



Chemical variation within fragments of Australasian tektites

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Abstract—In previous studies, intersample variation between compositions of different tektites from one particular group were studied and, in a few cases, major element variations within single tektites. No data for intra-sample trace element variations existed. Thus, we sectioned a Muong Nong-type tektite fragment from Vietnam and a splash-form tektite fragment from the Philippines into eleven and six pieces, respectively, and analyzed the individual fragments for major and trace element contents.

The compositions obtained agree well with those found in previous studies, supporting argument that tektites have been derived from terrestrial upper crustal sediments. Chemical variations within the tektite fragments are present, but do not show any systematic trends, probably reflecting incomplete mixing of parent rocks. The intra-sample heterogeneity of the Muong Nong-type tektite is more pronounced than that in the philippinite. For the Muong Nong-type tektite, the intra-sample variation in the trace element contents is higher than that for the major elements, again reflecting target rock properties. For the philippinite the intra-sample variations mostly do not exceed the limits imposed by the precision of the analytical data, confirming that the splash form tektites are indeed well homogenized.

INTRODUCTION

Tektites are natural glasses found in areas on the Earth's surface called "tektite strewn fields." There are four known Cenozoic tektite strewn fields, with corresponding ages (references for the ages in parentheses): North American-34.9 Ma (Storzer and Wagner 1971), Central European-14.5 Ma (Schwarz and Lippolt 2002, Laurenzi et al. 2003), Ivory Coast-1.07 Ma (Koeberl et al. 1997), and Australasian-0.77 Ma (Izett and Obradovich 1992).

The origin of tektites was the subject of a scientific controversy for many years, but today most authors agree that tektites are the melt product of a hypervelocity impact on Earth into target rock, which is melted and then ejected during crater formation (Glass 1990; Wasson 1991; Blum et al. 1992; Koeberl 1994). Recently, numerical models for tektite formation (Artemieva 2001, 2002; Stöffler et al. 2002) indicated that tektites can form in an oblique impact (around 30–50° from the horizontal) of a high-velocity impactor (>15 km/s) into silica-rich target rocks. There is no need for special impact conditions to produce tektites (Artemieva 2002).

Three out of the four tektite strewn fields have been

related to their possible source craters: North American tektites with the Chesapeake Bay impact crater (e.g., Koeberl et al. 1996), Central European tektites (moldavites) with the Ries crater (e.g., Engelhardt et al. 1987), Ivory Coast tektites with the Bosumtwi crater (e.g., Koeberl et al. 1997; Koeberl et al. 1998). At the time being, the source crater for the Australasian tektite strewn field remains unidentified, even though this is the youngest and the largest strewn field, covering one tenth of the Earth's surface. Many proposals for possible source craters at various locations were made and later discounted, but there tends to be a consensus that the source crater (50–120 km in diameter—e.g., Glass 2003; Glass and Pizzuto 1994; Lee and Wei 2000) could be in or near Indochina (e.g., Stauffer 1978; Schnetzler 1992; Glass and Wu 1993; Hartung and Koeberl 1994; Lee and Wei 2000; Ma et al. 2004). This is strongly supported by evidence of large-scale forest fires and floods in Thailand occurring contemporarily with the tektite formation event (Bunopas et al. 1999; Howard et al. 2003; Haines et al. 2004), especially by a possible presence of shocked quartz in a layer immediately above the tektite-bearing horizon in Thailand (Howard et al. 2000).

Tektites in each strewn field are related to one another

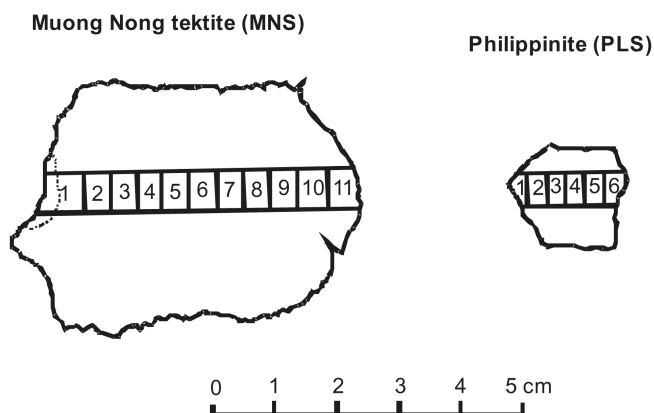


Fig. 1. Sketches of sub-samples cut from a Muong Nong-type tektite (MNS) and a philippinite (PLS).

with respect to their petrographical, physical, and chemical properties as well as their age. In general, tektites are chemically homogeneous. However, Koeberl (1992) noted that there were distinct chemical variations of major oxides along the traverse crossing dark and light layers of Muong Nong-type tektites, but no extensive data were available at that time for trace element contents between these layers and within single samples.

The purpose of the present study was to analyze the major and trace element contents (including the rare earth elements, REEs) within representative tektite samples to determine the extent of intra-sample variations in the contents of trace elements, and to compare inter-sample with intra-sample heterogeneity.

SAMPLES AND ANALYTICAL METHODS

A fragment of a Muong Nong tektite from Nghe An, Vietnam, and a fragment of a splash-form tektite from the Philippines were cleaned and cut into slabs using a micro-saw. Only clean interior parts of each tektite type, devoid of any visible inclusions or cracks, were used to avoid any contamination. From each slab we made a traverse of 5–6 mm in width, and then each traverse was cut into pieces of 4–5 mm (Muong Nong tektite) or 2–4 mm (philippinite) in width (Fig. 1). In the Muong Nong tektite, schlieren or minor layering was visible on a millimeter to sub-millimeter scale. These tektite pieces were analyzed without any further processing for their major and trace element contents.

