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Geochemistry of Tektites from Maoming of Guandong Province, China

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Abstract**—**We measured the major and trace element contents and Rb-Sr isotopic compositions of 12 tektites from the Maoming area, Guandong province (south China). All the samples studied are splash-form tektites which show pitted or grooved surfaces with schlieren structures on some surfaces. The trace element ratios Ba/Rb (avg. 4.33), Th/Sm (avg. 2.31), Sm/Sc (avg. 0.44), Th/Sc (avg. 1.01) , La/Sc (avg. 2.86), Th/U (avg. 7.47), Zr/Hf (avg. 46.01) and the rare earth elements (REE) contents of tektites of this study are similar to the average upper continental crust. From the chemical composition, it is suggested that tektites in this study are derived from similar parental terrestrial sedimentary deposit which may be related to post-Archean upper crustal rocks. The tektites from the Maoming area have high positive $\varepsilon^{Sr}(0)$ values-ranging from 176.9~190.5 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). The Sr isotopic data obtained by the present study support the conclusion proposed by Blum et al. (1992)[1] that the depositional age of sedimentary target materials is close to 170Ma (Jurassic). Mixing calculations based on the model proposed by Ho and Chen (1996)[2] for various amounts and combinations of target rocks indicate that the best fit for tektites from the Maoming area is a mixture of 40% shale, 30% greywacke, 30% quartzite.

Keywords**—**Geochemistry, Guandong province, South China, Tektites

I. Introduction

TEKTITES are terrestrial natural glasses of up to a few cm diameter size that are produced during the early phases of a hypervelocity impact of an asteroid or a comet into terrestrial rock [3]-[4]. The chemical and isotopic composition of tektites is similar to that of terrestrial upper continental crust which indicates that tektites must have formed by fusion of such target rock and not from projectile matter[5]. The tektites from a specific region are usually given a distinctive name derived from the geography. Previous studies of cosmogenic radioisotopes have pointed out tektites derived from the top of the impacted target lithologies [6]-[9]. Tektites are only found in a few distinct geographical areas called strewn fields which four are currently known[10]: the ~35Ma North American strewn field associated with the Chesapeak Bay impact structure; the Central European strewn field associated with the Ries crater in Bavaria, Germany (~14.7Ma); the ~1.07 Ma Ivory Coast tektite strewn field which are derived from the Bosumtwi impact structure in Ghana, and the Australasian strewn field of age ~0.8Ma[11]. The impact structure for the Australasian strewn field has not yet been found. The Australasian strewn field covers nearly 10% of the Earth's surface[12]. 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 (Fig. 1). The Australasian tektites probably originated somewhere in Southeast Asia [9]. The ^{10}Be concentrations of tektites increase slowly with increasing distance from Indochina: Southeast Asian tektites have the lowest values and australites the highest [9]. The systematic variation of ^{10}Be concentrations proposed by Ma et al. (2004) [9] may indicate a single impact event. Based on the thickness of the Australasian microtektite layer proposed by Glass and Pizzuto (1994)[13], the diameter of the source crater is estimated to be between 32 and 114 km. The tektites from these four strewn fields are characterized by different chemical compositions, petrological properties, and ages.The tektites found on land (as opposed to the microtektites found in deep-sea cores) can be classified into three groups: (1) aerodynamically shaped tektites; (2) normal or splash-form tektites, and (3) Muong Nong-type tektites (or layered tektites) [14]. Tektites of types (1) and (3) are predominantly found in the Australasian. 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 result from partial re-melting of the tektite glass during atmospheric re-entry, after the initial melt had been ejected outside the terrestrial atmosphere and solidified through quenching. The splash-form tektites may result mostly from the solidification of rotating liquids. 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[15]. Koeberl et al. (1984)[16] 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.

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Some authors[17]-[19] 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. Folo et al. (2008, 2009)[20][21] predicted a possible relationship between the processes controlling the loss of volatiles and ejection distance and suggested that the source crater location could be broadly constrained by investigating geographic variations in the concentrations of volatile elements that are lost during the impact.

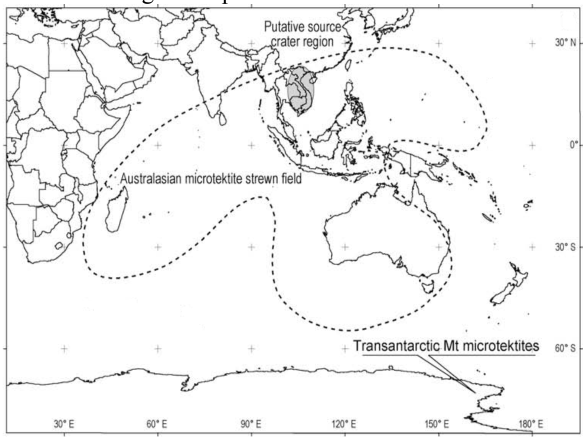

Fig. 1 Map showing the Australasian tektite/microtektite strewn field (dashed line) as defined by Glass and Koeberl (2006)[22].

