. 2). Both Na and K abundances scatter more widely than those of other oxides (Figs. 2 and 3). Commonly, the individual analyzed specimens show slight variations in chemical composition between each other. This variation, as indicated by the standard deviation (Table 1), is different for each of the localities. Some of the major elements, such as MgO (2.16 wt%), CaO (2.07 wt%), and Na_2O (1.18 wt%) show large deviations from their average contents, which may reflect a chemically inhomogeneous source rock. The contents of the oxides of Ca and Mg in our sample suite are quite variable and span a wide range. As Fig. 2 illustrates, these elements define two somewhat different groups: a high-Ca group extending to 3.5 wt% with small variation in Mg content, and a high-Mg group extending to 3.5 wt% with comparatively smaller variation in Ca. There are also related differences in the iron content. These variations significantly exceed analytical uncertainties. As expected the splash-form tektites are more homogeneous in composition, with silica contents ranging from 70 to 76 wt%, whereas the Muong Nong-type tektites have higher silica contents from 74 to 81 wt% (Table 2).

To minimize the overlap among the major element data for different groups of tektites, plots of FeO versus major oxides have been used (Figs. 3a–e). From these plots, differences between the sample locations are observed for FeO versus Na_2O, FeO versus CaO, and FeO versus K_2O. For FeO versus Al_2O_3 and FeO versus MgO (Figs. 3a and 3b) no differences are obvious between the Hanoi and Vinh groups or between the Saigon and Dalat groups. The Hanoi and Vinh samples have higher contents of CaO and lower FeO contents, and higher FeO and lower alkali contents than the Dalat and Saigon tektites (Figs. 3c–e). In addition, there is a reasonable correlation between the FeO and the Al_2O_3 and MgO contents (Figs. 3a and b), but poor correlations with CaO and Na_2O (Figs. 3c and 3e). On the other hand, the Na_2O versus K_2O plot shows no distinction between the different locations (Fig. 3f). Figure 4 shows oxide ratio plots for the Vietnam splash-form and Muong Nong-type tektites; the ratios plotted are those that seemed to show the best separation between the groups. In these diagrams (Figs. 4a–d) the distinction between the two groups (Hanoi + Vinh, and Dalat + Saigon) is even more clearly expressed than in Fig. 3. The Muong Nong-type tektites show a wide compositional range but seem to fit better to the Hanoi + Vinh group. Here, within the geographic groups there is higher variation in the CaO/TiO_2 ratio. The high-Ca Hanoi (1.8–3.01 wt%) and high-Ca Vinh tektites (1.63–2.76 wt%) show large variations of their Ca/TiO_2 ratios, whereas the high-Mg (1.8–3.4%) and FeO (4.4–5.5 wt%) tektites (Dalat and Saigon) are concentrated at the left-bottom side of the diagram with less spread than the Hanoi and Vinh tektites. Figure 5 shows the comparison of major and trace element compositions for the average splash-form tektites of the different locations of this study compared to each other. Based on major element data, there is a good correlation between tektites from the Hanoi and Vinh areas on the one hand (Fig. 5a) and among the Dalat and Saigon area tektites on the other (Fig. 5b); this is also expressed in trace element data (Figs. 5c–d). On the other hand, larger differences exist if the other groups are plotted against each other.

Trace Element Composition

Trace elements can be used to infer similarities and differences between tektites from a certain strewn field and source rocks (e.g., Koeberl 1986, 1990). Results of trace element contents for our sample suite are also given in Tables 1 and 2. Figure 6 shows the correlation for trace element abundances between the average data of our study (both splash-form and Muong Nong-type tektites) versus the literature data for average indochinites, Muong Nong-type tektites, and the upper continental crust. The average Vietnam tektites have somewhat higher contents in Zn and U, and slightly higher Co contents compared to average indochinites (Fig. 6a). Abundances are also within a factor of two or so of that of the average continental crust (Fig. 6c), whereas Muong Nong-type tektites show more variability (Figs. 6b and 6d). Further comparisons between Muong Nong-type tektites and splash-form tektites, both from Vietnam (our study), are shown in Fig. 7. Major element compositions are very similar (Fig. 7a), but there are some differences in the trace element compositions between the two types (Fig. 7b).

Siderophile Trace Elements

There is a good correlation in the abundance of Ni and Co between Hanoi and Vinh tektites, and between Dalat and Saigon tektites (Figs. 5c–f). The content of Cr is slightly depleted in the Saigon tektites (128 ppm) compared to the Dalat tektites (174 ppm). In terms of average siderophile element contents there is a difference between the Hanoi-Vinh and Dalat-Saigon tektites; e.g., the average Ni content of the Hanoi and Vinh samples is 36 and 48 ppm, respectively,

Table 2. Major and trace element compositions for Muong Nong-type tektites collected from Vinh, Dalat, and Saigon areas, Vietnam.

	1/2d (Vinh)	Tk18-c (Dalat)	Tk8-a (Saigon)	A55-c (Vinh)	A55-d (Vinh)	A64 (Dalat)	Avg.	Std. dev.	Range
Original weight (g)	1.20	0.94	0.20	6.83	4.49	4.59			
SiO_2	74.30	80.50	80.85	75.69	77.66	75.03	77.34	2.82	74.30–80.85
TiO_2	0.76	0.52	0.49	0.78	0.66	0.77	0.66	0.13	0.49–0.78
Al_2O_3	12.50	8.57	8.92	11.48	10.24	11.43	10.52	1.56	8.57–12.5
FeO	4.63	3.25	3.11	4.07	3.43	3.95	3.74	0.58	3.11–4.63
MnO	0.09	0.12	0.09	0.05	0.07	0.06	0.08	0.03	0.05–0.12
MgO	2.35	1.40	1.22	1.80	1.51	1.81	1.68	0.40	1.22–2.35
CaO	1.85	2.01	1.72	1.57	1.74	1.68	1.76	0.15	1.57–2.01
Na_2O	1.05	0.96	1.15	1.03	1.03	1.03	1.04	0.06	0.96–1.15
K_2O	2.36	2.16	2.29	2.47	2.28	2.41	2.33	0.11	2.16–2.47
Total	99.90	99.50	99.84	98.94	98.63	98.19			
Sc	10.3	11.2	14.1	11.8	9.51	10.8	11.3	1.58	9.51–14.1
Cr	153	80.1	100	92.6	75.2	80.6	96.9	29.0	75.2–153
Co	23.8	13.3	15.8	15.4	12.9	14.2	15.9	4.0	12.9–23.8
Ni	87	62	43	31	66	39	55	21	31.4–86.8
Zn	22	75	70	62	68	72	61	20	21.8–74.9
As	10.7	11.2	5.18	4.21	3.92	4.32	6.59	3.41	3.92–11.2
Br	2.6	2.5	1.0	0.9	1.9	1.1	1.7	0.8	0.85–2.60
Rb	122	119	142	116	96.8	109	117	15.0	96.8–142
Zr	287	292	307	414	361	354	336	49.4	287–414
Sb	1.56	1.17	0.96	0.64	0.62	0.67	0.94	0.37	0.62–1.56
Cs	6.88	7.18	9.39	8.32	7.98	7.31	7.84	0.93	6.88–9.39
Ba	315	297	315	349	302	335	319	19.8	297–349
La	38.4	40.6	45.1	43.0	40.5	42.2	41.6	2.32	38.4–45.1
Ce	80.7	75.1	87.6	82.2	79.6	84.1	81.6	4.23	75.1–87.6
Nd	43.1	36.1	36.5	36.3	35.9	32.7	36.8	3.4	32.7–43.1
Sm	6.58	6.51	7.52	7.03	5.92	6.80	6.73	0.54	5.92–7.52
Eu	1.47	1.22	1.34	1.27	1.39	1.41	1.35	0.09	1.22–1.47
Gd	5.96	5.28	5.70	5.49	6.11	5.11	5.61	0.39	5.11–6.11
Tb	0.98	1.00	1.12	0.98	1.01	0.89	1.00	0.07	0.89–1.12
Tm	0.61	0.47	0.50	0.57	0.51	0.54	0.53	0.05	0.47–0.61
Yb	3.77	3.26	3.45	3.46	2.89	3.44	3.38	0.29	2.89–3.77
Lu	0.59	0.52	0.53	0.56	0.52	0.54	0.54	0.03	0.52–0.59
Hf	8.27	7.66	7.72	10.9	10.7	11.3	9.43	1.71	7.66–11.3
Ta	1.46	1.28	1.38	1.48	1.31	1.49	1.40	0.09	1.28–1.49
W	8.1	9.1	1.0	4.5	6.7	2.9	5.4	3.1	1.0–9.1
Ir (ppb)	<1.8	<3.6	<0.4	<3.5	<1.8	<1.6			
Au (ppb)	1.8	0.4	1.0	1.2	0.9	1.3	1.1	0.46	0.40–1.8
Th	16.1	15.3	17.0	16.2	13.3	15.8	15.6	1.26	13.3–17.0
U	3.18	3.54	2.80	3.22	2.33	2.36	2.91	0.49	2.33–3.54
K/U	6184	5077	6815	6379	8149	8512	6853	1285	5077–8512
Th/U	5.06	4.32	6.07	5.03	5.71	6.69	5.48	0.85	4.32–6.69
La/Th	2.39	2.65	2.65	2.65	3.05	2.67	2.68	0.21	2.39–3.05
Zr/Hf	34.7	38.1	39.8	38.0	33.7	31.3	37.5	3.20	31.3–39.8
Hf/Ta	5.66	5.98	5.59	7.36	8.17	7.58	5.75	1.11	5.59–8.17
La_N/Yb_N	6.88	8.42	8.83	8.40	9.47	8.29	8.38	0.85	6.88–9.47
Eu/Eu*	0.72	0.64	0.63	0.62	0.71	0.73	0.67	0.05	0.62–0.73