First, the samples were analyzed for trace element contents by instrumental neutron activation analysis (INAA) at the Department of Geological Sciences, University of Vienna. Tektite pieces (ranging from 50–200 mg) and about 100 mg of standard reference materials were used for irradiation. The standard reference materials used in our analysis were the “ACE” granite (Centre de Recherche Petrographique et Geochemique, Nancy, France), mineralized gabbro-WMG-1 (Canadian Reference Materials Program,

CCRMP, Canada), and the Allende carbonaceous chondrite (Smithsonian Institution, USA). These samples and standards were irradiated for 8 hr at a neutron flux of $2.10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$ in the 250 kW Triga reactor of the Atomic Institute of the Austrian Universities, Vienna. Analytical techniques, instrumentation, data correction and information on accuracy and precision are described by Koeberl (1993).

After a cooling period of 8 months, the same samples were used for electron microprobe analysis to determine their major element contents. The samples were made into polished sections and then analyzed using a four-spectrometer Cameca SX-100 microprobe at the Department of Geological Sciences, University of Vienna. Natural and synthetic standards were used for calibration and the “PAP” correction of Pouchou and Pichoir (1991) (a variety of the ZAF correction procedure) was applied to the data. Samples were analyzed at 15 keV accelerating voltage, 20 nA sample current, and 5 μm beam diameter.

RESULTS AND DISCUSSION

Major Element Chemistry

Major element compositions of the eleven pieces of Muong Nong-type tektite and the six pieces of philippinite, together with average and standard deviation values, are given in Tables 1 and 2, including the average composition of Muong Nong-type tektites (Koeberl 1992) and of indochinites (Koeberl 1986), respectively. The results, for all main oxides, show a good agreement with the comparable figures of the known average compositions of Muong Nong-type tektites (Table 1) and indochinites (Table 2).

The Muong Nong-type pieces are higher in silica content, from 74–78 wt%, more variable (std. dev. = 0.89 wt%), and the philippinite pieces are lower in silica content, from 71.5–73 wt%, less variable (std. dev. = 0.54 wt%). In contrast, the philippinite pieces have much higher calcium oxide content (3.77 wt% on average, std. dev. = 0.05 wt%) when compared

Table 1. Major and trace element composition of pieces of a Muong Nong-type tektite fragment from Nghe An, Vietnam.