The tektites of this study were collected by K. S. Ho (Fig.2). The main purpose of this paper is to analyze the major and trace elements (including rare-earth elements, REE) and the Rb-Sr isotopes of the tektites from the Maoming area which can provide important information regarding the origin of the tektites, their parent material and the possible source crater.

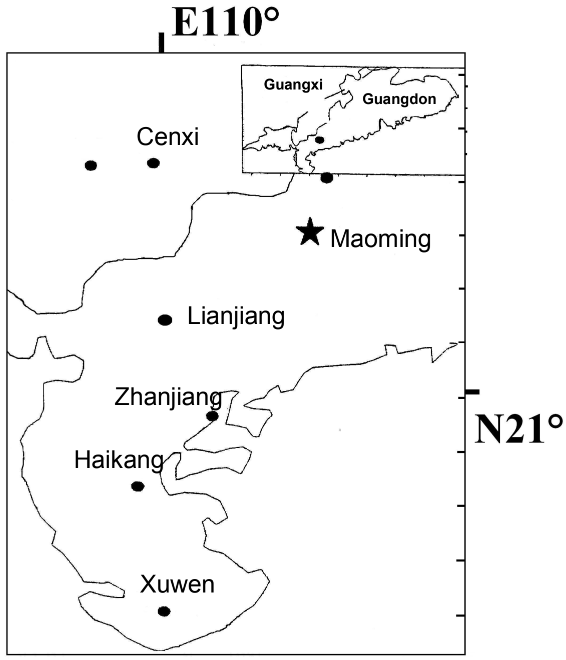

Fig. 2 Localities of tektites in the present study (star)

II. Analytical Methods

Twelve samples were cleaned ultrasonically and crushed into chips by a hammer wrapped with plastic sheets. Several larger glass chips were selected and ground to powder in an agate mortar. The chemical analyses of tektites from the Maoming area 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 rock standards and obsidian rock. 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 generally small (several centimeters in size), black and oval, dum-bell or disc shaped. Weight, refractive index and density measurements for twelve tektites are given in Table I. Refractive index and density of tektites of this study are closely similar. The average weight for the twelve tektites is approximately 57.5 g ranging from 34.8 to 74.5 g. Based on the shape, weight, refractive index and density, the tektites from the Maoming area are splash-form tektites. On the basis of surface feature and correlation plot of refractive index versus silica content, tektites of this study can be clearly distinguished from terrestrial volcanic glasses. These tektites have a pitted or grooved surface and preserve the schlieren structures on some surface, indicating high speed entry into the atmosphere and rapid solidification in flight.

TABLE I
WEIGHT, REFRACTIVE INDEX AND DENSITY OF TEKTITES

Sample No.	M-1	M-2	M-3	M-4	M-5
Weight(g)	34.8	60.2	74.5	42.1	52.2
Refractive index	1.506	1.500	1.512	1.500	1.480
Density(g/cm^3)	2.44	2.40	2.43	2.38	2.38

M-6	M-7	M-8	M-9	M-10	M-11	M-12
52.7	56.4	57.5	57.8	63.0	66.3	72.7
1.490	1.510	1.510	1.512	1.506	1.512	1.504
2.40	2.41	2.42	2.44	2.41	2.43	2.40

The major elements of tektites in the present study are heterogeneous. The average major and trace element compositions of 12 samples are listed in Table II. Tektites from the Maoming area are characterized by high SiO_2 content ranging from 71.06 to 80.61 wt% (avg. 75.38 wt%), which is consistent with previously published analyses of Muong Nong-type and aplash-form indochinites (Table II). The SiO_2 and Al_2O_3 contents of tektites from Maoming have higher variation.