N = chondrite-normalized (Taylor and McLennan 1985); major elements in wt%, trace elements in ppm, except as noted; all Fe given as FeO.

Table 3. Major and trace element compositions of the average Vietnamese tektites compared to average splash-form and Muong Nong-type indochinites, the average upper continental crust and the Post-Archean Australian Shale.

Avg.	Avg. Hanoi	Avg. Vinh	Avg. Dalat	Avg. Saigon	A	B	C	D	E
SiO_2	73.70	73.22	72.81	73.26	77.34	72.7	78.9	66.0	62.8
TiO_2	0.77	0.79	0.76	0.77	0.66	0.78	0.63	0.5	1.0
Al_2O_3	12.67	12.92	12.67	12.51	10.52	13.37	10.2	15.2	18.9
FeO	4.28	4.41	4.97	5.04	3.74	4.85	3.74	4.5	6.5
MnO	0.09	0.09	0.10	0.10	0.08	0.08	0.01	0.08	0.11
MgO	1.98	2.05	2.63	2.32	1.68	2.14	1.43	2.2	2.2
CaO	2.28	2.07	1.81	1.57	1.76	1.98	1.21	4.2	1.3
Na_2O	1.12	1.24	1.08	1.26	1.04	1.05	0.92	3.9	1.2
K_2O	2.40	2.53	2.37	2.76	2.33	2.62	2.42	3.4	3.7
Total	99.29	99.32	99.20	99.59	99.15	99.57	99.46	100.0	97.7
Sc	11.3	11.6	11.5	11.3	11.3	10.5	7.7	11	16
Cr	78	90.1	180	128	96.9	63	60.6	35	110
Co	14.1	14.8	24.3	18.7	15.9	11	12.6	10	23
Ni	38	48	173	152	54.6	19	49	20	55
Zn	11	24	20	39	61.3	5.7	67	71	85
As	0.69	1.17	1.24	2.95	6.59	0.9	4.75	1.5	–
Br	0.8	0.8	0.9	1.0	1.7	0.2	4.1	–	–
Rb	115	125	118	121	117	130	110	112	160
Zr	287	306	285	310	336	252	280	190	210
Sb	0.50	0.60	0.81	0.60	0.94	0.5	0.82	0.2	–
Cs	6.6	7.41	7.24	7.19	7.84	6.5	5.09	3.7	15
Ba	319	339	332	320	319	360	341	550	650
La	42.1	41.8	42.1	38.7	41.6	36.5	28.2	30	38
Ce	81.6	81.8	80.9	78.9	81.6	73.1	60.7	64	80
Nd	36.8	37.4	37.4	35.7	36.8	33.2	29.1	26	32
Sm	7.07	6.78	7.05	6.61	6.73	6.6	4.85	4.5	5.6
Eu	1.39	1.40	1.45	1.27	1.35	1.22	1.01	0.88	1.1
Gd	5.7	5.75	5.70	5.44	5.61	5.24	4.3	3.8	4.7
Tb	1.06	1.06	1.06	1.01	1.0	0.85	0.75	0.64	0.77
Tm	0.56	0.58	0.59	0.53	0.53	n.d	0.42	0.33	0.4
Yb	3.61	3.82	3.55	3.53	3.39	2.9	2.71	2.2	2.8
Lu	0.54	0.58	0.55	0.52	0.54	0.4	0.42	0.32	0.43
Hf	7.94	7.76	7.78	7.82	9.43	6.95	8.13	5.8	5
Ta	1.38	1.43	1.48	1.33	1.4	1.6	1.17	2.2	–
W	2.07	6.41	3.39	1.42	5.38	0.29	1.02	2.0	2.7
Ir (ppb)	<3.2	<3	<4	<2	<2	0.02	<1	0.02	–
Au (ppb)	0.8	1.2	0.8	0.5	1.1	2	2.1	1.8	–
Th	15.0	14.9	15.3	14.7	15.6	14.0	11.1	10.7	14.6
U	2.80	2.88	3.28	2.70	2.91	2.07	2.48	2.8	3.1

A = average Muong Nong–type (this study); B = average splash-form thailandites (Koeberl 1992); C = average Muong Nong-type indochinites (Koeberl 1992); D = average upper continental crust (Taylor and McLennan 1985); E = average Post-Archean Australian Shale (Taylor and McLennan 1985); major elements in wt%, trace elements in ppm, except as noted.

whereas that of the Dalat and Saigon tektites is 159 and 152 ppm, respectively. The Ni/Co ratio of the Dalat and Saigon samples is close to 8, but only 3 for the Hanoi and Vinh tektites. The average concentration of Ni for the splash-form tektites is 15 ppm and for the Muong Nong-type 64 ppm. Comparisons with crustal rocks are shown in Figs. 6–8. For example, the Cr and Co contents are similar to (Post-Archean Australian Shale (PAAS) values (Fig. 8).

Volatile Trace Elements

Some of the volatile trace elements analyzed in this study show great variability. Trace element studies demonstrated that the volatile elements, such as Sb, As, Br, and Zn, have considerably higher abundances in Muong Nong-type tektites than in splash-form tektites from the same strewn fields (Koeberl 1986, 1992). Similarly, the average Muong Nong-type tektites of this study shows enrichments for the Sb, As, Br, and Zn contents, respectively, compared to the average splash-form tektites (Figs. 6b, 6e, and 6f).