	MNS-1	MNS-2	MNS-3	MNS-4	MNS-5	MNS-6	MNS-7	MNS-8	MNS-9	MNS-10	MNS-11	Avg.	Std. dev.	Avg.-MN
SiO ₂	76.39	77.43	78.14	77.04	76.74	77.96	77.73	76.81	76.99	74.92	77.44	77.05	0.89	78.93
TiO ₂	0.77	0.71	0.65	0.75	0.69	0.67	0.66	0.70	0.75	0.77	0.68	0.71	0.04	0.63
Al ₂ O ₃	11.87	10.84	10.07	11.00	11.20	10.38	10.91	11.14	11.11	12.20	11.12	11.08	0.59	10.18
FeO	4.03	3.67	3.77	3.92	3.91	3.80	3.79	3.96	3.82	4.21	3.76	3.88	0.15	3.74
MnO	0.09	0.09	0.10	0.08	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.01	0.08
MgO	1.76	1.55	1.52	1.57	1.61	1.54	1.52	1.61	1.57	1.77	1.53	1.59	0.09	1.43
CaO	1.35	1.29	1.28	1.28	1.22	1.21	1.23	1.27	1.29	1.39	1.18	1.27	0.06	1.21
Na ₂ O	1.14	1.09	1.04	1.06	1.12	1.08	1.07	1.08	1.13	1.20	1.05	1.09	0.05	0.92
K ₂ O	2.53	2.47	2.35	2.43	2.45	2.43	2.50	2.46	2.42	2.53	2.46	2.46	0.05	2.42
P ₂ O ₅	0.12	0.10	0.07	0.08	0.10	0.10	0.11	0.11	0.10	0.11	0.10	0.10	0.01	
Total	100.05	99.22	98.99	99.20	99.15	99.24	99.62	99.24	99.27	99.17	99.42			99.54
Sc	8.9	9.3	8.9	9.7	9.0	9.4	9.2	9.8	10.0	10.2	9.2	9.4	0.43	7.70
Cr	65.4	68.7	67.9	71.9	65.7	73.2	67.9	70.6	73.7	75.2	68.7	69.9	3.27	60.6
Co	10.2	10.8	10.8	11.4	10.6	11.3	10.6	11.1	11.4	11.7	10.9	11.0	0.44	12.6
Ni	30	28	31	29	30	27	52	30	35	35	37	33	6.88	48.6
Zn	62	71	75	70	67	77	76	82	82	80	69	74	6.58	66.7
As	4.43	4.19	4.21	5.11	4.02	4.73	5.06	4.77	5.04	4.52	3.12	4.47	0.58	4.75
Se	0.1	0.1	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.3	0.3	0.11	0.2
Br	1.0	1.4	1.2	1.6	1.0	1.1	1.2	1.4	1.6	0.6	0.7	1.2	0.32	4.1
Rb	99	106	105	115	104	120	121	111	117	116	107	111	7.33	109.8
Zr	276	329	306	333	284	341	294	310	323	342	334	316	23.2	280
Sb	0.67	0.71	0.72	0.80	0.70	1.08	0.76	0.76	0.72	0.63	0.61	0.74	0.13	0.82
Cs	5.66	6.07	5.82	6.48	5.93	6.72	6.65	6.39	6.68	6.73	5.78	6.26	0.42	5.09
Ba	186	205	214	222	202	232	231	224	218	220	204	214	13.9	341
La	34.6	36.5	36.8	38.6	36.1	37.4	36.5	37.7	38.6	38.6	36.7	37.1	1.24	28.2
Ce	65.7	70.6	70.5	74.5	68.3	71.3	70.1	72.2	73.8	76.4	70.2	71.2	2.96	60.7
Nd	32.6	34.9	30.4	32.4	30.3	29.5	31.5	30.0	31.6	32.7	30.0	31.4	1.62	29.1
Sm	5.33	5.87	5.86	6.24	5.73	6.20	6.18	5.95	6.01	5.96	5.66	5.91	0.27	4.9
Eu	1.02	1.08	1.04	1.17	1.07	1.13	1.02	1.16	1.16	1.17	1.11	1.10	0.06	1.01
Gd	5.17	5.76	5.68	6.19	5.51	6.32	6.12	5.89	6.06	6.03	5.60	5.85	0.34	4.3
Tb	0.84	0.77	0.78	0.80	0.77	0.84	0.85	0.78	0.81	0.82	0.74	0.80	0.04	0.75
Tm	0.45	0.42	0.42	0.45	0.42	0.45	0.45	0.43	0.44	0.45	0.41	0.44	0.02	0.42
Yb	2.87	2.89	2.96	3.10	2.89	3.13	2.97	2.96	2.90	3.03	2.80	2.95	0.10	2.71
Lu	0.40	0.44	0.46	0.47	0.44	0.48	0.43	0.45	0.42	0.45	0.42	0.44	0.02	0.42
Hf	7.05	7.58	8.09	8.28	7.41	7.94	7.55	7.56	7.92	7.93	7.65	7.72	0.35	8.13
Ta	0.97	1.03	1.21	1.29	1.03	1.23	1.33	1.04	1.30	1.26	1.07	1.16	0.13	1.17
W	3.6	2.4	4.1	1.7	2.0	2.7	1.4	3.4	3.0	<0.8	1.6	2.6	0.92	1.0
Ir (ppb)	<0.8	<0.9	<0.9	<1	<0.8	<1	<0.9	<0.9	<1	<1.1	<1	<1.1		<1.5
Au (ppb)	0.8	0.8	0.5	0.8	0.9	0.7	<0.5	<0.5	0.5	<0.5	0.3	0.7	0.21	2.1
Th	12.3	13.5	13.5	14.8	13.0	14.6	14.9	14.1	14.3	14.6	13.0	13.9	0.86	11.1
U	2.00	2.35	2.35	2.53	2.30	3.01	2.88	2.44	2.47	2.40	2.23	2.45	0.28	2.48
K/U	7700	8170	7787	8221	8217	6379	6181	7746	7692	7958	8700	7705	767	8350
Th/U	6.15	5.74	5.74	5.85	5.65	4.85	5.17	5.78	5.79	6.08	5.83	5.70	0.38	4.54
La/Th	2.81	2.70	2.73	2.61	2.78	2.56	2.45	2.67	2.70	2.64	2.82	2.68	0.11	2.54
Zr/Hf	39.1	43.4	37.8	40.2	38.3	42.9	38.9	41.0	40.8	43.1	43.7	40.9	2.16	34.9
Hf/Ta	7.27	7.36	6.69	6.42	7.19	6.46	5.68	7.27	6.09	6.29	7.15	6.71	0.57	6.95
La _N /Yb _N	8.1	8.5	8.4	8.4	8.4	8.1	8.3	8.6	9.0	8.6	8.9	8.5	0.28	7.07
Eu/Eu*	0.59	0.57	0.55	0.58	0.58	0.55	0.51	0.60	0.59	0.60	0.60	0.57	0.03	0.68

N = chondrite-normalized (Taylor and McLennan 1985); major elements in wt%, trace elements in ppm, except when noted; all Fe given as FeO; average of Muong Nong tektites (Avg.-MN) from Koeberl (1992).

Table 2. Major and trace element composition of pieces of a splash-form tektite fragment from the Philippines.