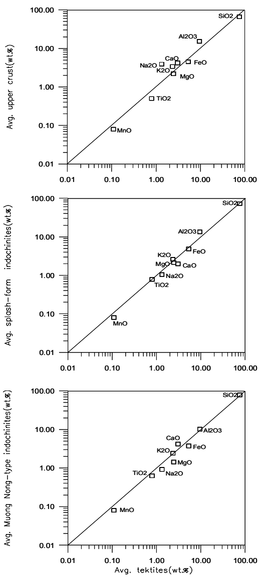

Fig 3 Comparison of major element composition of tektites in the present study with average Muong Nong-type indochinites, average splash-form indochinites and average compositions of upper continental crust

Based on the high content of SiO_2, the lunar volcanic origin for tektites may be excluded. The relative depletion of Al_2O_3 in tektites from Maoming area may be caused by lower shale involved during the production of tektites or different amounts and combinations of target material. Except for higher CaO, Na_2O, MnO, Co, Sr, Ga, Sc and lower Al_2O_3 contents, the chemical composition of tektites of this study closely resemble that of splash-form indochinites (Fig.3,4). Except for Al_2O_3 , Na_2O and K_2O, the concentrations of the major oxides are

TABLE II
MAJOR AND TRACE ELEMENT COMPOSITIONS OF TEKTITES FROM THE MAOMING AREA COMPARED WITH AVERAGE MUONG NONG-TYPE AND SPLASH-FORM INDOCHINITES, AND AVERAGE UPPER CONTINENTAL CRUST

	Avg. M	A	B	C
SiO_2 (%)	75.38	78.90	72.70	66.00
Al_2O_3	9.47	10.18	13.37	15..2
MgO	2.45	1.43	2.14	2.20
FeO	5.30	3.74	4.85	4.50
CaO	3.06	4.20	1.98	4.20
Na_2O	1.33	0.92	1.05	3.90
K_2O	2.35	2.42	2.62	3.40
MnO	0.11	0.08	0.08	0.08
TiO_2	0.79	0.63	0.78	0.50
total	100.22	99.54	99.57	99.98
Ba(ppm)	444	341	360	550
Co	24.3	12.6	11.0	10.0
Cr	69.3	60.6	63.0	35.0
Cs	6.32	5.09	6.50	3.70
Ga	18.0	8.13	6.95	5.80
Hf	8.64	24.20	8.20	17.00
Li	52.4	42.10	47.10	20.00
Nb	23.3	—	—	—
Rb	103	110	130	112
Sc	16.7	7.7	10.5	11.0
Sr	144	135	90	350
Ta	1.3	1.2	1.6	2.2
Th	16.8	11.1	14.0	10.7
U	2.25	2.48	2.07	2.80
V	107	72	63	60
Y	45.2	—	—	—
Zn	16	280	252	190
Zr	397	67	6	71
La	47.7	28.2	36.5	30.0
Ce	93.6	60.7	73.1	64.0
Nd	39.3	29.1	33.2	26.0
Sm	7.3	4.9	6.6	4.5
Eu	0.60	1.01	1.22	0.88
Gd	6.40	4.30	5.24	3.80
Tb	0.81	0.75	0.85	0.64
Yb	3.04	2.71	2.90	2.20
Lu	0.49	0.42	—	0.32

A, Average Muong Nong-type indochinites [14]; B, Average splash-form indochinites [14]; C, Average upper continental crust [23]. Avg. M, Average 12 tektites from Maoming area.

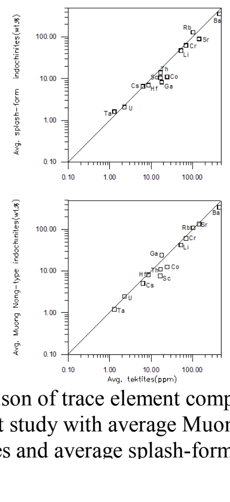

Fig. 4 Comparison of trace element composition of tektites in the present study with average Muong Nong-type indochinites and average splash-form indochinites.

similar to those of the upper continental crust (Fig.3). The relatively lower Na_2O and K_2O contents found in the tektites of this study indicate that the source material probably contains relatively low contents of feldspar. The REE patterns for tektites in this study are similar to those of previously analyzed splash-form indochinites (Fig.5), indicating that they are all derived from similar parent rocks of upper continental crust affinity. According to major and trace elements, it is suggested that the tektites of this study resemble in composition to the upper continental crust (UCC). Some trace elements are not closely correlated between the tektites analyzed and the upper continental crust which may be related to high temperature during impact melting. When comparing with the Early, Late and post-Archean upper continental crust, the REE patterns of tektites from Maoming area are quite similar to that of

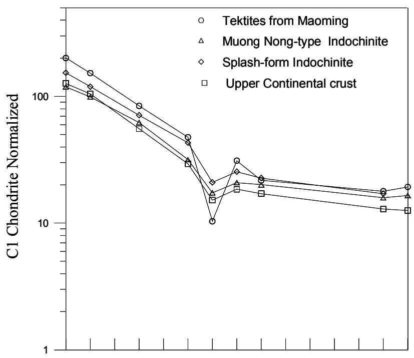

Fig. 5 Chondrite-normalized REE diagram of tektites in the present study. Data for Muong Nong-type and splash-form indochinites from Koeberl (1992)[14]; upper crust from Taylor and McLennan (1985)[23].

