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Geochemistry of Tektites from Hainan Island and Northeast Thailand

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***Abstract*—**Twenty seven tektites from the Wenchang area, Hainan province (south China) and five tektites from the Khon Kaen area (northeast Thailand) were analyzed for major and trace element contents and Rb-Sr isotopic compositions. All the samples studied are splash-form tektites. Tektites of this study are characterized by high SiO_2 contents ranging from 71.95 to 74.07 wt% which is consistent with previously published analyses of Australasian tektites. The trace element ratios Ba/Rb (avg. 3.89), Th/Sm (avg. 2.40), Sm/Sc (avg. 0.45), Th/Sc (avg. 0.99) and the rare earth elements (REE) contents of tektites of this study are similar to the average upper continental crust. Based on the chemical composition, it is suggested that tektites in this study are derived from similar parental material and are similar to the post-Archean upper crustal rocks. The major and trace element abundances of tektites analyzed indicate that the parental material of tektites may be a terrestrial sedimentary deposit. The tektites from the Wenchang area, Hainan Island have high positive $\varepsilon^{Sr}(0)$ values-ranging from 184.5~196.5 which indicate that the parental material for these tektites have similar Sr isotopic compositions to old terrestrial sedimentary rocks and they were not dominantly derived from recent young sediments (such as soil or loess). Based on Rb-Sr isotopic data, it has been suggested by Blum (1992) [1]that the depositional age of sedimentary target materials is close to 170Ma (Jurassic). According to the model suggested by Ho and Chen (1996)[2], mixing calculations for various amounts and combinations of target rocks have been carried out. We consider that the best fit for tektites from the Wenchang area is a mixture of 47% shale, 23% sandstone, 25% greywacke and 5% quartzite, and the other tektites from Khon Kaen area is a mixture of 46% shale, 2% sandstone, 20% greywacke and 32% quartzite.

***Keywords*—**Geochemistry, Hainan Island, Northeast Thailand, Tektites.

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I. INTRODUCTION

TEKTITES are natural glasses found in limited regions of the Earth's surface called strewn fields [3]-[4]. The tektites from a specific region are usually given a distinctive name derived from the geography. Geochemical indications have verified that tektites are glass objects produced by the melting of crustal material during large impact cratering events [3]-[5]. Previous studies of cosmogenic radioisotopes have pointed out tektites derived from the top of the impacted target lithologies [6]-[9]. Tektites are known from four distinct strewn fields which common names are: (1) Australasian, (2) Ivory Coast, (3) Central European, and (4) North American. The Australasian strewn field covers nearly 10% of the Earth's surface[10]. The Australasian strewn field extended from a small part of South China (including Hainan province) through Lao, Vietnam, Cambodia, Thailand, Malaysia, the Philippines, Brunei and North Borneo, Indonesia, to Australia. The radiometric age of Australasian tektites is well established at close to 0.8 Ma using ^{40}Ar-^{39}Ar dating methods [11]-[14]. The source craters for the North American, Ivory Coast, and Central European strewn fields have been identified: the Chesapeak Bay crater, the Bosumtwi crater and the Ries Crater [3],[4],[15]. The source crater for the Australasian strewn field has not yet been found. The source crater of Australasian tektites may be located in Southeast Asia [6]. The ^{10}Be concentrations of tektites increase solely with increasing distance from Indochina: Southeast Asian tektites have the lowest values and australites the highest (Ma et al., 2004). The systematic variation of ^{10}Be concentrations proposed by Ma et al. (2004)[6] may indicate a single impact event. Based on the thickness of the Australasian microtektite layer proposed by Glass and Pizzuto (1994)[16], the diameter of the source crater is estimated to be between 32 and 114 km.