Refractory Trace Elements

Refractory elements show less variation between the

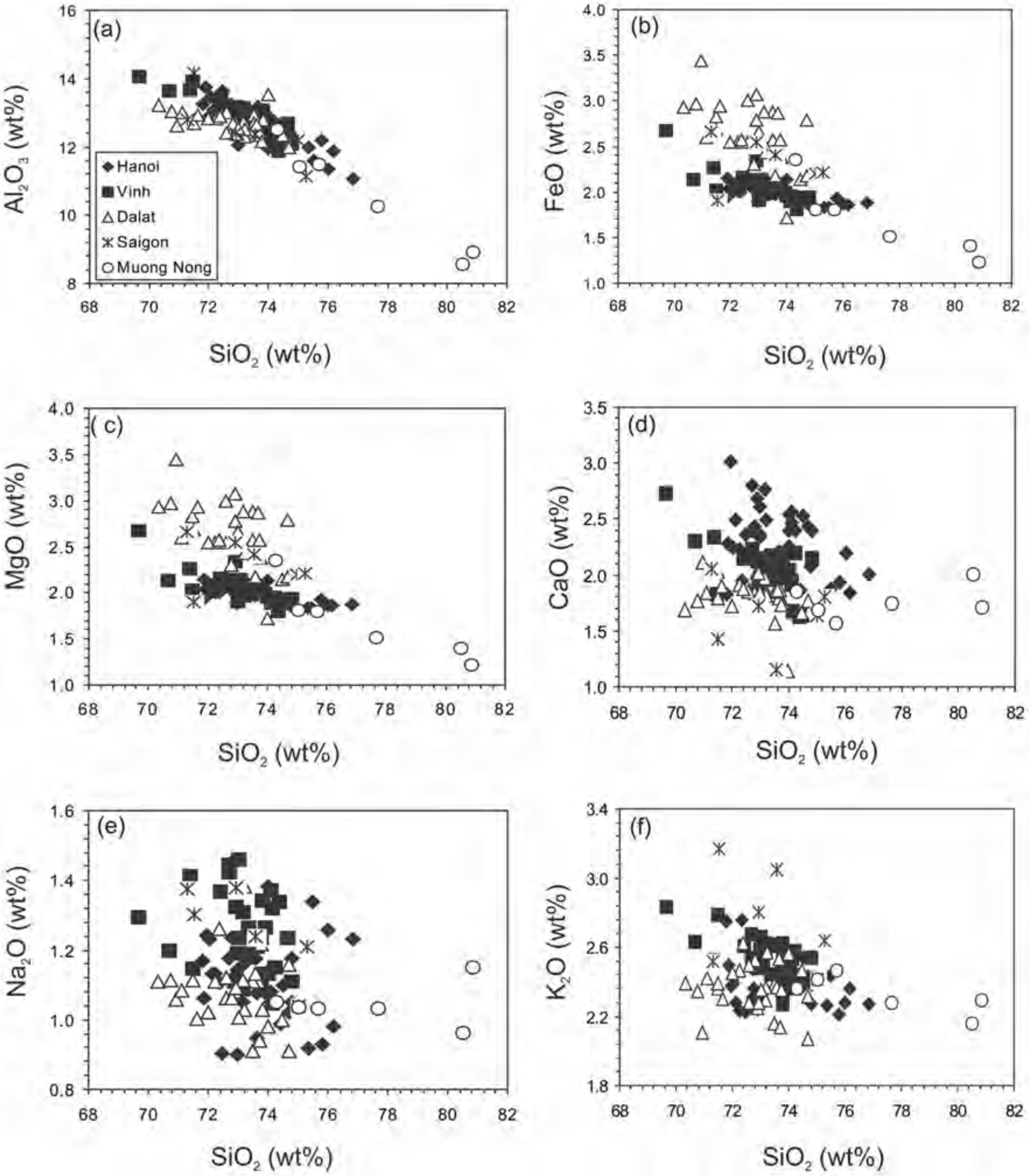

Fig. 2. Harker diagrams of major oxide contents versus silica contents for splash-form and Muong Nong-type Vietnam tektites (this study). a) Al_2O_3 and FeO: strong correlation; b) MgO and CaO: moderate correlation; c) Na_2O and K_2O: weak correlation.

locations and types (Fig. 8). Except for U and Sc, the data for splash-form and Muong Nong-type of this study resemble those of average splash-form and Muong Nong-type indochinites (Koeberl 1992). The contents of Rb, Zr, U, and Th are slightly depleted in both splash-form and Muong Nong-type tektites (this study) compared to PAAS (Fig. 8).

DISCUSSION

Here we discuss the abundances, distribution, and variation in chemical composition in the Vietnam tektites and the nature of their precursor material using major and trace element chemistry. The major element chemistry of most tektite classes is well known (e.g., Chao 1963; O'Keefe 1963; Barnes 1964; Chapman and Scheiber 1969). In particular, tektites are characterized by high SiO_2 contents (65–85 wt%) and by high FeO and low alkali contents compared to volcanic glasses such as obsidian (Koeberl 1990). About 530 Australasian tektites from 205 localities were chemically analyzed by Chapman and Scheiber (1969), among which significant chemical variations were found (see below). Clues to the source material of the Vietnam tektites are provided by

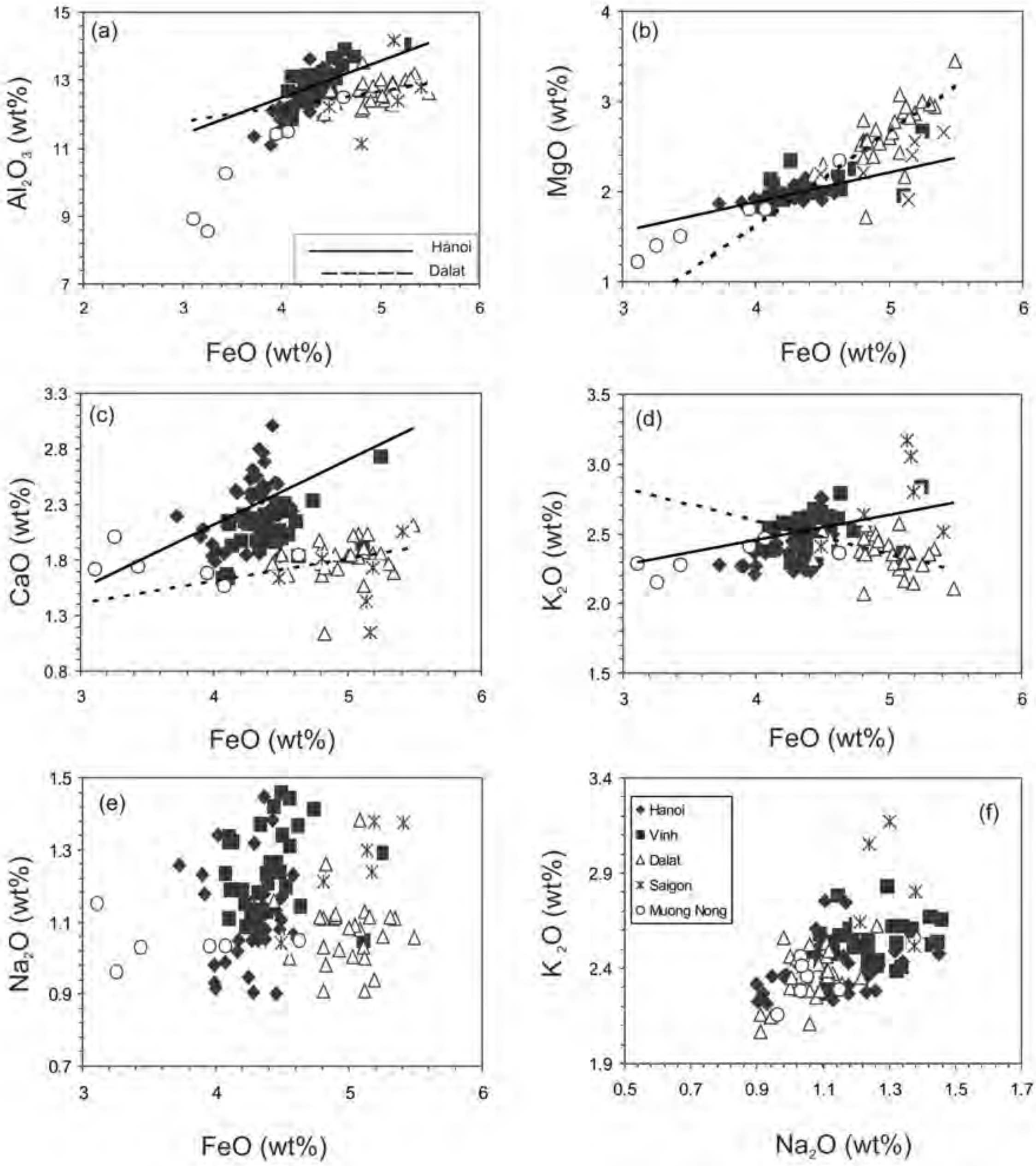

Fig. 3. Plots of total Fe (as FeO) versus the other major elements for splash-form tektites from Vietnam tektites (this study). Regression lines calculated from the data are shown in the cases where the correlations are statistically meaningful.

average abundances and relationships between individual components (Table 4). Correlation coefficients (r) were computed for major and some trace elements for each geographic group. A strong negative correlation is apparent between SiO_2-TiO_2 (r = –0.93), SiO_2-Al_2O_3 (r = –0.91), and SiO_2-FeO (r = –0.98) in the Saigon and Dalat tektites, south Vietnam. On the other hand, calcium has a significant positive correlation with SiO_2 contents in the Dalat and Saigon tektites, but a negative correlation in the Hanoi and Dalat tektites. Moreover, the CaO content is positively correlated with the abundances of all major oxides but silica in the Hanoi and Vinh samples, but negatively correlated with Al_2O_3, TiO_2, FeO, and MnO in the Dalat tektites. Contents of TiO_2 have a significant positive correlation with Al_2O_3 (r = +0.99) and FeO (r = +0.95) in the Dalat and Saigon areas; this is much less pronounced for the Vinh and Hanoi samples. The weak correlation of Mn (r = +0.25) with SiO_2 in Dalat and Saigon could be due to the mobility of manganese, probably during weathering processes (Taylor 1962). Differences exist for some of the major oxides, such as Mg, Fe, Ca, Na, and Al, between the various locations. There is a positive correlation of MgO with CaO in the Hanoi area tektites (r = +0.56),