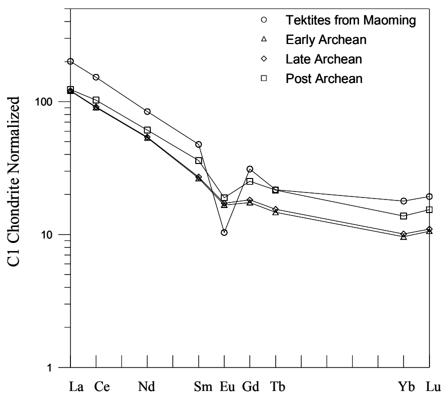

Fig. 6 Chondrite-normalized REE distribution in tektites of this study, as compared with average upper continental crust of various ages (Condie, 1993)[27].

TABLE III

SUMMARY OF RB-SR RESULTS AND MODEL AGE CALCULATIONS

Sample	Location	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr^*$	ε Sr	$f_{Rb/Sr}$	T_{Sr}^{UR}(Ma)
M-1	Maoming	348.3	106.9	155.3	1.994	176.9	23.11	459
M-2	Maoming	351	107.7	139.2	2.243	188.5	26.12	433
M-3	Maoming	349.7	107.3	147.8	2.104	190.5	24.44	468

post-Archean upper continental crust (Fig.6).Based on ^{10}Be contents of tektites, several authors [1][14] favor a sedimentary origin for the parental material of Australasian. Sedimentary rocks have higher Th/U ratios than igneous rocks[24]. The tektites of this study have high Th/U ratios (avg. 7.5, >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, Th/Sc, La/Sc, Th/U and Zr/Hf found in tektites analyzed are 4.33, 2.31, 0.44, 1.01, 2.86, 7.47 and 46.01 which are similar to those of average upper continental crust. It is noted that tektites are unlikely any lunar material, but close to terrestrial upper crustal sediments in composition. The La vs. Th plot (Fig.7) indicates that the tektites in this study cluster around the correlation line defined by post-Archean sediments (La/Th=2.8) and differ from the Archean sediment correlation line (La/Th=3.5) which indicate 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) [12]suggested that the normal Australasian microtektites appear to have been derived from a greywacke or lithic arenite with a range in clay and

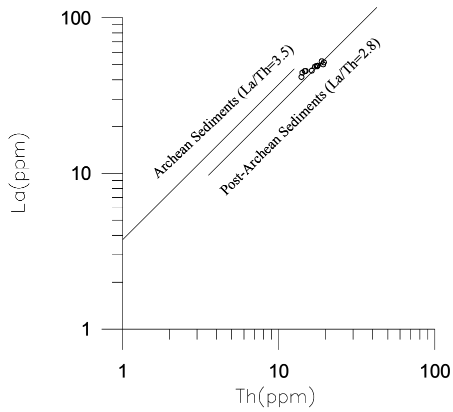

Fig. 7 Correlation diagram of La vs. Th for Maoming tektites (data for Archean and post-Archean sediments from Taylor and McLennan, 1985)[23].

quartz content. Based on the Nd and Sr isotopic studies, Blum et al. (1992)[1] revealed that the Australasian tektites were derived dominantly 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.8, Table III), since our data all fall within the wedge-shaped array defined by all Australasian tektites. The tektites from the Maoming area have high positive $\varepsilon^{Sr}(0)$ values-ranging from 176.9~190.5 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). On the basis of the fluence of microtektites (number per cm^2 of the column) recovered from marine cores from oceanic regions near southeast Asia, the East Indies and Australian, Schmidt et al. (1993)[25] concluded that microtektite fluences tend to decrease with increasing distance from southeast Asia. The southern part of the Thailand-Laos border has non-marine Jurassic exposures suggested by Sato

(1992)[26] 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)[26]. 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 IV), 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 Maoming area. In the mixing model, the best fit for tektites from the Maoming area is a mixture of 40% shale, 30% greywacke, 30% quartzite(Fig.9).

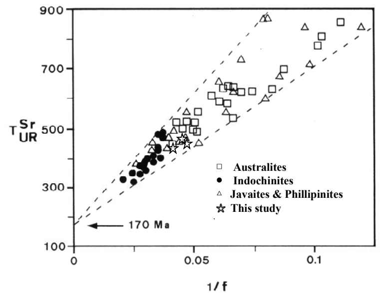

Fig. 8 Plot of T_{UR}^{Sr} vs. $1/f^{Rb/Sr}$ for Australasian tektites (this study and literature values by Blum et al., 1992)[1]. The Y-intercept gives the time of last Rb-Sr fractionation and corresponds to the time of sedimentation of a sedimentary parent material (Blum et al., 1992)[1].