	PLS-1	PLS-2	PLS-3	PLS-4	PLS-5	PLS-6	Avg.	Std. dev.	Avg.-indochinite
SiO ₂	72.67	72.92	71.63	72.81	73.21	72.50	72.62	0.54	72.70
TiO ₂	0.70	0.69	0.67	0.74	0.72	0.73	0.71	0.03	0.78
Al ₂ O ₃	11.69	11.94	11.75	11.87	11.92	12.04	11.87	0.13	13.37
FeO	4.19	4.17	3.89	4.23	4.20	4.30	4.16	0.14	4.85
MnO	0.12	0.11	0.09	0.09	0.11	0.10	0.10	0.01	0.08
MgO	2.08	2.10	2.07	2.13	2.14	2.28	2.13	0.08	2.14
CaO	3.81	3.79	3.68	3.79	3.80	3.78	3.77	0.05	1.98
Na ₂ O	1.22	1.19	1.15	1.15	1.16	1.09	1.16	0.04	1.05
K ₂ O	2.40	2.44	2.37	2.42	2.42	2.32	2.39	0.04	2.62
P ₂ O ₅	0.10	0.12	0.09	0.10	0.10	0.11	0.10	0.01	
Total	98.99	99.46	97.40	99.33	99.77	99.25			99.57
Sc	10.9	11.2	11.0	11.2	10.9	11.0	11.0	0.14	10.5
Cr	75.5	79.6	76.6	80.7	78.5	76.4	77.9	2.04	63.0
Co	12.4	12.8	12.7	13.1	12.8	12.7	12.8	0.23	11
Ni	31	45	34	25	39	26	33	7.73	19
Zn	27	19	27	25	27	26	25	3.09	5.7
As	0.94	1.61	1.65	1.14	1.92	1.07	1.39	0.39	0.9
Se	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.02	0.1
Br	0.6	0.5	1.2	0.8	2.0		1.0	0.62	0.23
Rb	106	116	118	115	111	104	112	5.68	130
Zr	278	257	298	289	302	253	280	20.7	252
Sb	0.33	0.63	0.50	0.54	0.44	0.47	0.49	0.10	0.5
Cs	6.25	6.68	6.78	6.72	6.37	6.18	6.50	0.26	6.5
Ba	221	273	249	264	225	217	242	23.9	360
La	38.9	40.9	39.1	41.5	38.7	41.0	40.0	1.25	36.5
Ce	75.9	78.6	76.7	79.4	75.9	73.7	76.7	2.06	73.1
Nd	34.1	36.1	34.9	34.7	34.4	34.9	34.9	0.69	33.2
Sm	6.13	6.94	6.76	7.08	6.36	6.61	6.65	0.36	6.6
Eu	1.25	1.31	1.28	1.32	1.30	1.29	1.29	0.02	1.22
Gd	6.09	6.94	6.88	7.09	6.38	6.64	6.67	0.38	5.24
Tb	0.84	0.91	0.89	0.97	0.86	0.89	0.89	0.05	0.85
Tm	0.46	0.50	0.47	0.51	0.47	0.50	0.49	0.02	—
Yb	3.00	3.40	3.20	3.40	3.07	3.37	3.24	0.18	2.9
Lu	0.43	0.51	0.48	0.50	0.44	0.50	0.48	0.03	—
Hf	6.72	7.00	7.01	7.04	6.75	6.76	6.88	0.15	6.95
Ta	1.34	1.27	1.22	1.15	1.24	1.24	1.24	0.06	1.60
W	<0.7	7.8	1.8	4.3	<2.3	2.0	3.9	2.81	0.3
Ir (ppb)	<1.5	<1	<1.7	<1.6	<1.1	<1.5			0.02
Au (ppb)	0.8	0.5	2.3	1.5	1.6	2.3	1.5	0.75	2
Th	14.1	15.2	16.1	15.5	14.6	14.0	14.9	0.83	14.0
U	1.91	2.35	2.65	2.50	2.20	2.17	2.30	0.26	2.07
K/U	9738	9064	8453	8200	10227	8664	9058	786	10530
Th/U	7.38	6.47	6.08	6.20	6.64	6.45	6.54	0.46	6.76
La/Th	2.76	2.69	2.43	2.68	2.65	2.93	2.69	0.16	2.61
Zr/Hf	41.4	36.7	42.5	41.1	44.7	37.4	40.6	3.06	36.3
Hf/Ta	5.01	5.51	5.75	6.12	5.44	5.45	5.55	0.37	4.34
La _N /Yb _N	8.8	8.1	8.3	8.2	8.5	8.2	8.3	0.24	8.5
Eu/Eu*	0.63	0.58	0.57	0.57	0.62	0.60	0.59	0.03	0.63

N = chondrite-normalized (Taylor and McLennan 1985); major elements in wt%, trace elements in ppm, except when noted; all Fe given as FeO; average of indochinites (Avg.-indochinites) from Koeberl (1986).

with that of Muong Nong-type pieces (1.27 wt% on average, std. dev. = 0.06 wt%). The other major elements behave in a similar way.

In the Harker diagrams (Fig. 2), Muong Nong-type tektites show a clear inverse relation between the contents of

SiO₂ and other major oxides: Al₂O₃, MgO, FeO, Na₂O, and K₂O (not clear for CaO)—this is in agreement with Koeberl (1990) for different tektite fragments in general; on the other hand, no such clear relation exists for the data of the philippinite pieces in this study. Our philippinite sample can