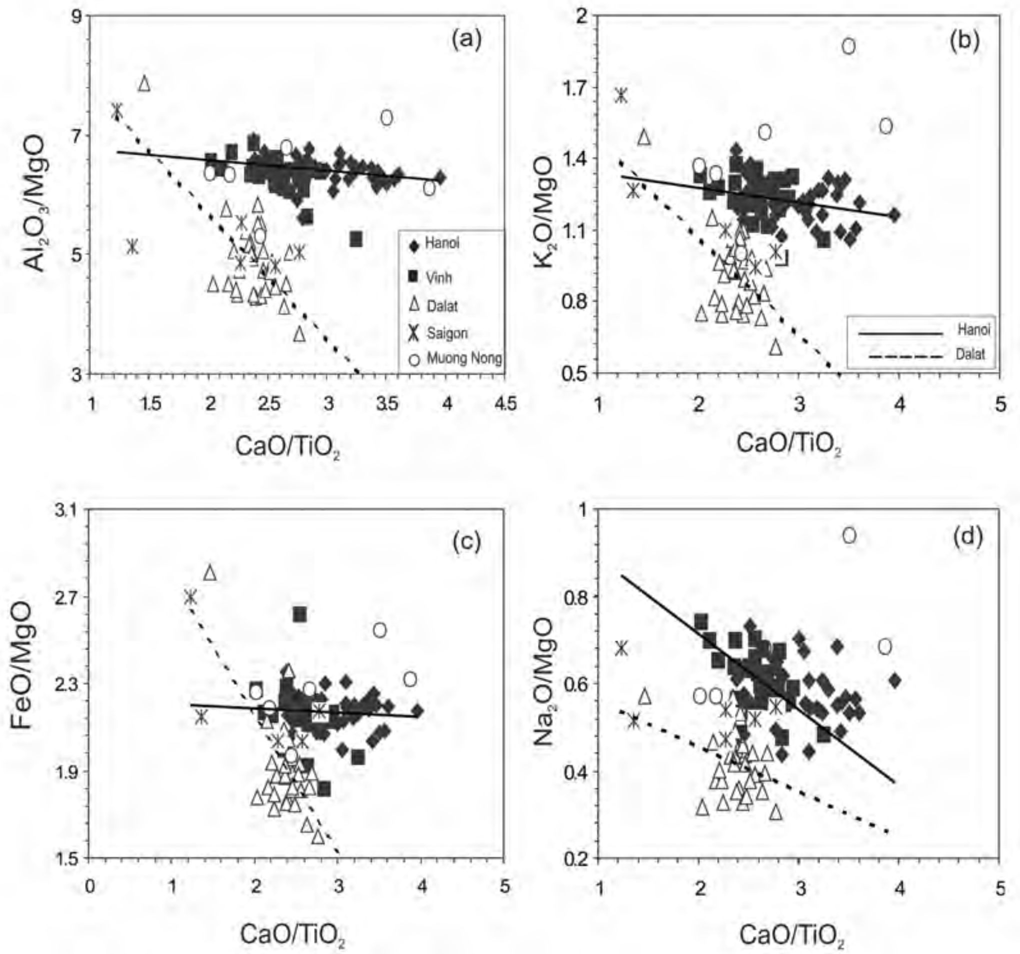

Fig. 4. Oxide ratio plots for Hanoi, Vinh, Dalat, and Saigon tektites of this study. The Hanoi-Vinh and Dalat-Saigon tektites define two clearly separated groups shown by regression lines.

which is absent in the Dalat and Saigon samples. A correlation of the CaO with MgO contents points to a dolomite component because the ratio of CaO/MgO, especially in samples from the Hanoi and Vinh areas, is approximately 1.3, which is close to the ratio in dolomite (1.39) (cf. Engelhardt et al. 1987). As mentioned above, the FeO versus major oxide plots (Fig. 3) show that there is a distinction between the Hanoi and Dalat tektites and an overlap between the Hanoi-Vinh and the Saigon-Dalat area tektites. The high FeO content in the South Vietnam tektites (Dalat and Saigon) compared to the North Vietnam tektites could result from the incorporation of residual iron oxide to the parent material during the formation of tektites. In addition, the oxide ratio plots (e.g., Al_2O_3/MgO, FeO/MgO, Na_2O/MgO, and K_2O/MgO; Fig. 4) distinguish clearly between the north (Hanoi-Vinh) and South (Dalat-Saigon) Vietnam tektites. Trace element contents in the tektites from the various localities are best used in the form of ratios, such as Ba/Rb, Th/Sm, K/U, and La/Sc, the values of which support the derivation of tektites from terrestrial post-Archean upper crustal sediments (e.g., Taylor 1973; Koeberl et al. 1986; Koeberl 1994); see Table 3 and Figs. 6–8. The Rb/Cs ratio is lower than that commonly encountered in igneous rocks and this holds also true for K/Cs (cf. Taylor 1962). The upper crustal Rb/Cs and K/Cs ratios of 30 and 5900, respectively, are close to the values for the Vietnamese tektites. The average K/U ratios range from about 4000 to 12,000, which is consistent with the range encountered in crustal rocks (Taylor and McLennan 1985). The average Th/U ratio of 5.0 for the splash-form and 5.1 for the Muong Nong-type tektites is somewhat higher than the average crustal value (3.5). Sedimentary rocks have higher Th/U ratios than igneous rocks (McLennan 1980). The high Th/U ratios of our samples indicate that sedimentary rocks played a major role in the source materials of these tektites; this is also indicated by the K/Sc, K/Rb, Rb/Sc. The elements Co, Ni, Cr, Zr, and Th are assumed to have a low mobility during sedimentary processes (Taylor and McLennan 1985). These elements are mainly transported in the terrigenous sedimentary components and, therefore, reflect the composition of the source materials. The Cr, Ni, Co, Zr, Th, and U contents are relatively uniform for both splash-form and Muong Nong-

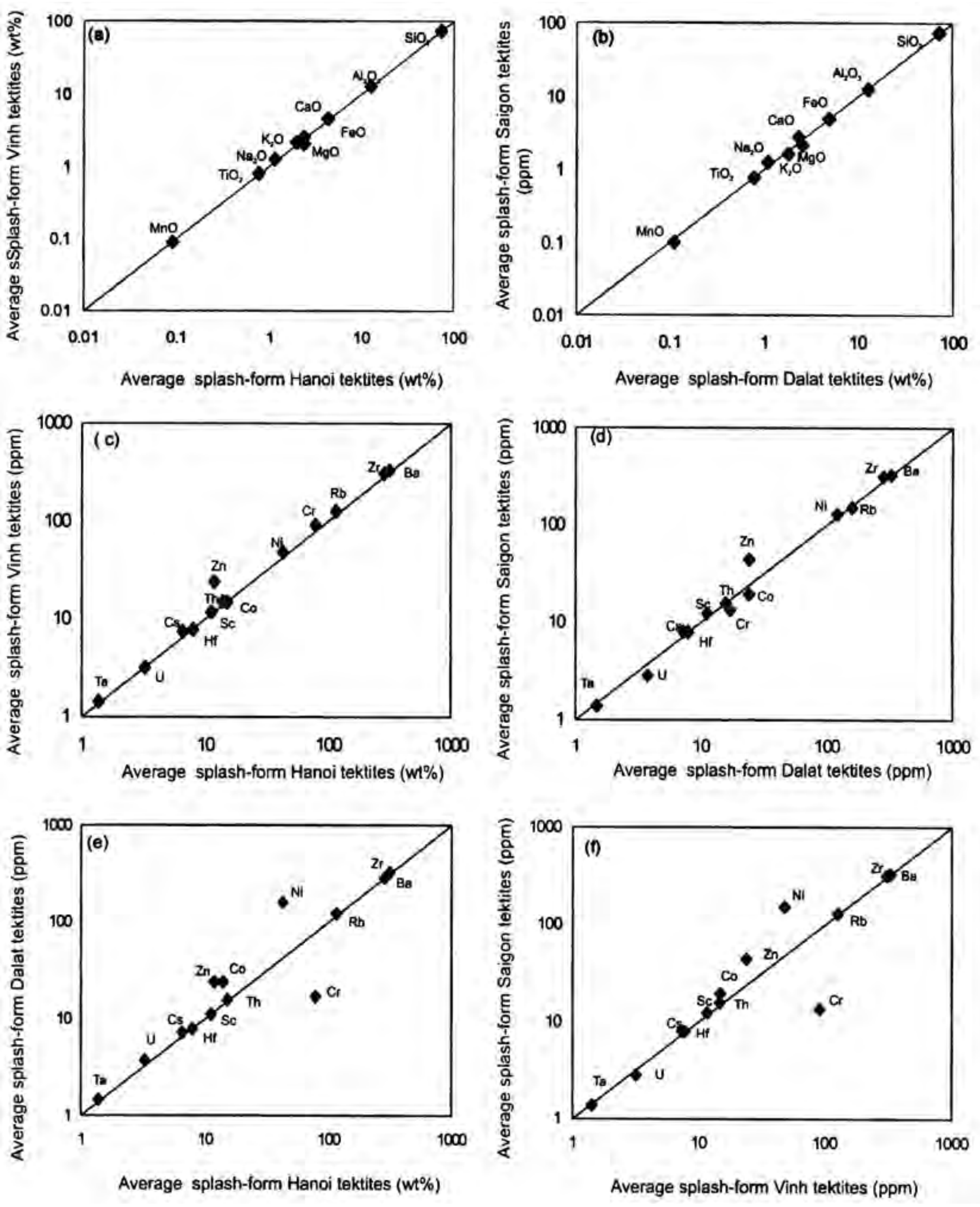

Fig. 5. A comparison of major and trace element compositions for the average splash-form tektites of this study: a) average major oxides of splash-form Hanoi with average splash-form Vinh tektites; b) average major oxides of splash-form Dalat versus average splash-form Saigon tektites; c) average trace elements of splash-form Hanoi versus average splash-form Vinh tektites; d) average trace element splash-form Dalat versus average splash-form Saigon tektites; e) average trace element splash-form Hanoi versus average splash-form Dalat tektites; f) average trace element contents of splash-form Vinh versus average splash-form Saigon tektites.