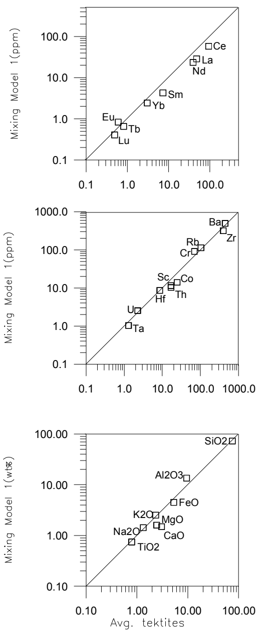

Fig. 9 Correlation plots of compositional data from the mixing model vs. compositional data for Maoming tektites. Mixture used for this model is 40% shale, 30% greywacke and 30% quartzite.

TABLE IV

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

	A	PAAS	APSS	AMCG	AQTZ	M1
SiO_2(%)	75.38	62.8	91.50	66.30	92.70	72.82
Al_2O_3	9.47	18.9	3.62	15.50	4.18	13.46
MgO	2.45	2.2	0.45	2.00	0.42	1.61
FeO	5.30	6.5	1.13	6.20	0.11	4.49
CaO	3.06	1.3	0.31	3.20	0.06	1.50
Na_2O	1.33	1.2	0.42	3.10	0.06	1.43
K_2O	2.35	3.7	0.91	2.30	1.15	2.52
TiO_2	0.79	1.00	0.25	0.72	0.44	0.75
Total	100.12	97.6	98.59	99.32	99.12	98.57
Ba(ppm)	444.33	650	150	650	133	494.9
Co	24.27	23	2.5	15	1.1	14.03
Cr	69.32	110	30	70	86	90.80
Hf	8.64	5.0	3.1	3.9	18	8.57
Rb	102.67	160	25	100	67	114.1
Sc	16.69	16	2.0	14	3.1	11.53
Ta	1.29	1.2	0.3	0.85	1.0	1.04
Th	16.83	14.6	4.0	8.5	6.2	10.25
U	2.25	3.1	1.1	1.8	2.5	2.53
Zr	397.33	210	105	145	634	317.7
La	47.69	38	10.3	28.0	17.0	28.70
Ce	93.58	80	22.3	61.0	25.7	58.01
Nd	39.34	32	8.4	26.0	9.8	23.54
Sm	7.29	5.6	1.63	4.90	2.0	4.31
Eu	0.60	1.1	0.34	0.90	0.4	0.83
Tb	0.81	0.77	0.21	0.66	0.5	0.66
Yb	3.04	2.8	0.61	2.20	2.2	2.44
Lu	0.49	0.43	0.11	0.38	0.4	0.41

A, average of 12 tektites from the Maoming area; PAAS, average post-Archean Australian Shales [27];APSS, average Phanerozoic sandstone [27]; AMCG, average Meso-Cenozoic greywackes [27];
M1: 40%PAAS+30%AMCG+30%AQTZ;

IV. CONCLUSIONS

All the samples studied are splash-form tektites which show pitted or grooved surfaces with schlieren structures on some surfaces. Tektites from the Maoming area are characterized by high SiO_2 content which is consistent with previous observation on Australasian tektites. Based on the high content of SiO_2 , the lunar volcanic origin for tektites may be excluded. The relative depletion of Al_2O_3 in tektites from Maoming area may be caused by lower shale involved during the production of tektites or different amounts and combinations of target material. Except for higher CaO, Na_2O, MnO, Co, Sr, Ga, Sc and lower Al_2O_3 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, Th/Sc, La/Sc, Th/U and Zr/Hf), it is suggested that the tektites of this study resemble in composition to the upper continental crust (UCC). The La/Th ratios and REE pattern indicate that the tektites in this study may be derived from post-Archean sedimentary rocks such as sandstones, greywacke and shale. 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)[26]. The Sr isotopic data obtained by the present study support the conclusion proposed by Blum et al. (1992)[1] that the depositional age of sedimentary target materials is close to 170Ma (Jurassic). Mixing calculations based on the model proposed by Ho and Chen (1996)[2] for various amounts and combinations of target rocks indicate that the best fit for tektites from the Maoming area is a mixture of 40% shale, 30% greywacke, 30% quartzite.

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