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MATHEMATICAL STATISTICS OF HEAVY MINERALS AND THEIR REE AND TRACE ELEMENTS IN THE NORTHWESTERN SEA AREA OF ANTARCTIC PENINSULA

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Abstract Based on the analysis and mathematical statistics of quantitative data on both the heavy minerals and their REE (La, Ce, Nd, Sm, Eu, Tb, Yb, Lu), trace (Zr, Hf, Th, Ta, U, Rb, Sr, Zn, Co, Ni, Cr, As, Sc) and major (Fe) elements in the surface sediments in the northwestern sea area of Antarctic Peninsula, the authors find that the heavy minerals as the carriers of REE and trace elements should not be overlooked.

Q-mode factor analysis of the heavy minerals provides a 3-factor model of the heavy mineral assemblages in the study area, which is mainly controlled by the origin of materials and sea currents. The common factor P_1, composed mainly of pyroxene and metal minerals, and common factor P_2, composed of hornblende, epidote and accessory minerals, represent two heavy mineral assemblages which are different from each other in both lithological characters and origin of materials. And common factor P_3 probably results from mixing of two end members of the above-mentioned assemblages. R-mode group analysis of the heavy minerals indicates that there are two heavy mineral groups in the sea area, which are different from each other in both genesis and origin of materials. With the help of R-mode analysis, 22 elements are divided into 3 groups and 9 subgroups. These element assemblages show that they are genetically related and that they are different in geochemical behaviors during diagenesis and mineral-forming process. In addition, the relationship between the heavy mineral assemblages and the element subgroups is also discussed.

Key Words Sea area of Antarctic Peninsula, Marine sediments, Heavy minerals, Rare earth and trace elements, Statistic analysis.

Analysis Methods for the Samples

During the period from Nov. 1984 to Apri. 1985, a marine comprehensive investigation, including biology, physics, chemistry, geology and geophysics, was carried out in the northwestern sea area of Antarctic Peninsula. The survey area is located in 55° to 69°30′W and 60° to 66°55′S. Sampling stations for surface sediments are shown in Fig. 1.

The heavy mineral samples from the surface sediments were studied by the authors under a microscope and using NAA, and much quantitative information was obtained about mineralogy, REE, and trace elements. In the twenty three of heavy mineral samples, approximately thirty one kinds of heavy minerals have been identified, of which the contents of pyroxene, amphibole, epidote, magnetite, ilmenite, pyrite, chlorite, muscovite, biotite, garnet, apatite, zircon, and altered ferromagnesian silicate minerals are relatively high, and the contents of weathered mica, limonite, and hematite relatively low. The observed data for REE, trace (Zr, Hf, Th, Ta, U, Rb, Sr, Zn, Co, Ni, Cr, As, Sc) and major (Fe) elements in the samples are shown in Table 1.

The research shows that the REE and trace elements in the surface sediments of the study area, probably, exist mainly in the heavy minerals. At the same station, usually the content

Table 1. Initial variables of heavy minerals, REE and trace elements for statistic analysis.