type of this study and similar (but not identical) to PAAS values (Fig. 8d). The lower contents of Ba, Cs, and Zn in the tektites could be due to the precursor rock, which was depleted during sedimentation processes. The elements Th, U, Ni, Ba have higher abundance in Dalat and Saigon tektites (South Vietnam), while Zr, Rb, and Sc are more abundant in Vinh and Hanoi tektites. Rubidium shows highly significant negative correlation ($r = -0.96$) with silica in the Dalat tektites and poor correlations in the Vinh and Hanoi samples. The depletion of volatile elements (Fig. 7b) in the splash-form tektites compared with that of Muong Nong-type tektites of this study is likely due to a temperature effect during the formation of tektites, as was suggested earlier (e.g., Koeberl 1992). Regional variations have already been described by Taylor (1962) and Taylor and Sachs (1964), who commented on the decrease in the alkali element concentration in

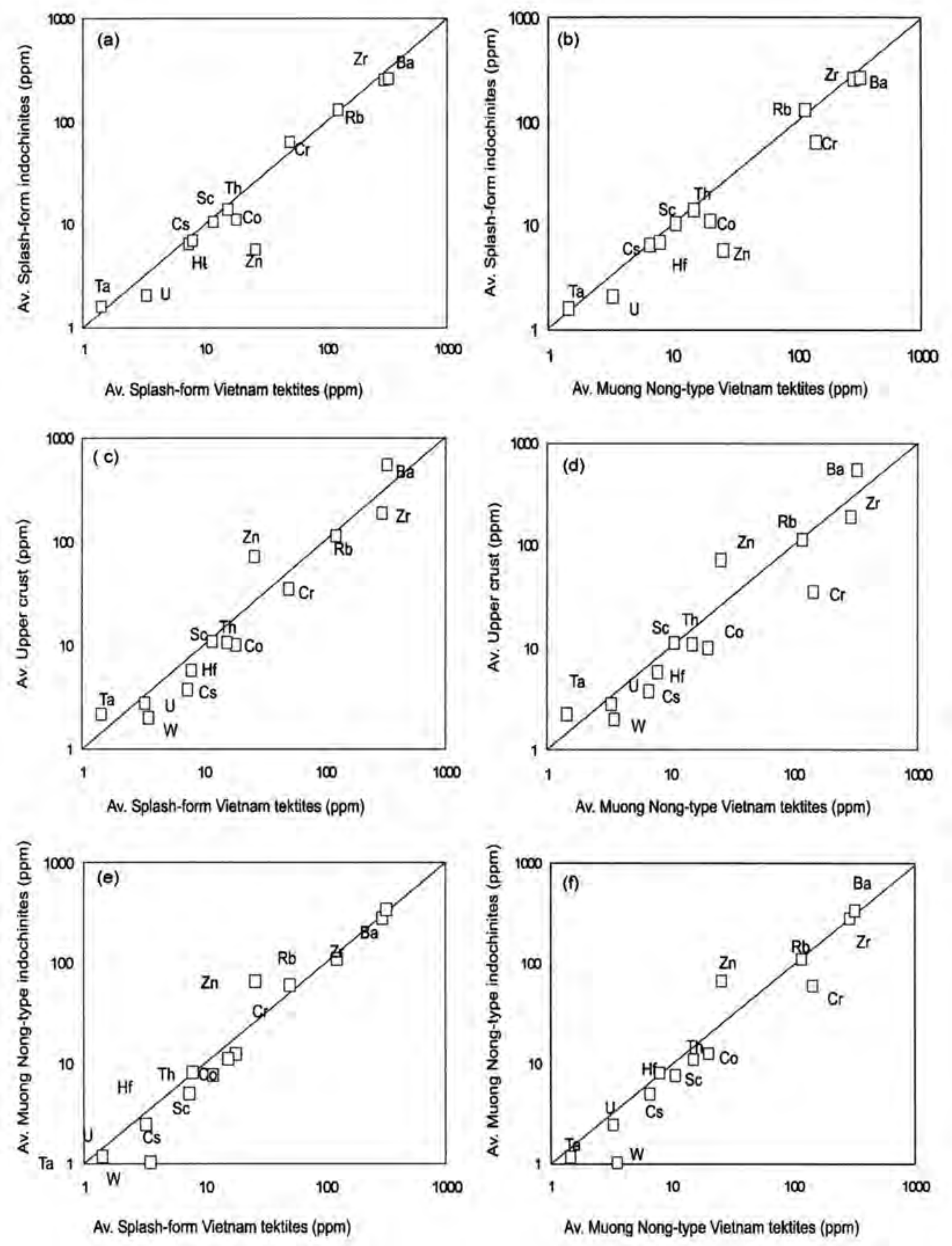

Fig. 6. A comparison of the average splash-form tektites (this study) and the average Muong Nongtype tektites of this study with: (a) and (d) average splash-form indochinites (Koeberl 1992); (b) and (e) average Muong Nong-type indochinites (Koeberl 1992); (c) and (f) average upper crust (Taylor and McLennan 1985).

australites from west to east across Australia. A similar variation exists in our data set, with variations in the contents of a number of elements from North to South Vietnam. Furthermore, Taylor (1962) suggested that tektites may be the result of mixing or fusion between at least two materials such as quartz-sandstone and shale; our data confirm this as well. Geochemical studies of tektites have shown that their compositions can be explained as melts of upper crustal target rocks, with a very small projectile contribution (<< 1%) and possibly loss of some elements by selective volatilization (e.g., Blum et al. 1992; Koeberl and Shirey 1997; Barrat et al. 1997). No extraterrestrial component is evident from the data for the Vietnam tektites, as the contents of Ni and other siderophile elements are within the range of sedimentary

