3-3 Flood Basalt Stratigraphy of the Paraná Basin

3-3-1 Classifications of the Paraná Flood Basalts by Chemical Compositions

(1) Geochemical Characteristics of Paraná Flood Basalts

a) Classification of Basalts

Tholeiitic basalt or basaltic andesite accounts for 90 vol% of the entire Paraná flood basalts.

Ruegg (1975) classified basalts into two groups by the TiO_2 content. Subsequently, this is explained as two origin magmas by examining trace elements and isotopic ratios (Atalla et al., 1982; Bellieni et al., 1984; Mantovani et al., 1985).

The definition of the two magmas are recognized by Karoo (Erlanket et al, 1986). Some suggestion is existing for other LIPs around the southern Atlantic Ocean. These characteristics of trace elements and isotopic ratios are defined as "Dupal anomaly" (Hart, 1984).

Piccirillo et al. (1988) divided the Paraná basin into three major sectors after analyzing samples collected from huge area of the basin.

- Southern side of Uruguay River: Rocks include tholeiitic basalt, andesite, and rhyolitic dacite to rhyolite (Palmas type), and their TiO_2 contents are less than 2 % ("Low-Ti" type).
- Northern side of Piquiri River: Rocks include tholeiitic basalt and rhyolitic dacite to rhyolite (Chapeco type), and their TiO_2 contents exceed 2 % ("High-Ti" type).
- Transition zone of the both sides: The TiO_2 content is middle value between southern side and northern side of the Paraná basin.

However, because it was unreasonable to classify lavas by their TiO_2 content, an classification method has been suggested by including some elements to distinguish lava types (Davis, 1986; Peate et al., 1988). The lavas (magmas) were classified 6 types by this method. The elements used for classification included HFS elements (Ti, Zr, Y) which are hard to removed in alteration, and Sr and Ba. Because these elements are incompatible elements, they are characterized by accumulating during fractional crystallization. In addition, their elements ratios used to distinguish magma types by their chemical characteristics.

According to the classification of the six-types magma, three types of magma were distributed in northern part of the Paraná basin. In particular, two types of lavas are dominant in this area. They are "High-Ti" type lava: Pitanga, Paranápanema and Ribeira. Although Pitanga is poor in SiO_2, TiO_2 and K_2O, it is characterized by rich $Fe_2O_{3\,total}$ among "High-Ti" type magma. Also the Sr content is poor. The Sr versus Fe_2O_3 diagram can be used to divide Pitanga and Paranapanema.

"Intermediate-Ti" type indicates 2-3 wt% of TiO_2. Piccirillo et al. (1988) included this classification for the middle part of the Paraná basin. "Intermediate-Ti" type magma is considered as a transition zone between "High-Ti" and "Low-Ti" type magma. According to the classification of Peate et al. (1992), Ti/Y and Zr/Y ratios in Paranapanema are lower compared with those in Pitanga. Thus, the magma type of Paranapanema is classified into a different types.

At first, Fodor et al. (1983) suggested about "Low-Ti" type magma for classification of the Paraná flood basalts. Later, Peate et al. (1988) named magma types Gramado and Esmeralda.

Petrini et al. (1987) proposed a small-scale "Low-Ti" type magma based on the Sr isotopic ratio. This magma is relatively rich in incompatible elements, which is identified in Ribeira according to Peate et al. (1988).

The MgO contents of other two "Low-Ti" type magmas are the same in Ribeira. These two types are characterized by rich TiO_2, Fe_2O_8, P_2O_5 and Sr, and poor SiO_2. In addition, Ribeira is characterized by high Ti/Y and Zr/Y ratios, compared with Gramado and Esmeralda. The "Intermediate-Ti" type magmas as Ribeira and Paranapanema can be classified with the MgO-TiO_2 diagram.

In Petrochemical study, all of the magma types are considered as identical, except Esmeralda. In addition, it is clear that the chemical composition of the Paraná flood basalts and of the basalt in the ocean area are different.