Site	depth (m)	heavy mineral (%)												REE
		A	B	C	D	E	F	G	H	I	J	K	L	La+Ce +Nd
SM_2	260	6.0	0.6	31.3	21.2	2.7	14.0	3.9	0.3	2.1	—	17.0	0.9	230.4
SM_3	450	9.2	1.5	28.2	12.2	9.8	11.2	2.4	1.9	20.3	—	2.9	0.5	491.3
SM_4	1843	5.5	0.5	30.6	37.4	2.3	7.7	1.8	1.4	3.7	—	8.6	0.9	99.8
SM_5	478	10.9	0.3	5.5	5.1	18.5	4.5	—	6.5	4.7	—	44.0	—	137.7
SM_6	451	10.6	—	24.7	18.3	4.8	12.8	1.6	0.9	4.1	—	20.8	1.2	76.0
SM_8	190	2.0	3.7	56.2	18.8	8.2	9.2	0.7	—	0.7	—	—	0.3	68.2
SM_9	176	15.8	—	12.3	3.2	30.3	5.7	3.5	7.0	2.9	—	19.0	0.4	144.9
SM_{10}	1669	25.4	1.7	5.6	6.3	16.7	2.8	0.7	1.0	0.3	—	37.2	2.1	96.8
SM_{11}	4105	13.5	0.4	19.7	5.3	17.7	16.2	—	6.1	2.9	—	17.5	0.4	156.9
SM_{19}	3026	27.6	0.2	7.0	5.6	24.4	9.0	0.5	2.9	1.1	—	21.6	—	176.6
SM_{20}	300	32.6	—	2.5	1.4	10.6	1.8	—	14.2	0.7	—	35.4	0.7	289.6
SM_{21}	330	16.8	0.4	16.0	19.6	24.9	3.5	1.1	3.5	2.6	—	11.8	—	384.5
SM_{23}	510	2.6	1.3	41.8	11.5	10.2	22.9	1.8	0.4	2.2	—	0.9	4.4	184.0
SM_{24}	479	6.2	4.6	16.5	18.5	33.8	13.4	1.2	0.8	0.4	0.4	3.8	—	205.2
SM_{25}	780	17.0	4.0	22.4	5.0	26.8	11.7	1.7	11.4	—	—	—	—	113.5
SM_{26}	339	28.0	—	5.4	3.5	18.6	7.0	2.4	7.3	1.6	—	25.9	0.3	321.9
J	470	2.1	9.7	53.4	10.6	4.6	7.9	5.0	—	0.6	0.6	2.5	3.2	98.5
R_1	522	1.7	15.5	49.3	16.7	2.9	9.0	4.0	—	0.6	0.2	—	—	100.7
R_4	402	1.4	0.4	12.1	6.3	20.3	9.2	2.8	—	1.4	29.5	14.0	2.8	153.7
M_1	106	3.3	—	46.7	12.8	10.8	13.9	4.2	1.4	0.6	1.1	5.3	—	131.9
M_3	406	5.8	0.4	54.2	6.9	2.9	15.5	9.4	0.8	0.2	0.7	2.9	—	98.8
L_1	851	5.6	—	24.0	27.3	0.8	9.6	0.4	0.4	1.6	—	20.0	10.0	122.2
L_6	130	2.7	2.4	31.7	25.0	13.4	13.4	1.3	0.8	0.9	0.3	8.1	—	119.4

Note A: green amphibole; B: brown amphibole; C: augite; D: hypersthene; E: epidote; F: ilmenite, mag-
L: other mineral.

of REE in the heavy minerals is several times to over ten times higher than that in the sediments (Zhao Yunlong, in press). Most of the trace elements listed in Table 1 should exist in the heavy minerals also. It can be seen from this that the heavy minerals are the REE and trace element carrier in the surface sediments of the sea area, and that it is very necessary for us to discuss the relationship between the heavy minerals and REE and trace elements in it. (Xu Butai *et al.*, 1987; Wang Dezi, 1975).

In addition, to obtain more reliable geological information from data analysis and to change the qualitative method used before, the authors analyzed the variables in Table 1 with mathematical statistics (i.e. Q-mode factor and R-mode group analyses).

There are 23 heavy mineral samples and decades of observed data in the study area. Mathematically when number of variables is more than that of samples, the solution of the equation is absent. To find the solution, 31 heavy minerals are divided into 12 kinds and 8 REE are merged into 3 groups, and then a method of group analysis is used. First, Q-mode factor analysis is used for 12 kinds of heavy minerals, and then, group analysis is used for all of elements, and at last, group analysis is used for the heavy minerals. The result is in keeping with expectations.

It is the similarity of their physicochemical properties and their association in the ocean environment that constitutes the principles of merging into the REE and the heavy minerals. For example, in Table 1, five light REE are merged into two groups, i.e. La+Ce +Na and Sm +Eu; three kinds of heavy REE are merged into one group, i.e. Tb+Yb+Lu. In the heavy minerals, epidotes variable takes epidote as the dominant factor, with less clinozoisite, and