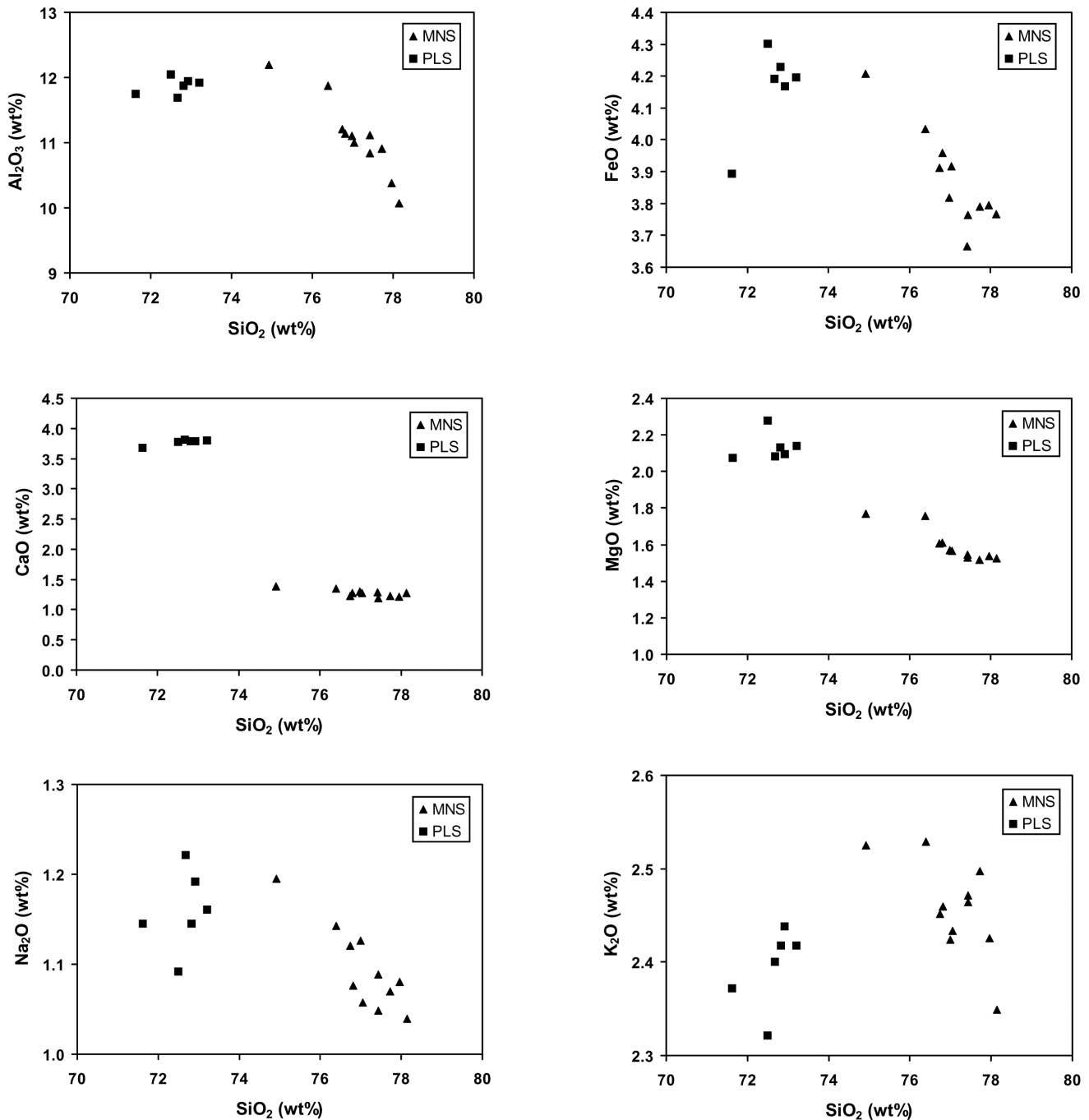


Fig. 2. Harker diagrams of major element versus silica content for splash-form (PLS) and Muong Nong-type (MNS) tektites in this study.

be assigned to the normal group of philippinite according to the classification of Chapman and Scheiber (1969).

The major oxide contents show variations along the traverse (Fig. 3), but they vary arbitrarily. No trend of this variation is obvious, neither along the traverse nor from the inside outwards. The correlation coefficients of major-element data between two close pieces of Muong Nong-type tektite (e.g., MNS1 with MNS2-1/2; MNS2 with MNS3-2/3; etc.) are very high (~ 1); and two-tailed, paired t-tests between

them return high probabilities (Table 4). However, the values of correlation coefficients and t-test probabilities also vary. This likely is the result of the intra-sample heterogeneity. The data for the pieces of the philippinite are different: the t-tests between two close pieces return variable, but low probabilities. This is due to the fact that there is no clear relationship between major elements as above mentioned and, thus, no measurable intra-sample heterogeneity. Besides, the standard deviation and the relative standard deviation (the

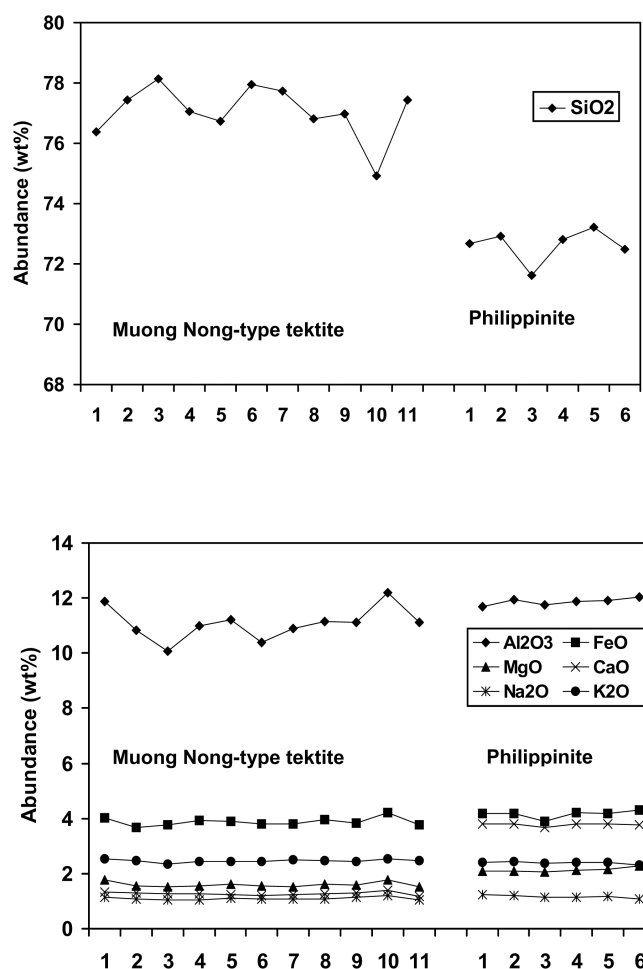


Fig. 3. Chemical variations of selected major elements along traverses within the Muong Nong-type tektite and the philippinite: a) Silica content; b) Al, Fe, Mg, Ca, K, and Na-oxide contents. Numbers on the x-axis are sample numbers.

ratio between standard deviation over the average) in the pieces of Muong Nong-type tektite are always larger than that of splash-form philippinite. Thus, the chemical variations within a fragment of Muong Nong-type tektite are larger than those in the splash-form philippinite (see Tables 1 and 2).