The tektites found on land can be subdivided into three groups: (1) aerodynamically shaped tektites; (2) normal or splash-form tektites, and (3) Muong Nong-type tektites (layered tektites) [17]. The first two groups are only slight different in their appearance and physical characteristics. The splash-forms include spheres, droplets, dumbbells, and teardrops tektites, and they are generally one to a few centimeters in size. The aerodynamically shaped tektites are splash forms that may have undergone a second period of melting resulting in the formation of a flange. Muong Nong-type tektites named after a locality in Laos are usually considerably larger than splash-form tektites and are blocky appearance. They are larger in size, less homogeneous, having higher abundances of volatile elements and water. Muong Nong-type tektites contain more bubbles and some relict minerals (e.g., coesite, zircon, corundum, rutile, chromite, etc.) which imply a sedimentary rock as the source rock[17]. Koeberl et al. (1984)[18] pointed out the Muong Nong-type tektites generally have a lower FeO/Fe_2O_3 ratio than the splash-forms, indicating a lower formation temperature. Some authors[19]-[21] believed that Muong Nong-type tektites have been formed under somewhat different conditions than other tektites, and were likely formed close to the center of the impact site. The aerodynamically shaped and Muong Nong-type tektites are predominantly found in the Australasian fields.

The tektites of this study were collected by K. S. Ho (Fig.1). The aim of this paper is to analyze the major and trace elements (including rare-earth elements, REE) and the Rb-Sr isotopic ratios and to date the tektites by Ar-Ar method in order to provide important information regarding the origin of the tektites, their parent material and the possible source crater.

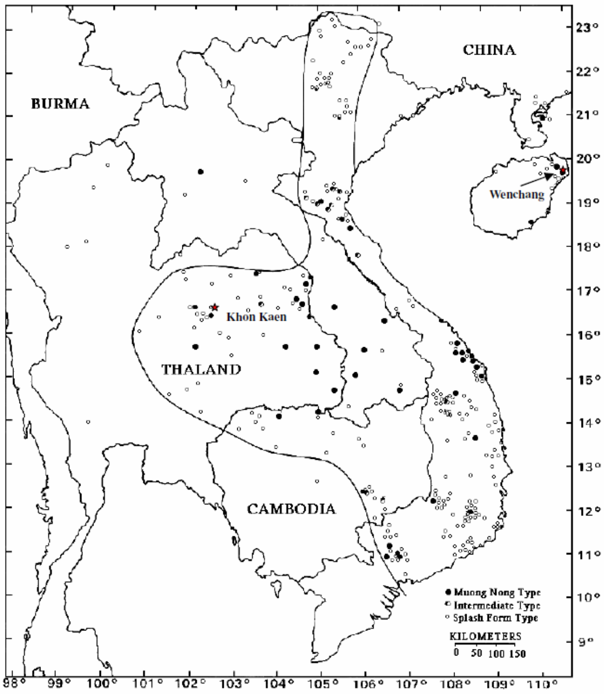

Fig. 1 Localities of tektites in the present study (stars).

II. ANALYTICAL METHODS

Thirty two samples were cleaned ultrasonically and crushed into chips by a hammer wrapped with with plastic sheets. Several larger glass chips were selected and ground to powder in an agate mortar. The chemical analyses of tektites from the Wenchang and Khon Kaen areas have been carried out by the colorimetry(Si, Al, Ti, P), atomic absorption(Fe, Mg, Ca, Na, K, Mn) and inductively coupled plasma mass spectrometry(Ba, Co, Cr, Cs, Cu, Hf, Ga, Li, Nb, Ni, Rb, Sc, Sr, Ta, Th, U, V, W, Y, Zr, Zn and REEs) at National Taiwan and Tsing-Hua Universities. The calibration curves were constructed using U.S.G.S. standard rocks Agv-1, BCR-1, W-2, G2 and NBS stand rock obsidian. The precision is estimated to be around ±2%for colorimetric and atomic absorption methods(for trace elements around ±5%) and better than 5% for all ICP-MS analyses. Three tektites were selected for Rb-Sr isotopic composition analyzed. Each tektite was cleaned with acetone and distilled water. Each sample was then individually dissolved in a HF-HNO_3 mixture; and the tracers addition(^{84}Sr and ^{87}Rb) and chemical separations were followed. The isotopic compositions of the Rb and Sr were measured using a Finnigan MAT 261 mass spectrometer at AMDEL, Thebarton, Australia.