(ppm)		trace element (ppm)													major element (%)
Sm+Eu+Tb+Lu		U	As	Th	Hf	Sr	Zr	Ni	Sc	Rb	Zn	Ta	Co	Cr	Fe
15.49′	7.92	5.0	2.2	12.7	47.3	114	850	1.04	132.6	27.0	132	2.80	68.5	663	16.20
31.18	12.51	5.0	4.1	34.9	93.3	333	3030	16.8	111.9	52.5	138	7.20	52.8	570	11.80
7.93	5.42	5.0	1.7	13.2	23.9	346	440	0.31	112.4	14.4	88	3.20	59.0	566	10.70
13.32	8.60	5.8	3.2	10.9	10.5	692	520	0.55	88.0	40.3	89	0.99	31.9	302	7.97
7.18	4.99	4.4	2.2	11.6	26.9	156	840	0.64	113.9	27.5	82	1.44	60.5	690	12.90
7.52	6.60	3.6	4.5	2.0	7.3	626	520	0.76	125.3	36.5	138	1.01	58.2	634	10.60
16.6	10.88	2.9	4.8	3.7	14.9	1060	860	0.97	106.2	99.5	145	1.81	38.9	290	12.10
13.44	13.38	4.3	3.9	1.9	5.3	1180	380	1.66	96.5	66.3	114	0.55	43.0	281	9.60
16.85	13.95	3.8	7.6	4.4	2.4	422	930	1.81	102.8	53.4	186	0.89	54.8	328	13.50
18.26	9.17	4.5	6.5	4.8	14.9	960	910	0.67	105.7	30.2	97	1.09	43.1	449	13.90
21.09	9.51	2.9	8.6	13.1	15.1	985	710	0.88	80.4	88.5	129	1.20	27.7	179	7.01
23.31	8.12	4.2	4.0	13.3	33.3	129	1160	1.01	120.0	25.1	117	1.73	48.4	386	11.67
15.72	10.11	2.6	8.2	8.8	14.7	355	650	1.09	118.8	21.6	121	1.66	56.2	433	11.36
15.49	4.95	2.6	20.8	5.7	8.3	710	280	0.37	103.7	52.3	101	0.97	50.6	330	11.37
11.59	4.40	1.2	8.3	2.3	3.5	529	550	0.73	102.3	33.4	101	0.61	50.0	264	9.04
20.77	7.53	5.8	31.5	13.8	13.2	635	730	0.66	97.5	66.34	222	1.81	51.5	181	12.10
9.49	3.29	3.6	7.7	3.2	4.8	637	450	0.80	129.7	31.7	127	0.61	66.7	608	12.90
10.29	6.33	1.7	10.1	2.2	3.8	347	670	1.04	141.1	47.6	136	1.00	70.5	495	13.90
15.54	6.66	0.7	66.5	3.5	2.9	430	320	1.61	69.5	14.1	107	0.25	125.4	225	22.50
11.54	6.52	1.0	8.7	6.1	5.4	847	640	0.94	140.8	35.9	125	0.85	77.0	285	16.80
10.27	5.29	4.0	9.4	3.0	3.3	540	520	1.14	132.9	34.6	178	0.60	72.8	490	16.80
9.62	4.96	2.7	22.7	7.3	15.2	496	1090	1.34	82.0	57.5	158	0.47	82.9	481	11.40
12.34	6.79	1.2	14.4	2.7	5.3	796	1260	1.74	148.2	61.3	97	1.50	54.4	324	12.70

netite; G: limonite, hematite; H: schistose mineral; I: aceessory mineral; J: pyrite; K: rock fragment; zoisite. Schistose minerals refer to chlorite, muscovite, biotite, and weathered mica. Having unstable hydrodynamic nature, they are very easy to be suspended in running water, and being mass-deposited only in a low-energy environment. Accessory minerals refer to garnet, apatite, titanite, zircon, and tourmaline. Having stronger antiweathering and stable hydrodynamic properties, they are only concentrated in a high-energy environment. Rock fragments or combination minerals refer to altered ferromagnesian silicate minerals. The last heavy mineral variable is other minerals, including andalusite, basaltic hornblende, glaucophane, orthite phlogopite, actinolite, carbonates, rutile, xenotime, and olivine. Due to their very low content (amounting to about 3 percent) and weak influence on the content of the heavy minerals, they are merged into one variable.

Statistical Analysis and Geological Interpretation

1. Q-mode factor analysis for minerals

A 3-factor model of the heavy mineral assemblages in the study area has been established by way of Q-mode factor analysis. The variance contributions of three common factors are 66.81%, 19.14% and 5.17%, respectively, and cumulative contribution is 91.12%. This shows that the 3-factor model has over 90 percent of the variation information of the heavy minerals. Three common factors represent three heavy mineral assemblages respectively (Fig. 1, Table 2).