In conclusion, lavas of the Paraná flood basalts are thickest in the center, and the northern part of Paraná basin, and three types of major magmas exist, namely "Pitanga," "Paranápanema" and "Ribeira." The difference of these magma types are explained as the degree of partial melting of the same source mantle. However, a difference of chemical composition is recognized with Gramado, the major magma type in the southern part of the Paraná basin. This is considered as the effect of contamination of crust materials. Moreover, an old and enriched source is suggested by the high Rb/Sr ratio and the low U/Pb ratio of Gramado.

The source magma of Urubicí is similar to the "High-Ti" type magma distributed in the northern part of the Paraná basin.

Meanwhile, Esmeralda is considered to have erupted during continental breakup because the chemical composition of Esmeralda is characterized by asthenosphere.

Pitanga and Urubicí are classified as "High-Ti" type magma. Meanwhile, Paranapanema was classified as "High-Ti" type magma because it has many similar characteristics of "High-Ti" type magma.

Gramado of the "Low-Ti" type magma is distributed widely in the southern part of the Paraná basin, followed by Ribeira and Esmeralda. The magma type of latter phase is characterized by poor trace elements and a high Nd isotopic ratio. Ribeira is similar to Paranapanema and Pitanga in terms of the Ti/Zr ratio and other ratios of trace elements, and they are also related spacially.

b) Classification of Acidic Rocks

In the southeastern part of the basin, in the proximity to a marginal part of the continent, huge volumes of acidic rocks are recognized on the upper part of stratigraphy. The SiO_2 content indicates 60-64 wt%, which is used as a sample of the classification of the Paraná flood basalts. In general, rhyolite exceeds 64% of SiO_2 content, while basalts are considerd as having less than 60 wt% of SiO_2. An existence of acidic rock is predominant in Serra Gaucha in the southeastern part of the Paraná basin. The acidic rock decreases on the northern part of Paraná basin.

Mantovani et al. (1985) divided acidic rocks into two types by using incompatible elements. Subsequently, Bellieni et al. (1986) classified acidic rocks into the Palmas type that has low contents of incompatible elements and the Chapeco type that is rich in incompatible elements. The Chapeco type is characterized by low SiO_2 content and high TiO_2 and P_2O_5 content.

c) Characteristics of Sr and Pb Isotopic Ratios of the Paraná Flood Basalt

Initial ratio of Sr isotope of "High-Ti" type magma in the northern part of the Paraná basin is 0.7055-0.7060. Urubicí tends to be rather high Initial ratio of Sr isotope (Mantvani, 1985; Peate, 1989; Cordani et al., 1989).

The isotopic ratio of "Low-Ti" type magma is characterized by enrichment, affected by the contamination of crust materials. Also, the source is old and enrichment in incompatible elements in the upper mantle.

"High-Ti" type magma in the northern part of the Paraná basin does not enrich. The magma indicates low Nb and Ta contents, compared with ocean crusts.

They may have been formed after separated from the source enriched in the mantle under continental crust. Esmeralda, which has characteristics that is younger than rhyolite in the southern Paraná basin is not similar. Esmeralda is clearly characterized by ocean crusts.

According to the Pb isotopic ratio, all of the Paraná flood basalts are on the reference line of the Northern Hemisphere. Data from India and from the southern Atlantic Ocean are also on the reference line owing to Dupal anomaly.

"High-Ti" type magma is equivalent to 1.8 Ga mantle isochran. Different Pb isotopic ratios of Gramado were considered as indicating assimilation of other magma and fractional crystallization. However, Mantvani and Hawkesworth (1990) proposed an idea as contamination of lithosphere.