III. RESULTS AND DISCUSSIONS

Tektites in the present study are black and oval, dum-bell or

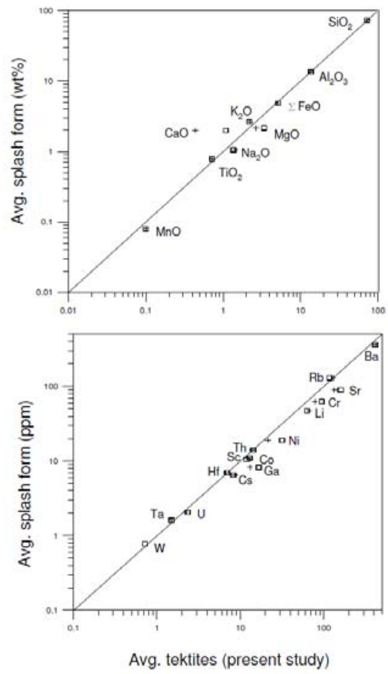

Fig. 2 Comparison of Major and trace element compositions of tektites in the present study with average splash-form indochinites [17].

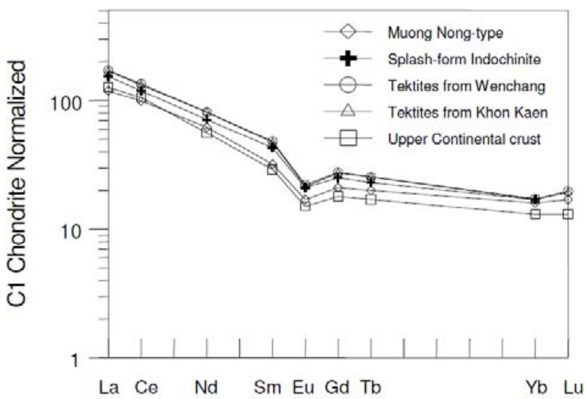

Fig 3 Chondrite-normalized REE diagram of tektites in the present study. Data for Muong Nong-type and splash-form indochinites from Koeberl (1992)[17]; upper crust from Taylor and McLennan (1985)[23].

disc shaped. Tektites from the Khon Kaen area are larger (avg. 14.78 g) than those from the Wenchang area (avg. 5.62 g). Refractive index and density of tektites analyzed are closely similar. These tektites have a pitted or grooved surface and preserve the schlieren structures on some surface, indicating high speed entry into the atomosphere and rapid solidification in flight. The major elements of tektites in the present study, except CaO, are generally uniform. Tektites from the Wenchang and Khon Kaen areas are characterized by high SiO_2 content ranging from 71.57 to 73.40 wt% (avg. 72.55 wt%) and 72.18 to 74.07 wt% (avg. 73.41%), respectively, which is consistent with previously published analyses of Australasian tektites (Table I). Based on the high content of SiO_2 , the lunar volcanic origin for tektites may be excluded. Tektites from the Wenchang and Khon Kaen areas have similar chemical compositions, except for CaO content. The lower content of CaO in tektites from Khon Kaen area may be caused by lower limestone involved during the production of tektites or different amounts and combinations of target material. Except for higher MgO, Na_2O, Ni, Ga, Zn, Ni and lower CaO contents, the chemical composition of tektites of this study closely resemble that of splash-form indochinites (Table I, Fig.2). The REE patterns for tektites from the Wenchang and Khon Kaen areas are similar to those of previously analyzed splash-form indochinites, indicating that they are all derived from similar parent rocks of upper continental crust affinity (Fig.3). According to major and trace elements, it is suggested that the tektites of this study resemble in composition to the upper continental crust (UCC) (Table I, Fig.2). The tektites of this study have relatively lower

volatile elements (such as Cu, Ga and Zn) as compared with the average upper crust, indicating high temperature during impact melting.

The more recent studies agree with a terrestrial sedimentary precursor material for tektites[6],[15],[21],[22]. Sedimentary rocks have higher Th/U ratios than igneous rocks[23]. The tektites of this study have high Th/U ratios (avg. 7.6, >6), indicating that sedimentary rocks may be the major source materials of these tektites. The average element ratios of Ba/Rb, Th/Sm, Sm/Sc and Th/Sc found in tektites analyzed are 3.89, 2.40, 0.45 and 0.99 which are similar to those of average upper continental crust. Based on La/Th ratio of tektites from East Asia, Lee et al. (2004)[14] suggested that these tektites may be derived from post-Archean sedimentary rocks such as sandstones, greywacke and shale. Based on the

major and trace element compositions, Glass et al. (2004) [10]suggested that the normal Australasian microtektites appear to have been derived from a graywacle or lithic arenite with a range in clay and quartz content. When comparing with the Early, Late and post-Archean upper continental crust, the REE patterns of tektites in the present study are quite similar to that of post-Archean upper continental crust (Fig.4). From the Nd and Sr isotopic studies, Blum et al. (1992) [1]found that the Australasian tektites were derived dominantly from a