Common factor P1 has 13 samples, representing heavy mineral assemblage-type I, and pyroxene, magnetite, and ilmenite occupy a dominant position. Based on location of samples, the variation of accessory mineral content as well as if having pyrite, the type I can be

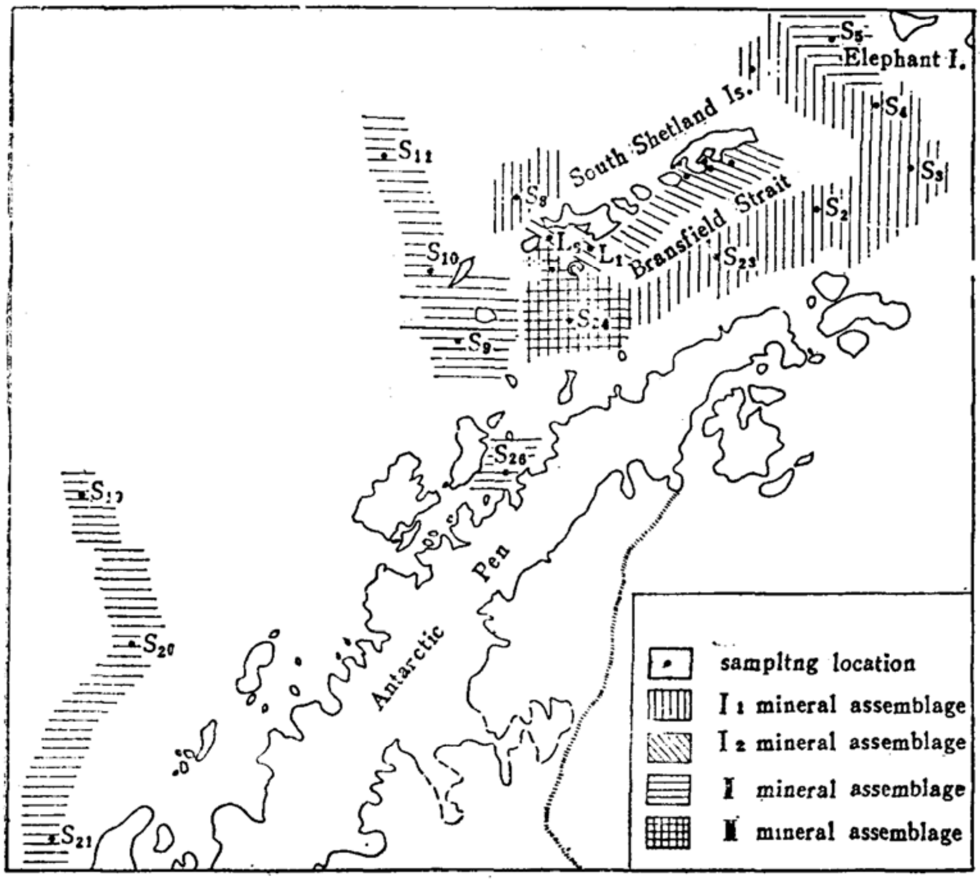

Fig. 1 Map showing locations of samples and zones of heavy mineral assemblages.

further divided into I_1 and I_2 subtypes. The subtype I_1 is distributed in the east of the study area (Fig. 1), and the heavy mineral assemblage is characteristic of being short of pyrite and of higher accessory mineral content (Table 2). In addition to basic volcanic rocks, on the islands of the eastern study area there are also some metamorphic and intermediate acidity rocks, not only providing the sediments of this region with a lot of pyroxene, magnetite and ilmenite, but also with some accessory minerals (Berkenmajer, 1982). It is clear that the subtype I_1 is under the control of sources.

The subtype I_2 is distributed over the bay around the South Shetland Is. and the content of accessory minerals is very low, but the pyrite content much high in the heavy mineral assemblage-type (Fig. 1, Table 2). This assemblage feature fully corresponds to that of the minerals of the propylite and basic volcanic rock which outcrop extensively on the South Shetland Is. The subtype I_2 is, undoubtedly, affected by the source too, at the same time the cold and close bay is also advantageous to the preservation of pyrite.

The common factor P_2 includes 8 samples, and corresponding heavy mineral assemblage-type II, in which rock fragment, green amphibole, and epidote are taken as the dominant component with more schistose minerals, is distributed over the western study area. Such mineral composition should be derived from the weathering products of metamorphic, sedimentary and intermediate acidity rocks on the Antarctic Peninsula (Fig. 1, Table 2).