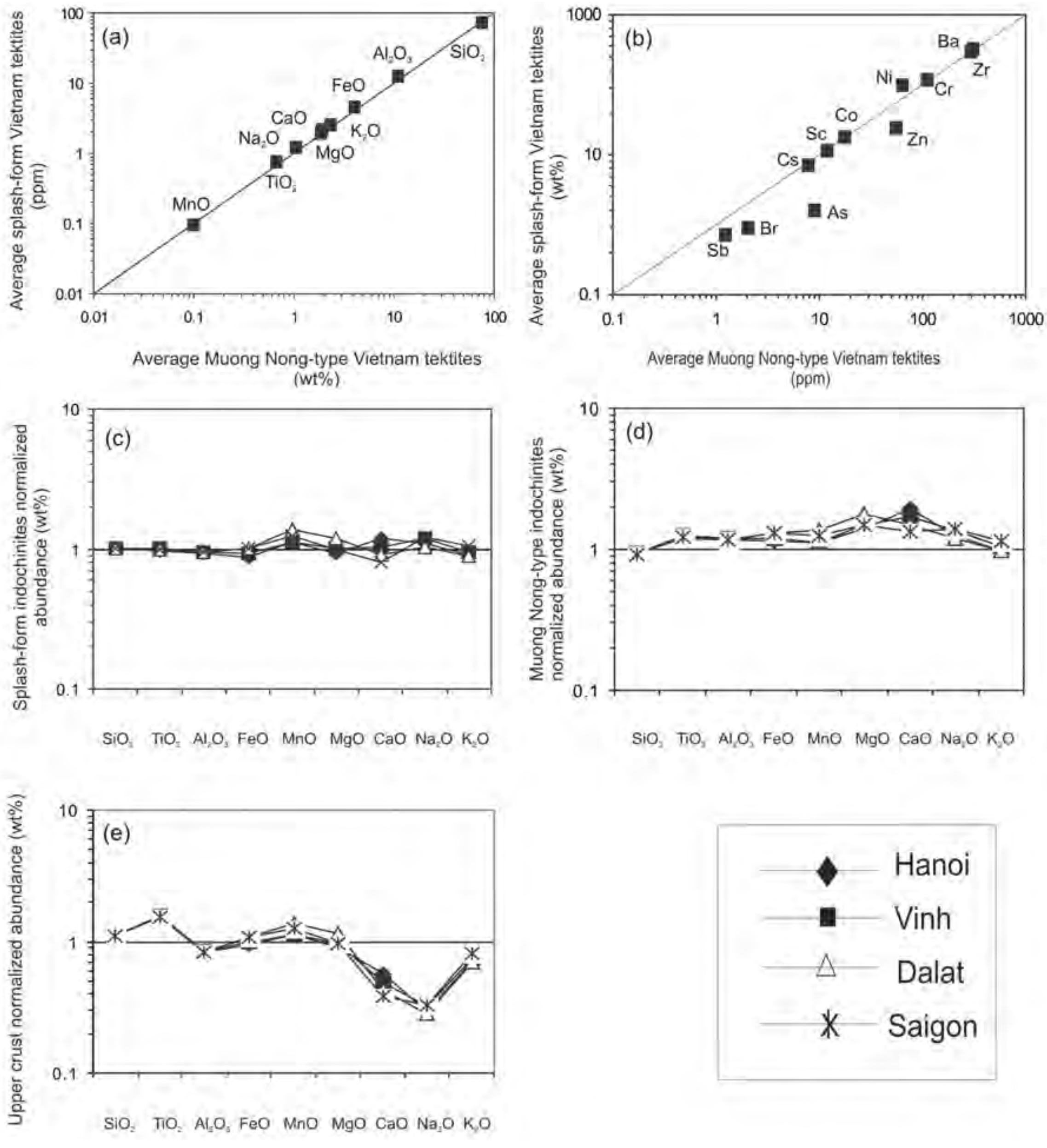

Fig. 7. A comparison of major elements and selected trace elements of average splash-form tektites and Muong Nong-type tektites from Vietnam (this study) with (a) and (b) average splash-form (this study) versus average Muong Nong-type (this study); c) average major oxides normalized to average splash-form indochinites (data from Koeberl 1992); d) average major oxides versus average normalized Muong Nong-type indochinites (data from Koeberl 1992); e) average major oxides in Vietnam tektites normalized to average upper continental crust (data from Taylor and McLennan 1985).

precursor materials. The REEs are particularly useful to determine the source of tektites; several authors (e.g., Taylor and McLennan 1979; Koeberl 1990, 1992; Wasson 1991) have noted that the REE patterns of tektites are similar to those of the upper crustal sedimentary rocks. Figure 9 shows the (very narrow) range of the chondrite-normalized REE patterns for four major areas of Vietnam tektites compared to the patterns of the Muong Nong-type and splash-form indochinites. The REE patterns of the tektites are very similar to those of post-Archean upper continental crust rocks, with enriched LREE, relatively flat HREE patterns, and significant negative Eu anomalies (average Eu/Eu* = 0.6–0.8). Other element ratios, such as La/Th and Th/Sc, are also in agreement with sedimentary values.

COMPARISON OF VIETNAMESE AND OTHER AUSTRALASIAN TEKTITES

Chapman and Scheiber (1969) analyzed major and selected trace element abundances of about 530 Australasian

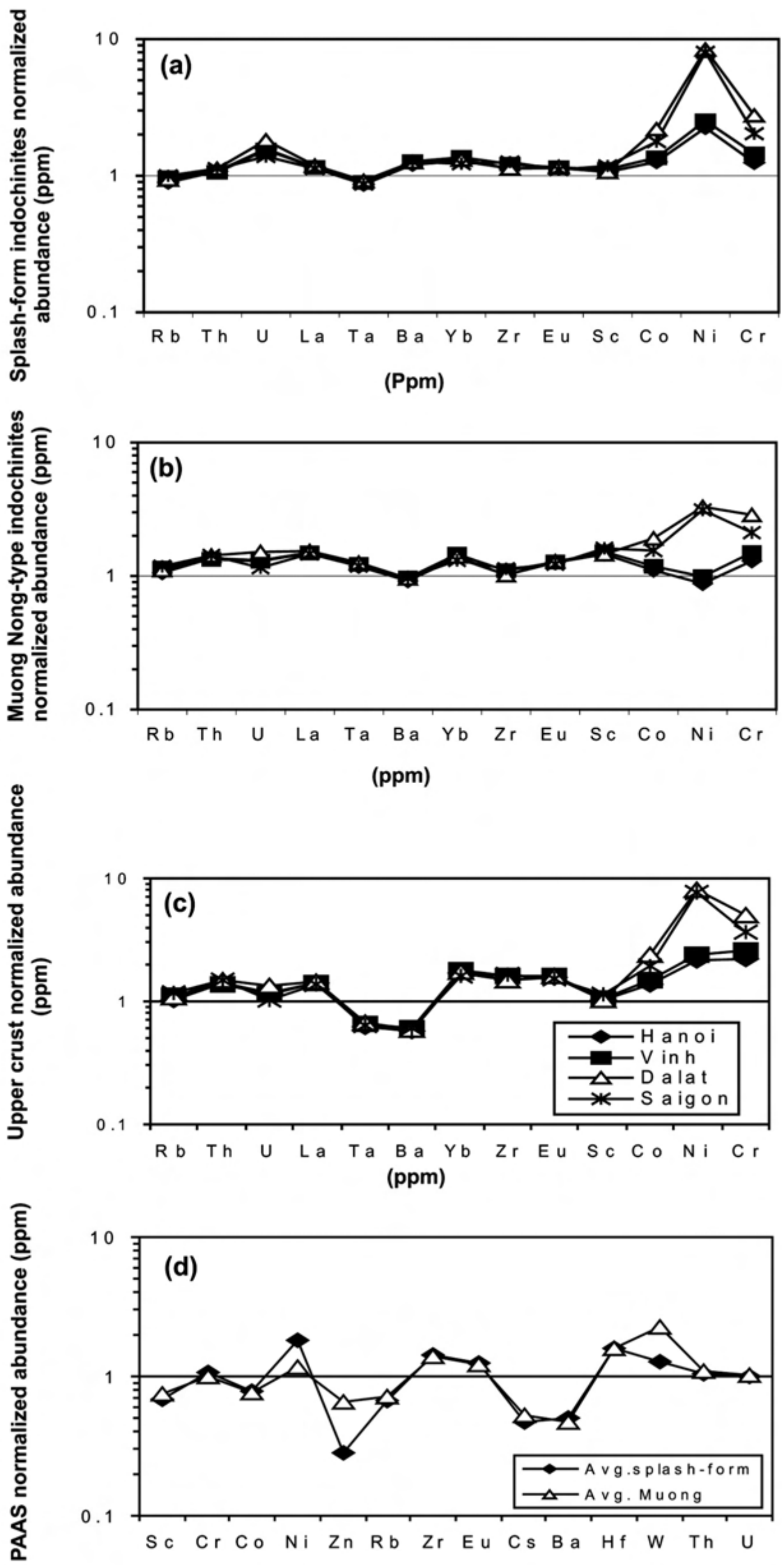

Fig. 8. A comparison of some selected trace elements of splash-form tektites (this study) with: a) average Vietnam tektites normalized to average indochinites (data from Koeberl 1992); b) average Vietnam tektites normalized to Muong Nong-type indochinites (data from Koeberl 1992); c) average 15 Vietnam tektites normalized to the upper crust (Taylor and McLennan 1985); d) average Vietnam tektites normalized to PAAS (Taylor and McLennan 1985).

Table 4. Linear correlation coefficients (r) between major element oxides and selected trace elements of data (a) Hanoi, (b) Vinh, (c) Dalat, and (d) Saigon tektites.