TABLE I
MAJOR AND TRACE ELEMENT COMPOSITIONS OF TEKTITES FROM THE WENCHANG AND KHON KAEN AREAS COMPARED WITH AVERAGE MUONG NONG-TYPE AND SPLASH-FORM INDOCHINITES, AND AVERAGE UPPER CONTINENTAL CRUST

	Avg. W	Avg. KK	A	B	C
SiO_2□%□	72.55	73.25	78.90	72.70	66.00
Al_2O_3	13.62	13.75	10.18	13.37	15..2
MgO	3.39	2.69	1.43	2.14	2.20
FeO	5.18	5.15	3.74	4.85	4.50
CaO	1.08	0.43	4.20	1.98	4.20
Na_2O	1.36	1.40	0.92	1.05	3.90
K_2O	2.18	2.15	2.42	2.62	3.40
MnO	0.10	0.10	0.08	0.08	0.08
TiO_2	0.72	0.74	0.63	0.78	0.50
P_2O_5	0.09	0.04	—	—	—
total	100.27	99.71	99.54	99.57	99.98
Ba(ppm)	412	419	341	360	550
Co	13.0	11.9	12.6	11.0	10.0
Cr	94.4	77.3	60.6	63.0	35.0
Cs	6.35	6.68	5.09	6.50	3.70
Cu	5.3	15.6	14.3	4.0	25.0
Hf	6.94	6.65	8.13	6.95	5.80
Ga	12.80	20.12	24.20	8.20	17.00
Li	50.52	54.12	42.10	47.10	20.00
Nb	17.56	17.90	—	—	—
Ni	31.71	20.08	48.60	19.00	20.00
Rb	117	130	110	130	112
Sc	11.9	13.4	7.7	10.5	11.0
Sr	160	134	135	90	350
Ta	1.6	1.5	1.2	1.6	2.2
Th	14.3	14.0	11.1	14.0	10.7
U	2.34	2.17	2.48	2.07	2.80
V	80	80	72	63	60
W	0.66	0.45	1.02	0.29	2.00
Y	39.1	41.2	—	—	—
Zr	271	273	280	252	190
Zn	20	28	67	6	71
La	40.5	40.3	28.2	36.5	30.0
Ce	82.7	80.7	60.7	73.1	64.0
Nd	37.7	37.8	29.1	33.2	26.0
Sm	7.4	7.2	4.9	6.6	4.5
Eu	1.27	1.24	1.01	1.22	0.88
Gd	5.63	5.58	4.30	5.24	3.80
Tb	0.95	0.95	0.75	0.85	0.64
Dy	5.81	5.68	4.75	5.58	3.50
Yb	2.92	2.89	2.71	2.90	2.20
Lu	0.50	0.49	0.42	—	0.32

A, Average Muong Nong-type indochinites [17]; B, Average splash-form indochinites [17]; C, Average upper continental crust [23].

Avg. W, Average 27 tektites from Wenchang area; Avg. KK, Average 5 tektites from Khon Kaen area.

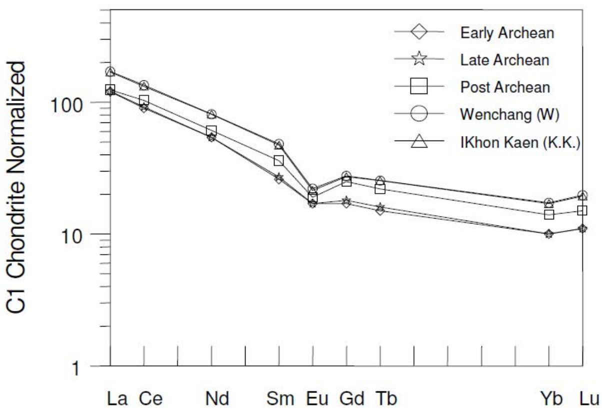

Fig 4 Chondrite-normalized REE distribution in tektites of this study, as compared with average upper continental crust of various ages [25].