For the characteristics of chemical compositions of the Paraná flood basalts, Herget et al. (1991) suggested the effect of sediments transported by the subduction during the Pre-Cambrian age, based on similar characteristics of the isotopic ratios of basaltic rocks in Tasmania. Hawkesworth et al. (1994) considered that the enrichment characterized by a low U/Pb ratio and a high Rb/Sr ratio suggested the contamination of lithosphere. Therefore, isotopic data of Pb and Sr suggested as indicating different tectonic environments, and the possibility of meaning the ratio of mixed materials from the lithosphere and the athenosphere. In other words, "High-Ti" type magmas of the Paraná flood basalts had no effection of contamination of lithosphere because they generated under the Gondowana continent (Hawkesworth et al., 1988).

(2) Application of a Method for Classifying the Paraná Flood Basalts by Peate et al. (1992)

For examining analytical values, we classified collecting basalt lavas into "High-Ti" type (Pitanga, Urubicí), "Intermediate-Ti" or Transition type (Paranapanema-Ribeira) and "Low-Ti" type (Gramado, Esmeralda) based on Peate et al. (1992). Table II-3-3-1 shows the classification of Paraná flood basalt by Peate et al. (1992). Moreover, Table II-3-3-2 shows the results of analysis of basalt lava in this survey.

Note, we grouped "Intermediate-Ti" type as the Paranapanema-Ribeira group because it is difficult to classify into two groups by Peate et al. (1992).

Fig. II-3-3-1 shows the results of classification. The distribution of lava (magma) types depended on our analytical results and the past report is the same.

(3) Examination by Major Elements

Fig. II-3-3-2 shows Mg# (100 Mg/(Mg+Fe total), $Fe^{2+}/Fe^{3+}=0.85$) versus SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O_3, and K_2O diagrams.

Individual diagrams have a clear trend by crystallization differentiation. In particular, trend in crystallization differentiation of "Low-Ti" type magma in the diagram of Al_2O_3 and CaO indicates the change in control from the crystallization of olivine to the crystallization of augite + plagioclase. Existences of different magma types are estimated in diagrams of Mg#-SiO_2, TiO_2, and K_2O, with no relation to crystallization differentiation. Because three

Table II-3-3-1 Classification criteria for basalt magma types (Peate et al.,1992)

	"High-Ti"			"Low-Ti"		
	Urubicí	Pitanga	Paranapanema	Ribeira	Esmeralda	Gramado
SiO_2	> 49	> 47	48 - 53	49 - 52	48 - 55	49 - 60
TiO_2	> 3.3	> 2.8	1.7 - 3.2	1.5 - 2.3	1.1 - 2	0.7 - 2.0
P_20_5	> 0.45	> 0.35	0.2 - 0.8	0.15- 0.50	0.15 - 0.50	0.05 - 0.40
Fe_20_3 total	< 14.5	12.5-18	12.5 - 17	12 - 16	12 - 17	9 - 16
Sr	>550	>350	200 - 450	200 - 375	<250	140 - 400
Ba	>500	>200	200 - 650	200 - 600	90 - 400	100 - 700
Zr	>250	>200	120 - 250	100 - 200	65 - 210	65 - 275
Ti/Zr	> 57	> 60	> 65	>65	>60	
Ti/Y	>500	>350	>350	>300	<330	<330
Zr/Y	> 6.5	> 5.5	4.0 - 7	3.5 - 7.0	2.0 - 5.0	3.5 - 6.5
Sr/Y	> 14	> 8	4.5 - 15	5 - 17	< 9	<13
Ba/Y	> 14	> 9	5 - 19	6 - 19	< 12	<19

Table II-3-3-2 Analytical results of major, trace and metal elements for Paraná flood basalts in this survey