(a)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr	Co	Ni	Rb	Zr
SiO_2	1													
TiO_2	–0.56	1												
Al_2O_3	–0.84	0.67	1											
FeO	–0.86	0.53	0.93	1										
MnO	–0.29	–0.12	0.26	0.34	1									
MgO	–0.75	0.69	0.80	0.73	0.15	1								
CaO	–0.62	0.06	0.45	0.53	0.48	0.54	1							
Na_2O	–0.30	0.22	–0.02	0.09	–0.28	0.16	0.03	1						
K_2O	–0.08	0.01	0.18	0.34	0.19	0.07	0.17	0.23	1					
Cr	–0.01	0.07	0.09	0.18	–0.05	0.20	–0.09	0.15	0.47	1				
Co	0.14	–0.07	0.04	0.07	–0.03	–0.08	0.01	–0.06	0.57	0.40	1			
Ni	0.07	0.13	0.02	0.04	–0.35	0.21	–0.13	0.19	0.25	0.53	0.58	1		
Zn	–0.32	0.14	0.42	0.40	0.29	0.19	0.42	–0.11	0.35	–0.13	0.44	–0.04		
Rb	–0.11	–0.08	0.28	0.35	0.47	0.06	0.30	–0.29	0.59	0.07	0.61	0.07	1	
Zr	0.33	0.05	–0.28	–0.30	–0.22	–0.19	–0.20	–0.11	–0.09	–0.21	–0.15	–0.05	–0.07	1

(b)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr	Co	Ni	Rb	Zr
SiO_2	1													
TiO_2	–0.56	1												
Al_2O_3	–0.84	0.56	1											
FeO	–0.76	0.18	0.47	1										
MnO	–0.24	0.01	0.34	0.27	1									
MgO	–0.60	0.02	0.27	0.95	0.22	1								
CaO	–0.71	0.39	0.87	0.38	0.31	0.26	1							
Na_2O	–0.32	0.72	0.23	0.06	–0.12	–0.12	0.05	1						
K_2O	–0.42	0.49	0.61	0.04	0.23	–0.14	0.64	0.50	1					
Cr	–0.21	0.08	0.07	0.47	0.06	0.48	0.14	0.17	0.18	1				
Co	–0.32	0.22	0.26	0.52	0.19	0.47	0.21	0.32	0.24	0.83	1			
Ni	–0.19	0.13	0.08	0.53	0.03	0.54	0.07	0.12	0.03	0.90	0.84	1		
Zn	0.15	0.08	–0.38	–0.28	–0.45	–0.24	–0.46	0.32	–0.11	–0.03	–0.14	–0.08		
Rb	–0.20	0.20	0.23	0.01	0.17	–0.08	0.32	0.54	0.59	0.13	0.35	–0.08	1	
Zr	0.02	0.21	–0.12	–0.17	–0.24	–0.18	–0.09	0.30	0.04	0.29	0.13	0.21	0.05	1

(c)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr	Co	Ni	Rb	Zr
SiO_2	1													
TiO_2	–0.93	1												
Al_2O_3	–0.91	0.94	1											
FeO	–0.81	0.74	0.76	1										
MnO	0.25	–0.28	–0.25	0.03	1									
MgO	–0.61	0.49	0.45	0.88	–0.04	1								
CaO	0.09	–0.19	–0.32	–0.27	–0.44	0.06	1							
Na_2O	–0.35	0.28	0.16	–0.15	–0.26	–0.22	0.37	1						
K_2O	–0.28	0.37	0.35	–0.24	–0.28	–0.55	0.02	0.71	1					
Cr	0.03	–0.17	–0.22	0.18	0.02	0.42	0.40	–0.09	–0.51	1				
Co	–0.12	0.01	–0.02	0.32	–0.16	0.55	0.33	–0.13	–0.50	0.92	1			
Ni	–0.30	0.10	0.06	0.36	–0.06	0.49	0.35	0.09	–0.26	0.81	0.82	1		
Zn	0.14	0.01	0.04	–0.39	0.03	–0.57	–0.12	0.17	0.55	–0.78	–0.78	–0.67		
Rb	–0.15	0.04	0.06	–0.06	–0.50	0.01	0.41	0.35	0.22	0.37	0.54	0.56	1	
Zr	0.11	–0.09	–0.02	–0.09	–0.14	–0.11	–0.07	–0.24	–0.08	0.07	0.14	0.02	0.28	1

Table 4. *Continued.* Linear correlation coefficients (r) between major element oxides and selected trace elements of data (a) Hanoi, (b) Vinh, (c) Dalat, and (d) Saigon tektites.

(d)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr	Co	Ni	Rb	Zr
SiO_2	1													
TiO_2	–0.98	1												
Al_2O_3	–0.96	0.99	1											
FeO	–0.98	0.95	0.92	1										
MnO	–0.34	0.35	0.27	0.26	1									
MgO	–0.78	0.72	0.65	0.86	0.34	1								
CaO	0.37	–0.46	–0.57	–0.31	0.46	0.11	1							
Na_2O	–0.72	0.61	0.53	0.71	0.07	0.51	–0.14	1						
K_2O	–0.73	0.75	0.78	0.62	0.02	0.17	–0.74	0.59	1					
Cr	–0.52	0.48	0.41	0.63	0.46	0.90	0.38	0.21	–0.18	1				
Co	–0.45	0.44	0.41	0.58	0.30	0.85	0.22	0.03	–0.22	0.96	1			
Ni	–0.24	0.24	0.21	0.37	0.30	0.73	0.35	–0.18	–0.43	0.90	0.97	1		
Zn	–0.22	0.28	0.33	0.06	–0.10	–0.43	–0.70	0.26	0.80	–0.70	–0.72	–0.82		
Rb	–0.96	0.93	0.92	0.94	0.14	0.72	–0.47	0.70	0.79	0.40	0.36	0.15	1	
Zr	–0.54	0.44	0.35	0.46	0.46	0.34	0.17	0.76	0.51	0.09	–0.15	–0.27	0.54	1

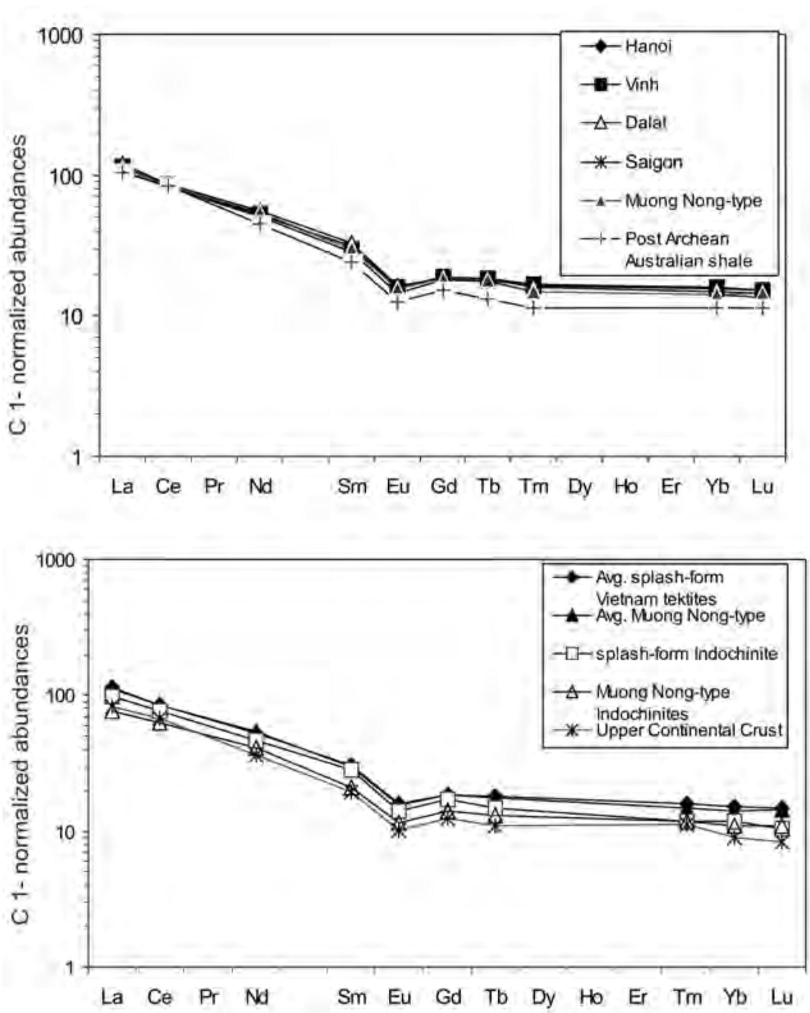

Fig. 9. Chondrite-normalized REE distribution in the Vietnam tektites (this study), as compared with: a) average splash-form Vietnam tektites (this study), splash-form indochinites (Koeberl 1992), Muong Nong-type indochinites (Koeberl 1992) and the upper crust (Taylor and McLennan 1985); b) average splash-form Muong Nong-type (this study), average splash-form Hanoi, Vinh, Dalat, and Saigon tektites (this study), and PAAS (Taylor and McLennan 1985). Chondrite normalization factors from Taylor and McLennan (1985).