Trace Element Chemistry

Trace elements can be used to distinguish tektites from different strewn fields, or even sub-fields, as well as to infer the source rock (Koeberl 1990, 1992). Moreover, many authors have used the ratios of trace elements, including the REEs, to distinguish the provenance of tektites (Koeberl 1990, 1992; Lee et al. 2004; among others). The data of trace elements and REEs of this study are comparable to those of the literature mentioned above (Tables 1 and 2).

It is well known that Muong Nong-type tektites have higher contents of volatile elements (Chapman and Scheiber 1969; Koeberl 1986, 1992) compared to splash-form tektites. The enrichment of volatile elements is also present in this study, for example: Zn (by a factor of 3), As (3.2), Br (1.2),

Sb (1.5). The enrichment of volatile elements in Muong Nong-type tektites could both be due to incorporation of slightly different parent rocks, and/or imply their lower-temperature formation when compared to splash-form tektites (Koeberl 1992).

Ratios of La/Th are less than 2.8 (Table 1 and 2), confirming a post-Archean sediment source (Taylor and McLennan 1985). Ratios of Th/U are high (~6), also in favor of sedimentary parent rocks (McLennan and Taylor 1980). Ratios of Th/U are higher in the philippinite pieces (6.54) than in the Muong Nong-type pieces (5.70), which is in agreement with observations by Wasson (1991).

Diagrams for the variation of the contents of selected trace elements (Co, Sc, Cs, Hf, Th and Cr, Rb, Zr, Ba, La) along traverses (Fig. 4) show that, as for the major elements, the trace element contents vary arbitrarily, and no trend for these variations can be noted, neither along the traverse nor from the inside outwards. However, the standard deviations of trace elements for pieces of philippinite are smaller or approximately equal to the precision of the analysis (see Table 3), therefore no intra-sample variation in the trace

Table 3. Typical precision of INAA (in relative %) at the lab at the University of Vienna, Department of Geological Sciences. Data obtained by at least 10 replicate analyses of international geological standard reference materials.

1	Na (wt%)	2
2	K (wt%)	5
3	Sc	2
4	Cr	3
5	Fe (wt%)	4
6	Co	2
7	Ni	15
8	Zn	3
9	As	10
10	Se	10
11	Br	10
12	Rb	2
13	Sr	5
14	Zr	10
15	Sn	2
16	Sb	5
17	Cs	2
18	Ba	10
19	La	2
20	Ce	3
21	Nd	5
22	Sm	2
23	Eu	2
24	Gd	5
25	Tb	2
26	Tm	5
27	Yb	2
28	Lu	2
29	Hf	2
30	Ta	2
31	W	10
32	Ir (ppb)	Below detection limit 1 ppb
33	Au (ppb)	15
34	Th	2
35	U	10

(All data in ppm, except as listed)

element contents of the philippinite can be discerned. The standard deviations of selected trace elements for pieces of Muong Nong-type tektite are larger than the precision of the data (1.5 to 4 times, except for Ba and Zr). Thus we find, as for the major elements, that the variations of trace elements in pieces of Muong Nong-type tektite are larger than that of philippinite (splash-form).

The REEs are among the most important trace elements used in petrogenesis studies of the parent rocks because they are refractory, and their patterns are not affected by melting or metamorphic processes. Besides, impact processes do not alter the REE patterns significantly, with the possible exception of affecting the most volatile REEs if fractional vaporization took place (Koeberl 1990). Previous studies (Taylor and McLennan 1979; Koeberl 1990, 1992; Wasson 1991) confirmed that the REE patterns of tektites are similar

to those of upper crustal sedimentary rocks. These observations are expressed in this study in that the ratio of La_N/Yb_N is close to 10 (8.5 in the Muong Nong-type tektite, and 8.3 in the philippinite), and that the Eu anomaly is very pronounced (0.57 in the Muong Nong-type tektite, and 0.59 in the philippinite).

The REE patterns for Muong Nong-type tektites and philippinites in this study (Fig. 5) are similar to those of comparative patterns—of average Muong Nong-type tektites (a) and of average indochinites (b)—indicating that they can be derived from similar parent rocks.

Inter-Sample versus Intra-Sample Heterogeneity

Compared to Koeberl (1992), in which 19 Muong Nong-type tektites from one location—Ubon Ratchatani in East Thailand—were analyzed, it is clear that the major and trace element contents from those 19 samples are similar to those from the pieces of the Muong Nong-type tektite in our study, but they vary in a wider range. This is true for all major and trace elements: for example, average of SiO_2 is 77.05 ± 0.89 wt% (within sample, this study), and 78.93 ± 1.50 wt% (inter-sample from one site, Koeberl 1992), Th (13.9 ± 0.86 ppm, and 11.1 ± 1.48 ppm, respectively), etc. This implies that the inter-sample heterogeneity is larger than the intra-sample heterogeneity in the case of the Muong Nong-type tektites.