The common factor P_3 includes only 2 samples, and in the corresponding heavy mineral

Table 2. Contributions of 3-factor variance and types of heavy mineral assemblages.

common factor	variance contribution (%)	accumulative total (%)		heavy mineral (%) assemblage	classification of sample	location
P_1	66.81	66.81	I_1	pyroxene (55.4)-magnetite + ilmenite (13)-rock fragment (8.4)-epidote (6.3)-green amphibole (6.0)-accessory mineral (5.6)	S_2 S_3 S_4 S_6 S_8 S_{23}	east of the study area
			I_2	pyroxene (53.8)-magnetite + ilmenite (11.2)-epidote (8.0)-rock fragment (7.5)-pyrite (4.6)	J R_1 R_4 M_1 M_3 L_1 L_6	bay around South Shetland Is.
P_2	19.14	85.95	II	rock fragment (26.2)-green amphibole (21.30)-epidote (20.2) -pyroxene (15.6)-magnetite + ilmenite (6.3)-schistose mineral (6.1)	S_5 S_9 S_{10} S_{11} S_{19} S_{20} S_{21} S_{26}	west of the study area
P_3	5.17	91.12	III	pyroxene (31.3)-epidote (30.3)-magnetite + ilmenite (12.6)-green amphibole (11.6)-schistose mineral (6.1)	S_{21} S_{25}	west Bransfield Strait

assemblage-type III, main minerals are pyroxene and epidote, and magnetite, ilmenite and green amphibole take the second place. Such an assemblage belongs to a transition type, and its space distribution is also between the assemblage II and the assemblage III, probably results from mixing of two above-mentioned end member assemblages by currents. It is possible that Bellingshausen current transports the sediments of mineral assemblage zone I to the assemblage zone II, when it gets from northwest into Bransfield Strait (Shen Yichu *et al.*, 1988) (Fig. 1, Table 2).

2. R-mode group analysis for heavy minerals

12 kinds of heavy mineral variable are divided into two groups (Fig. 2). The first group is made up of green amphibole, schistose minerals, epidote, titanite, and accessory minerals. They originate from metamorphic, sedimentary and intermediate acidity rocks. The second group includes pyroxene, iron oxide, brown amphibole, and pyrite. They have genetic relationship with basic volcanic rock, and pyrite is often the marker of late alteration and mineralization of this rock.

The result of R-mode group analysis of minerals conforms with that of Q-mode factor analysis, and both show that the detrital sediments in the study area probably come from the source area of two different rocks.

3. R-mode group analysis for REE and trace elements

22 elements are divided into 3 groups and 9 subgroups (Fig. 3, Table 3). This fact shows that elements have genetic relationship with rocks. As shown in Fig. 3 and Table 3, the first

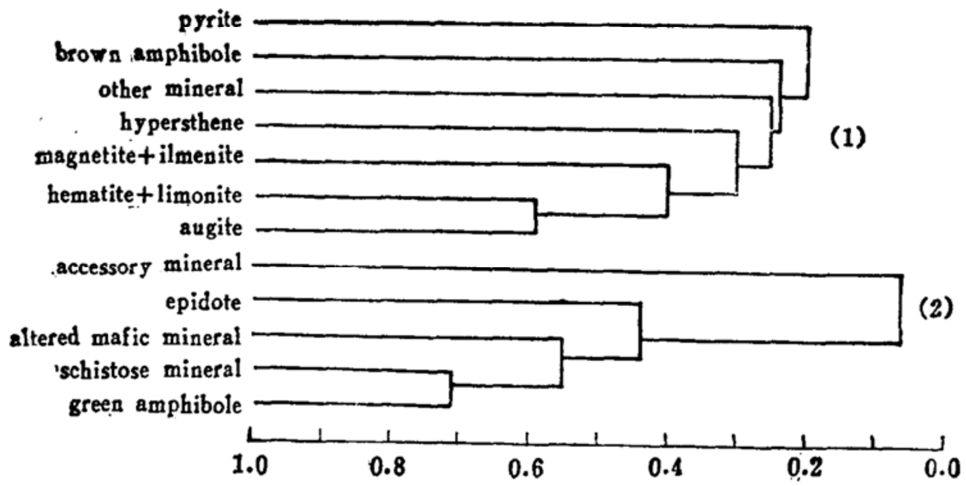

Fig. 2 Genetic association of minerals by R-mode group analysis.