Proterozoic crustal terrane (Nd model age fall with the 1490-1620 Ma) and derived from a sedimentary formation with a narrow range of stratigraphic ages, close to 170 Ma (Jurassic sedimentary rocks), by a single impact event. The Sr isotopic data obtained by the present study support the conclusion proposed by Blum et al. (1992) [1](Fig.5, Table II), since our data all fall within the wedge-shaped array defined by all Australasian tektites. The southern part of the Thailand-Laos border has non-marine Jurassic exposures suggested by Sato (1992)[24] which reveal that the source crater for Australasian strewn field appears to be located in a limited area near the southern part of the Thailand-Laos border.

Based on chemical elements and the Sr and Nd isotopic variations, we suggest that the Australasian tektites are not likely to be formed from local melting at a variety of different sites. The tektites of the present study may be the result of melting at a single site which may be located of the southern part of the Thailand-Laos border where Jurassic non-marine sandstone, siltstone, shale, mudstone and conglomerates with minor intercalation of limestone are exposed (Sato, 1992)[24]. The main limitation at present is still the lack of appropriate chemical data of target materials available for this study. The present authors selected a variety of target rocks in the literatures including average post-Archean Australian shale, average Phanerozoic sandstone, average Meso-Cenozoic greywacke and quartzite in Tasmania (Table III), and mixing calculations for various amounts and combinations of these rocks have been performed in order to build up a geochemical relationship between the tektites analyzed and its parent material. The model is useful in determining the most possible fit for the parent material of the tektites from the Wenchang and Khon Kaen areas. In the two different mixing models, the best fit for tektites from the Wenchang area is a mixture of 47% shale, 23% sandstone, 25% greywacke and 5% quartzite, and the other tektites from Khon Kaen area is a mixture of 46% shale, 2% sandstone, 20% greywacke and 32% quartzite.

TABLE II
SUMMARY OF RB-SR RESULTS AND MODEL AGE CALCULATIONS

Sample	Location	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$
W-28	Wenchang	100	129	2.268
W-29	Wenchang	100	154	1.915
W-30	Wenchang	101	128	2.258

$^{87}Sr/^{86}Sr^*$	εSr	$f_{Rb/Sr}$	T_{Sr}^{UR}(Ma)
0.717520±13	184.8	26.42	420
0.718346±26	196.5	22.16	532
0.717510±10	184.5	26.39	418

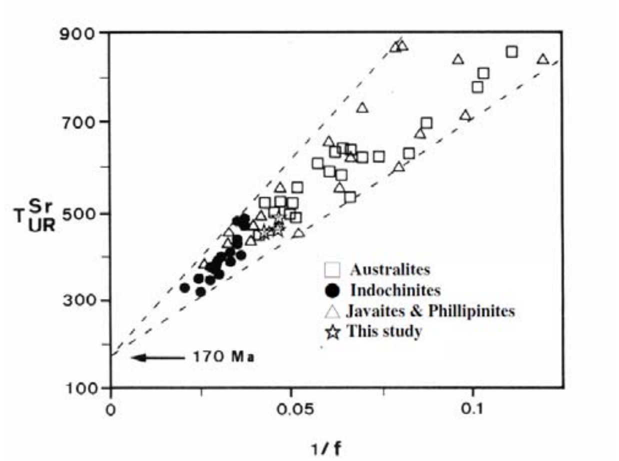

Fig.5 Plot of T_{UR}^{Sr} vs. $1/f^{Rb/Sr}$ for Australasian tektites (this study and literature values by Blum et al., 1992)[1]. The Y-intercept gives the time of last Rb-Sr fractionation and corresponds to the time of sedimentation of a sedimentary parent material [1].

TABLE III
AVERAGE DATA FOR TEKTITES OF THIS STUDY COMPARED WITH MIXING MODELS (M1 AND M2). THE MIXING MODEL IS CONSTRUCTED BASED ON ALL THE MAJOR AND TRACE ELEMENTS ANALYZED.