In the case of the philippinite, a major-element variation is apparent (albeit at much smaller range and standard deviation compared to the Muong Nong-type tektite), but the trace-element variation is smaller than, or approximately equal to, the analytical precision. This is in agreement with Schnetzler (1992), who noted that the major-element heterogeneity of Muong Nong-type tektites, both within a site and within a sample, can be high relative to the splash-form tektites. It is probable that parent materials of philippinites (splash-form) were better mixed during its higher-temperature formation (compared to that of Muong Nong-type tektite).

Schnetzler (1992) concluded that “the variability of composition within a single sample of Muong Nong-type tektite is not predictable” and no consistency in the composition of light or dark bands. He found that in seven of eleven cases the dark bands have SiO_2 concentrations between 80 and 82 wt%, but in the other four cases the concentrations fall as low as 71 wt%, while most light bands have compositions between 76 and 77 wt%. This contradicts the data of Koeberl (1992), who found that there is a clear chemical variation between dark (high-silica zone) and light (low-silica zone) layers of a Muong Nong-type tektite, and that a positive correlation between Al_2O_3 , TiO_2 , FeO , MgO , CaO , and K_2O , but a negative correlation exists between the contents of these elements with the SiO_2 content. This is consistent with data from the present study, i.e., that there is

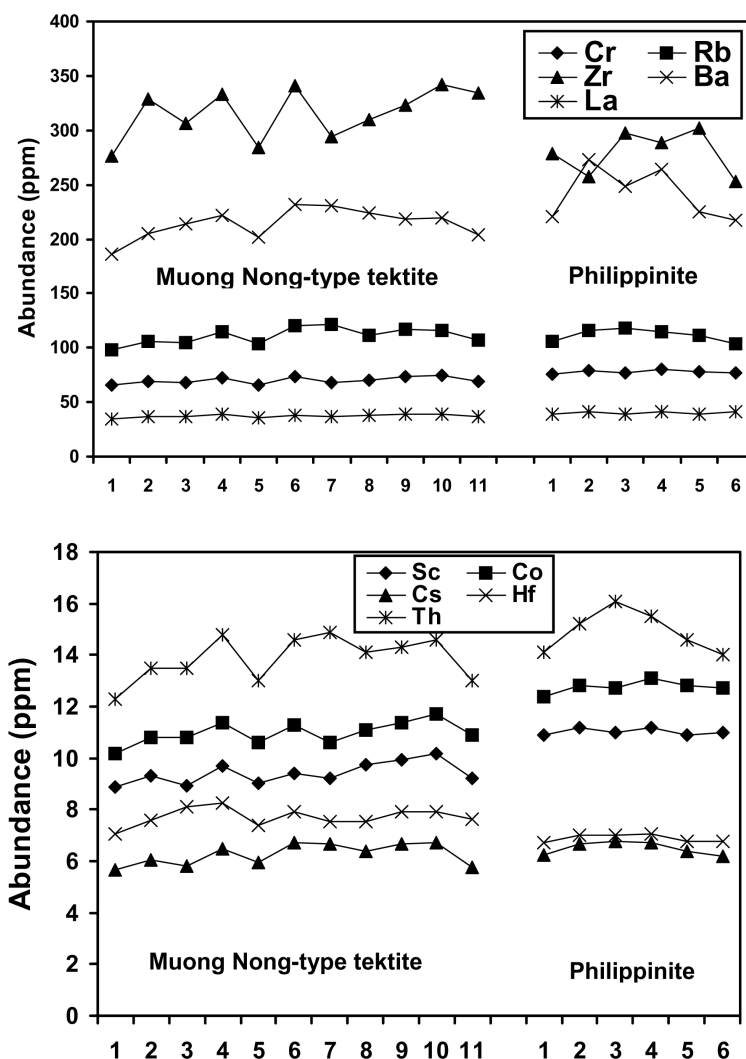


Fig. 4. Chemical variations of selected trace elements along the traverses of a Muong Nong-type tektite and a philippinite. Numbers on the x-axis are sample numbers: a) Elements with abundance ranges of about 30–350 ppm; b) Elements with lower abundances.

an inverse correlation between the contents of SiO_2 and those of the other major elements (Al_2O_3 , TiO_2 , FeO , MgO , Na_2O , and K_2O , except CaO). This is more likely the result of incomplete mixing of different parent materials of similar provenance, because, as explained by Koeberl (1992), simple dilution of the tektite material with silica (e.g., quartz sand) cannot account for the chemical differences between the layers due to the fact that the other major elements are enriched or depleted to various degrees.

CONCLUSIONS

Several conclusions can be drawn based on geochemical data along a traverse in a Muong Nong-type tektite (eleven pieces in a row) and in a philippinite (six pieces). The contents of the major and trace elements from this study are comparable with corresponding data from previous studies. In the case of the Muong Nong-type tektite, the usual

characteristics, such as the inverse relation between SiO_2 and all other major elements (except CaO), wide variation in major element contents, and enrichment of volatile elements compared to splash-form tektites, were found. The trace element ratios (such as La/Th , Th/U), and the patterns of the REEs, of both samples are typical for post-Archean sedimentary, upper crustal rocks.

Chemical variations within each of the tektite fragments exist, but do not show any systematic trends for both major and trace elements. These variations are distinct and statistically significant for both major and trace elements in a Muong Nong-type tektite; on the other hand, in the case of the splash-form philippinite, the intra-sample is noticeable (albeit of limited extent) only for the major elements, but not noticeable and not statistically significant for the trace element contents. The intra-sample chemical variations in the Muong Nong-type tektite fragment are larger than those in the splash-form tektite, as standard deviations for both major and

Table 4. Results of correlations and t-tests between two neighboring pieces of a fragment of a Muong Nong-type tektite and in a philippinite.