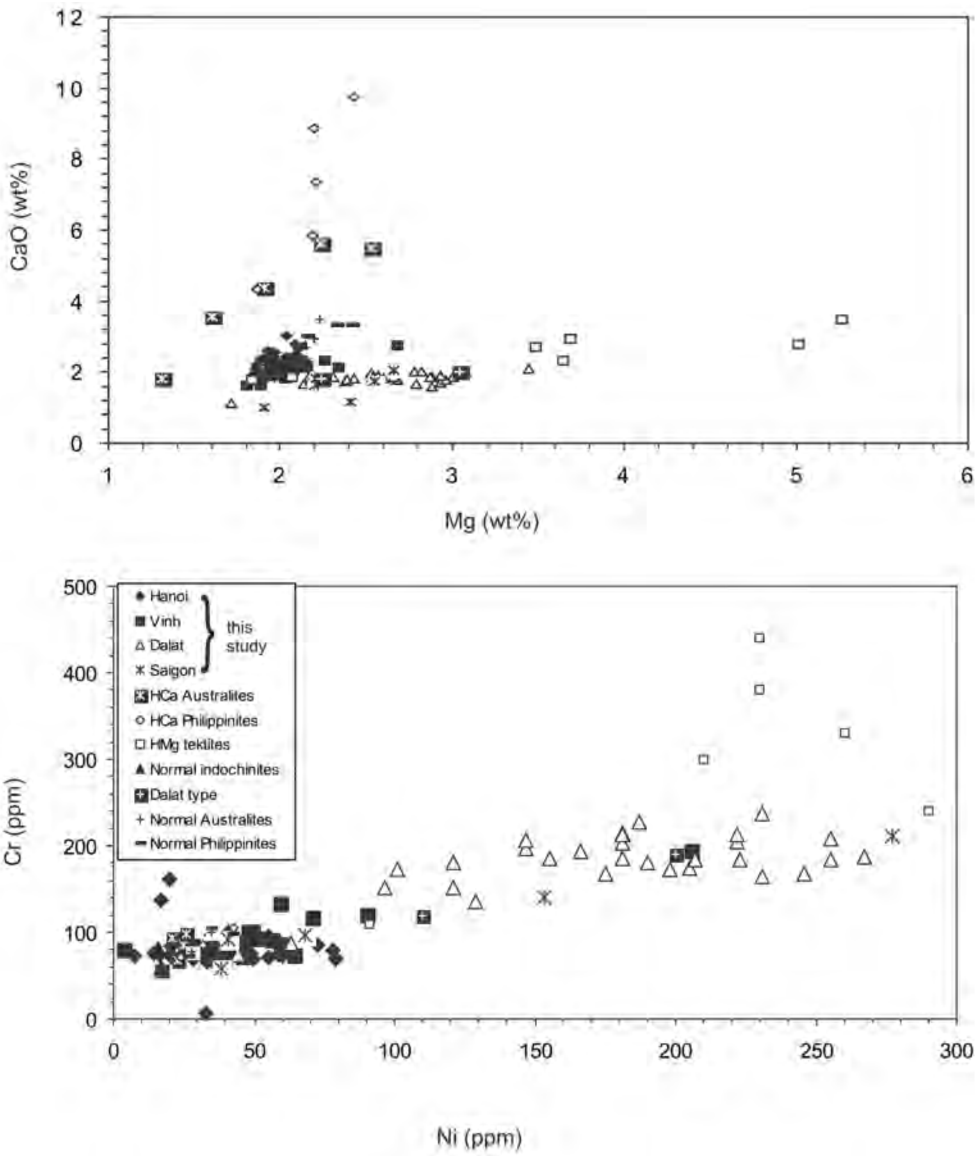

Fig. 10. Comparison of major elements and some selected trace elements of Vietnamese tektites (this study, the first four symbols of the legend) with data (all others) from Chapman and Scheiber (1969). a) Plots of MgO versus CaO; b) plots of Ni versus Cr.

tektites from 205 localities and, based on the major and some trace element contents, these authors have classified the Australasian tektites into 14 groups. Some of their more distinct groups included high-Mg tektites, high-Ca (philippinites and australites), high-Na/K australites, high-Cu, B indochinites, low-Ca high-Al philippinites, normal (philippinites, indochinites, australites), and Dalat type. Some of the compositions found in our study (Tables 1–3) are similar to those reported by Chapman and Scheiber (1969). The MgO-CaO plot shows an overlap between normal indochinites, australites, and philippinites, and Dalat-type tektites of this study, but the high Mg, high Ca (philippinites and australites) are distinctly higher in Mg (up to 8.5 wt%) and Ca (up to 10 wt%), compared to our samples with up to 3 wt% MgO and 3.5 wt% CaO. The Dalat and Saigon tektites of our study are similar to the Dalat-type samples of Chapman and Scheiber (1969), whereas their high-Mg group has higher contents of Cr (400 ppm) than the Dalat and Saigon tektites of this study (200 ppm). The range of variability in some trace elements such as Ba, Cr, and Zr given by Chapman and Scheiber (1969) is higher than in this study. The chemical composition of splash-form and Muong Nong-type tektites of this study is compared to that of other indochinites in Tables 2 and 3 and Figs. 5–8. The major elements of the splash-form tektites for Hanoi, Vinh, Dalat, and Saigon are similar in composition to the average splash-form indochinites. Except for higher CaO and Na_2O contents, the Muong Nong-type Vietnam tektites have similar major element compositions to those of the Muong Nong-type indochinites from Thailand (Koeberl 1992). Similarly, the average trace element abundance of this study and the average splash-form and Muong Nong-type indochinites are shown in Fig. 6. Except for higher Zn and U contents the chemical composition of splash-form Vietnam tektites resemble those of splash-form indochinites (Fig. 6a). Also, aside for higher Co, Cr, and W contents, the chemical composition of Muong Nong-type Vietnam tektites closely resembles the average composition of Muong Nong-type indochinites. As Muong Nong-type tektites represent melt from lower parts of the target stratigraphy compared to splash-form tektites (e.g., Koeberl 1992; Ma et al. 2004) and have not traveled very far from their source, such a limited range in composition argues against derivation of these glasses from many different local sources as advocated by Wasson (1991). Instead, a single source region is indicated. The comparison between average continental crust and average splash-form and Muong Nong- type tektites of this study is shown in Figs. 6 and 7, and it is evident that the correlation is not good for some elements. Also, a comparison of trace element data between tektites of this study and the average upper crust (Figs. 6c and 6d) shows that some trace element correlations do not correspond. This indicates that the tektites are a mixture of different source rocks. Chemical compositions alone will not allow to determine the exact source rocks of the tektites; this requires isotopic studies.

SUMMARY AND CONCLUSIONS

The main target of this study was to determine the range in chemical composition within tektites from a restricted sub-area of the Australasian strewn field and, in particular, to provide a large data base for trace element contents. We measured the major and trace element contents of 113 tektites from four different areas in Vietnam and draw the following conclusions:

1. Distinct chemical differences exist between the splash-form and Muong Nong-type tektites from Vietnam, in agreement with observations made before for similar samples from Thailand. For example, the splash-form tektites have lower silica contents (70–76 wt%) and higher average contents of MgO (1.7–3.1 wt %) and Al_2O_3 (11.1–14.7 wt%), compared to the ranges for the Muong Nong-type tektites of 74–81 wt% SiO_2, 1.4–2.4 wt% MgO, and 8.6–12.5 wt% Al_2O_3. Also, the Muong Nong-type tektites have higher contents of the volatile elements than the splash-form tektites.
2. The major and trace element of the splash-form and Muong Nong-type tektites of this study closely resembles the compositions of the average splash-form and Muong Nong-type indochinites from other locations in the strewn field. This uniform chemical composition clearly supports a similar and single source region for all those tektite types.
3. The tektites from the four regions in Vietnam can be separated into two chemically distinct groups. The Hanoi and Vinh tektites (north Vietnam) have similar abundances of major and trace elements; on the other hand, Dalat and Saigon tektites (south Vietnam) also have similar values. Tektites found in northern Vietnam have higher contents of Na_2O, K_2O, and CaO, whereas tektites in the south have higher contents of MgO, FeO, Cr, and Ni. In addition, the South Vietnam tektites (Dalat and Saigon) are distinguished from those of north Vietnam (Hanoi and Vinh) by having higher Mg/Ca and Ni/Co ratios of 1.5 and 7, respectively, compared to Hanoi and Vinh tektites, where these ratios are 0.9 and 2.6, respectively. The variation in some specific chemical characteristics among the tektite groups in this study most likely reflects variation in the parent material composition.
4. The trace element ratios Ba/Rb, Th/Sm, and Th/Sc, and the REE patterns of the tektites of Vietnam show sedimentary values and are similar to those of typical post Archean upper crustal rocks, although there are some differences to the average continental crust.

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