	A	B	PAAS	APSS	AMCG	AQTZ	M1	M2
SiO_2(%)	72.55	73.41	62.8	91.50	66.30	92.70	71.77	73.66
Al_2O_3	13.62	13.50	18.9	3.62	15.50	4.18	13.80	13.2
MgO	3.39	2.66	2.2	0.45	2.00	0.42	1.66	1.55
FeO	5.18	5.10	6.5	1.13	6.20	0.11	4.87	4.29
CaO	1.08	0.44	1.3	0.31	3.20	0.06	1.71	1.29
Na_2O	1.36	1.43	1.2	0.42	3.10	0.06	1.44	1.20
K_2O	2.18	2.2	3.7	0.91	2.30	1.15	2.58	2.55
TiO_2	0.72	0.72	1.00	0.25	0.72	0.44	0.73	0.75
P_2O_5	0.09	0.05	0.16	0.02	0.14	—	0.11	0.10
Total	100.27	99.62	97.76	99.61	99.46	99.12	98.67	98.59
Ba(ppm)	412	419	650	150	650	133	509	474
Co	13.0	12.0	23	2.5	15	1.1	15.2	14.0
Cr	94.4	78.4	110	30	70	86	80.4	92.5
Hf	6.94	6.74	5.0	3.1	3.9	18	4.93	8.87
Nb	17.6	17.9	19.0	4.0	10	—	12.4	10.8
Ni	31.7	21.4	55	8.0	30	5.0	35.5	33.0
Rb	117	130.4	160	25	100	67	109	115
Sc	11.9	13.3	16	2.0	14	3.1	11.6	11.2
Sr	160	135	200	35	280	—	172	149
Ta	1.5	1.5	1.2	0.3	0.85	1.0	0.9	1.0
Th	14.3	13.8	14.6	4.0	8.5	6.2	10.2	10.5
U	2.34	2.23	3.1	1.1	1.8	2.5	2.29	2.60
V	80	82	150	15	130	—	106	95
Y	38.8	41.3	27	6.8	28	—	21.3	18.2
Zr	271	279	210	105	145	634	191	329
La	40.5	40.1	38	10.3	28.0	17.0	28.1	28.7
Ce	82.7	80.6	80	22.3	61.0	25.7	59.3	57.6
Nd	37.7	37.4	32	8.4	26.0	9.8	24.0	23.2
Sm	7.4	7.2	5.6	1.63	4.90	2.0	4.3	4.2
Eu	1.27	1.23	1.1	0.34	0.90	0.4	0.84	0.82
Gd	5.63	5.54	4.7	1.44	4.34	—	3.63	3.06
Tb	0.95	0.96	0.77	0.21	0.66	0.5	0.60	0.65
Yb	2.92	2.88	2.8	0.61	2.20	2.2	2.12	2.44
Lu	0.50	0.50	0.43	0.11	0.38	0.4	0.34	0.40

A, average of 27 tektites from the Wenchang area; B, average of 5 tektites from the Khon Kaen area ;PAAS,. average post-Archean Australian Shales [25];APSS, average Phanerozoic sandstone [25]; AMCG, average Meso-Cenozoic greywackes [25];
M1: 47%PAAS+23%APSS+25%AMCG+5%AQTZ;
M2: 46%PAAS+2%APSS+20%AMCG+32%AQTZ

IV. CONCLUSIONS

Tektites from the Wenchang and Khon Kaen areas are characterized by high SiO_2 content which is consistent with previous observation on Australasian tektites. Except for higher MgO, Na_2O, Ni, Ga, Zn, Ni and lower CaO contents, the chemical composition of tektites of this study closely resemble that of splash-form indochinites According to major, trace elements (including rare earth elements) and the trace element ratios (Ba/Rb, Th/Sm, Sm/Sc and Th/Sc), it is suggested that the tektites of this study resemble in composition to the upper continental crust (UCC). Based on chemical elements and the Sr and Nd isotopic variations, we suggest that the Australasian tektites are not likely to be formed from local melting at a variety of different sites and they were not dominantly derived from recent young sediments (such as soil and loess). The tektites of the present study may be the result of melting at a single site which may be located of the southern part of the Thailand-Laos border where Jurassic non-marine sandstone, siltstone, shale, mudstone and conglomerates with minor intercalation of limestone are exposed (Sato, 1992)[24]. Mixing calculations for various amounts and combinations of these rocks have been performed in order to build up a geochemical relationship between the tektites analyzed and its parent material. We consider that the best fit for tektites from the Wenchang area is a mixture of 47% shale, 23% sandstone, 25% greywacke and 5% quartzite, and the other tektites from Khon Kaen area is a mixture of 46% shale, 2% sandstone, 20% greywacke and 32% quartzite.

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