Major elements in a Muong Nong-type tektite											
MNS	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/1
Correlation	0.99988	0.99994	0.99991	0.99999	0.99992	0.99997	0.99999	1.00000	0.99983	0.99982	0.99994
t-test	0.61	0.84	0.89	0.90	0.95	0.55	0.72	0.89	0.97	0.94	0.66
Selected trace elements in a Muong Nong-type tektite											
	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/1
Correlation	0.99875	0.99801	0.99961	0.99928	0.99960	0.99614	0.99813	0.99918	0.99954	0.99954	0.99827
t-test	0.13	0.56	0.07	0.09	0.08	0.27	0.90	0.27	0.26	0.02	0.14
Major elements in a philippinite											
	1/2	2/3	3/4	4/5	5/6	6/1					
Correlation	0.99999	1.00000	0.99999	1.00000	0.99999	0.99998					
t-test	0.21	0.13	0.13	0.30	0.52	0.61					
Selected trace elements in a philippinite											
	1/2	2/3	3/4	4/5	5/6	6/1					
Correlation	0.98474	0.98940	0.99842	0.99271	0.99622	0.99875					
t-test	0.41	0.77	0.63	0.40	0.21	0.30					

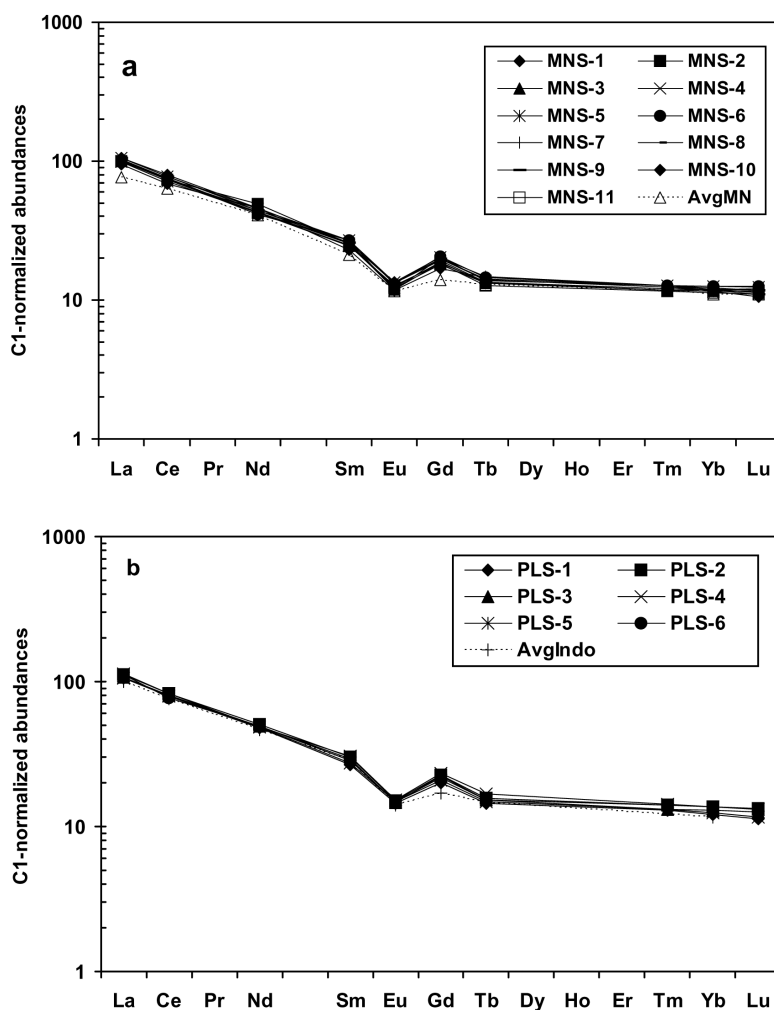


Fig. 5. Chondrite-normalized REE distribution (normalization factors from Taylor and McLennan [1985]) of a) a Muong Nong-type tektite slices compared with the average composition of Muong Nong-type tektites ("AvgMN") from Koeberl (1992) and b) of the philippinite slices compared with average indochinites given by Koeberl (1986) ("AvgIndo" = Average indochinites).

trace elements in Muong Nong-type tektite are always larger than in the splash-form sample. Trace element variations are generally larger in the Muong Nong-type tektite than for major elements. Thus we were able to confirm that intra-sample variations in the trace element contents of a Muong Nong-type tektites exist as well (as was previously indicated by major element variations), and that these variations are statistically significant (as opposed to those in a splash-form tektite), and exceed the variations observed in major element contents. This could be due to the fact that Muong Nong-type tektites formed at lower temperature and pressure when compared with splash-form tektites (Koeberl 1992). It should be noted that the Muong Nong-type tektites have simply lost less of their original complement of volatile elements than the splash-form tektites (such as the philippinite).

The chemical variations within a sample (this study) are always smaller than that between different specimens from a specific site (compared to the work of Koeberl 1992), both for major and trace elements. There are two main conclusions from the present study: first, the trace elements contents do show variations that parallel those found before for the major element contents (which may not be all that surprising), but also that the trace element variations are in most cases larger than those of the major elements, which would lead to the second main conclusion: given the fact that normal crustal rocks vary more in trace element composition than in major element composition, this would mean that it is likely that the short fusion time during shock melting is not enough to mix completely the parent materials, therefore, this variation may reflect only the chemical variations between the different types parent rocks involved.

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