Table 3. Grouping of REE and trace elements by group analysis.

group	element association	subgroup	element subassociation
1	LRE (La+Ce+Na, Eu+Sm) Th, Hf, Ta, Zr, U Ni, HRE (Tb+Yb+Lu) Sr, Rb, Zn	①	La+Ce+Nd, Sm+Eu, Er, Zr, Hf, Th, Ta
		②	U
		③	Tb+Yb+Lu
		④	Ni
		⑤	Sy, Rb
		⑥	Zn
2	Sc, Cr	⑦	Sc
		⑧	Cr
3	Fe, Co, As	⑨	Fe, Co, As

group consists of 17 elements, and most of them are lithophile ones, having exclusive relationship with intermediate acidity rocks. The second and third groups are composed of two and three elements, respectively. They are basically rock-forming and siderophile elements, having exclusive relationship with basic rocks. In Fig. 3, if correlation factor is taken as 0.6, then three groups can be divided into nine subgroups: (1) LRE and Zr, Hf, Th, and Ta; (2)

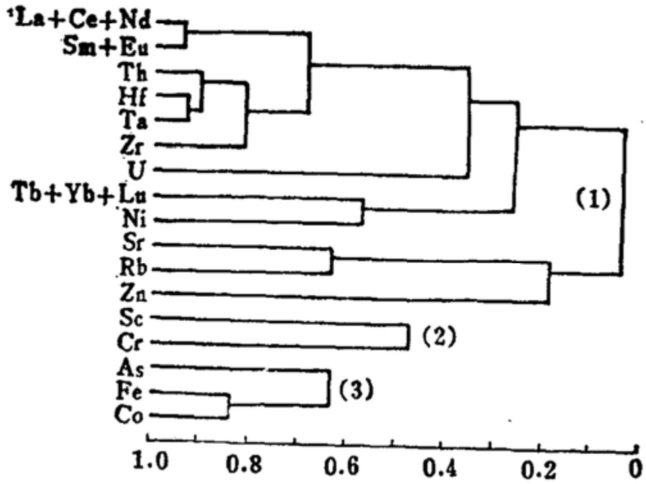

Fig. 3 Paragenetic associations of elements by R-mode group analysis.

U; (3) HRE; (4) Ni; (5) Sr, and Rb; (6) Zn; (7) Sc; (8) Cr; and (9) Fe, Co, and As. These subgroups reflect the elementary difference in geochemical property and the closeness of element association in geological process. The nearer to 1.0 correlation factor, the closer elementary association.

Discussion and Conclusions

1. Relationship between the heavy mineral assemblage-types and element subgroups

In the study area, the heavy mineral assemblages are divided into 4 types, and 22 elements 9 subgroups by way of methods of Q-mode factor and R-mode group analyses. The relationship between assemblages and the subgroups is shown in Fig. 4.

Mineral assemblage I_1 is distributed over the east of the study area, taking pyroxene, magnetite, and ilmenite as dominant minerals, and having more accessory minerals. This area is rich in U, Th, Zr, Hf, Ta, Sc, and Cr.

Mineral assemblage I_2 is located in the bay around the South Shetland Is. Here the main minerals are pyroxene, magnetite, and ilmenite, with more pyrite, and being rich in Fe, Co, As, Ni, Sc, Cr, Sr, and Zn. Heavy mineral assemblage II is situated in the western study area, taking rock fragment, green amphibole, and epidote as dominant minerals, and RE, U, Yh, Rb, Sr, and Zn are quite abundant.

Heavy mineral assemblage III lies in the west of Bransfield Strait. In the assemblage, pyroxene, epidote, magnetite, ilmenite, and green amphibole are much abundant, and the trend of dispersion and enrichment of the subgroup elements is not clear (except Sr). The assemblage is situated between the assemblage I and the assemblage II, having the dominant minerals from both the assemblages I and II and with close content. Therefore, it should be born of transporting and mixing of the east and west end member assemblages by currents.

2. Relationship between the heavy mineral groups and the mother rock

The two heavy mineral groups obtained by way of R-mode group analysis show that the surface sediments of the study area basically come from two kinds of mother rock area. One of them is intermediate acidity, distributed over Elephant Is. (northeast of the study area) and

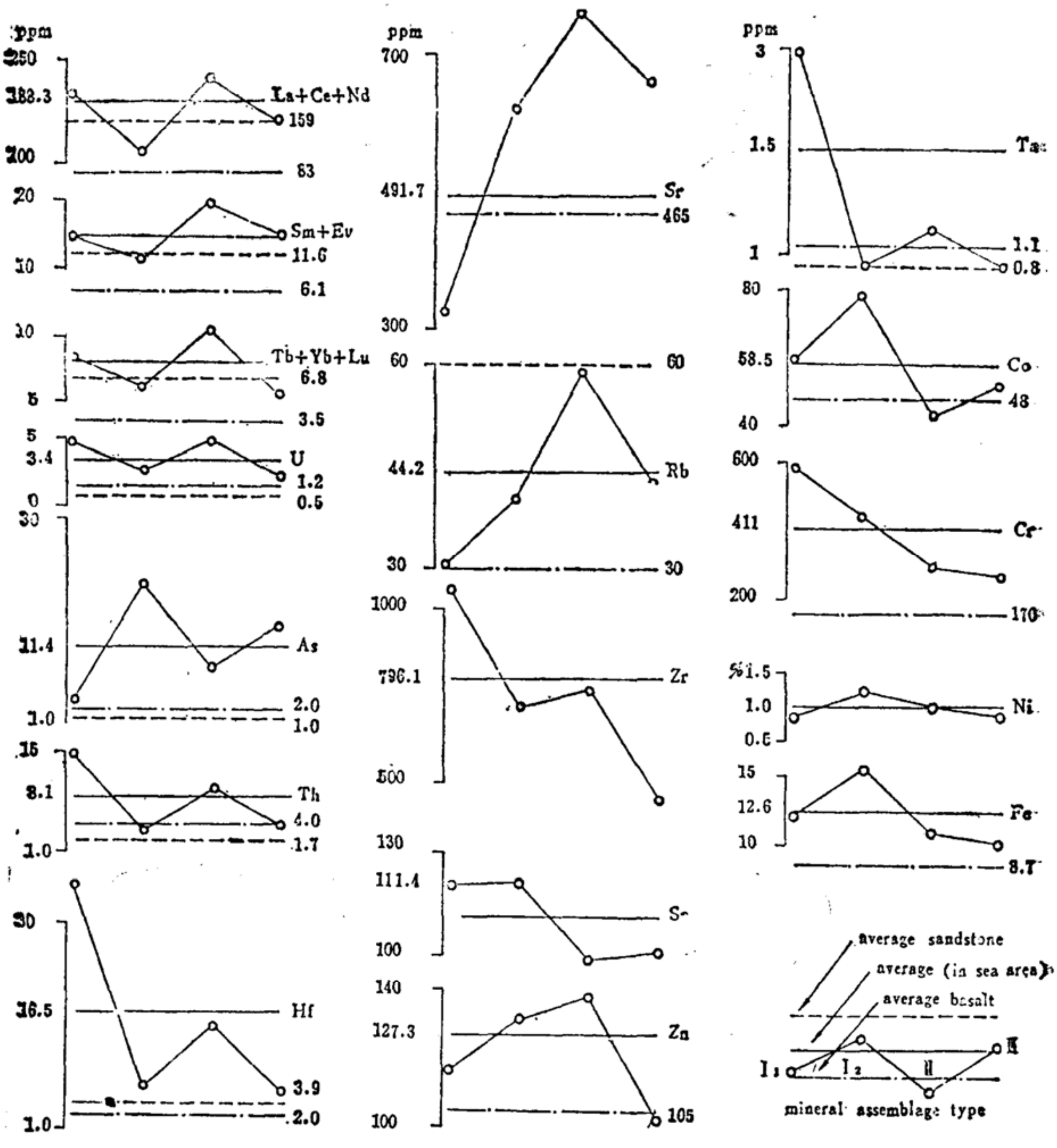

Fig. 4 Correlation between types of heavy mineral assemblages and REE and trace elements.

Antarctic Pen. (southeast of the study area). Characteristic weathering products of this area are green amphibole, epidote, schistose minerals, undissociated altered mafic silicate minerals (rock fragments), and accessory minerals. The other is basic volcanic, namely South Shetland volcanic arc, basalt and basaltic andesite are widely dispersed over it. Characteristic weathering products of it are pyroxene, magnetite, ilmenite, volcanic, and glass. And pyrite is the marker of late alteration and mineralization for this kind of rock.

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