Lava type	Low-Ti				Intermediate-Ti		High-Ti			
	Gramado		Esmeralda		Paranapanema-Ribeira		Pitanga		Urubicí	
Number of samples	19		9		32		5		1	
	Avarage	Range	Avarage	Range	Avarage	Range	Avarage	Range	Avarage	Range
Major elements (wt%)										
SiO_2	54.11	52.25-57.63	51.94	50.81-53.48	50.79	49.65-52.64	49.96	49.33-50.85	51.60	---
Al_2O_3	13.86	12.28-15.85	13.84	13.16-14.92	13.19	12.35-13.96	12.51	11.81-12.83	13.31	---
Fe_2O_3	12.60	10.16-15.90	13.10	11.78-14.54	14.62	12.62-16.16	15.61	15.31-15.91	13.42	---
MnO	0.18	0.15-0.22	0.21	0.19-0.22	0.21	0.18-0.24	0.22	0.21-0.24	0.17	---
MgO	5.03	3.10-6.70	5.78	4.26-6.43	5.50	4.09-6.47	4.95	4.13-6.82	4.15	---
CaO	8.57	6.75-10.15	10.17	8.22-10.99	9.66	8.38-10.76	8.71	8.20-9.40	8.07	---
Na_2O	2.62	2.25-3.33	2.56	2.44-2.76	2.51	2.32-2.87	2.62	2.33-2.71	2.56	---
K_2O	1.49	0.84-2.84	0.88	0.49-1.43	1.10	0.75-1.45	1.47	1.20-1.64	1.89	---
TiO	1.35	0.99-1.98	1.36	1.21-1.72	2.16	1.67-2.60	3.45	2.69-3.77	4.22	---
P_2O_5	0.18	0.13-0.27	0.16	0.12-0.21	0.25	0.18-0.33	0.50	0.32-0.58	0.61	---
Mg #	64.55	48.26-75.10	67.10	57.72-70.95	63.47	54.12-70.52	59.16	55.67-66.74	59.04	---
Trace elements (ppm)										
Ba	337	202-685	194	112-296	312	238-363	465	376-559	683	---
Sr	208	123-243	179	162-213	313	229-381	400	378-412	801	---
Y	34	22-105	29	26-37	31	23-42	35	28-38	38	---
Zr	142	92-183	115	82-93	156	120-198	223	196-250	343	---
Nb	11	7-17	7	5-10	14	10-19	24	19-26	31	---
Ti/Zr	57	40-75	73	62-98	84	75-96	93	82-110	74	---
Ti/Y	259	97-313	280	257-311	426	358-497	594	569-651	665	---
Zr/Y	5	1.5-5.8	4	3.2-4.5	5	4.6-5.7	6	5.9-7.1	9	---
Sr/Y	7	2-10	6	5-8	11	6-16	12	11-14	21	---
Ba/Y	11	3-20	6	4-9	10	8-13	13	13-15	18	---
Cu	139.41	58-250	165.92	132-204	230.94	172-308	185.08	152-209	226.13	---
Ni	48.29	23-117	50.31	28-63	53.17	26-87	39.92	22-73	40.26	---
Pd (ppb)	6.95	0.16-14.09	9.92	6.31-13.46	15.50	6.24-22.35	0.48	<0.1-1.26	6.95	---
Pt (ppb)	6.36	0.31-15.17	5.10	2.31-11.96	9.67	4.04-18.11	0.44	0.15-0.62	3.68	---
Au (ppb)	7.71	0.75-68.59	2.81	1.35-4.10	5.03	1.34-9.06	1.14	<1-2.68	5.19	---
Isotope										
$^{143}Nd/^{144}Nd$	0.51219	0.51213-0.51226	0.51233	0.51226-0.51241	0.51227	0.51225-0.51233	0.51227	---	0.51228	---
$^{87}Sr/^{86}Sr$	0.70928	0.70815-0.71022	0.70633	0.70619-0.70643	0.70582	0.70560-0.70602	0.70548	---	0.70512	---
ε Nd	-8.7	-7.5 - -9.8	-6.0	-4.4 - -7.4	-7.2	-7.6 - -6.0	-7.2	---	-6.9	---
ε Sr	67.9	51.8-81.2	26.0	23.9 - 27.4	18.8	15.6 - 21.6	13.9	---	8.8	---

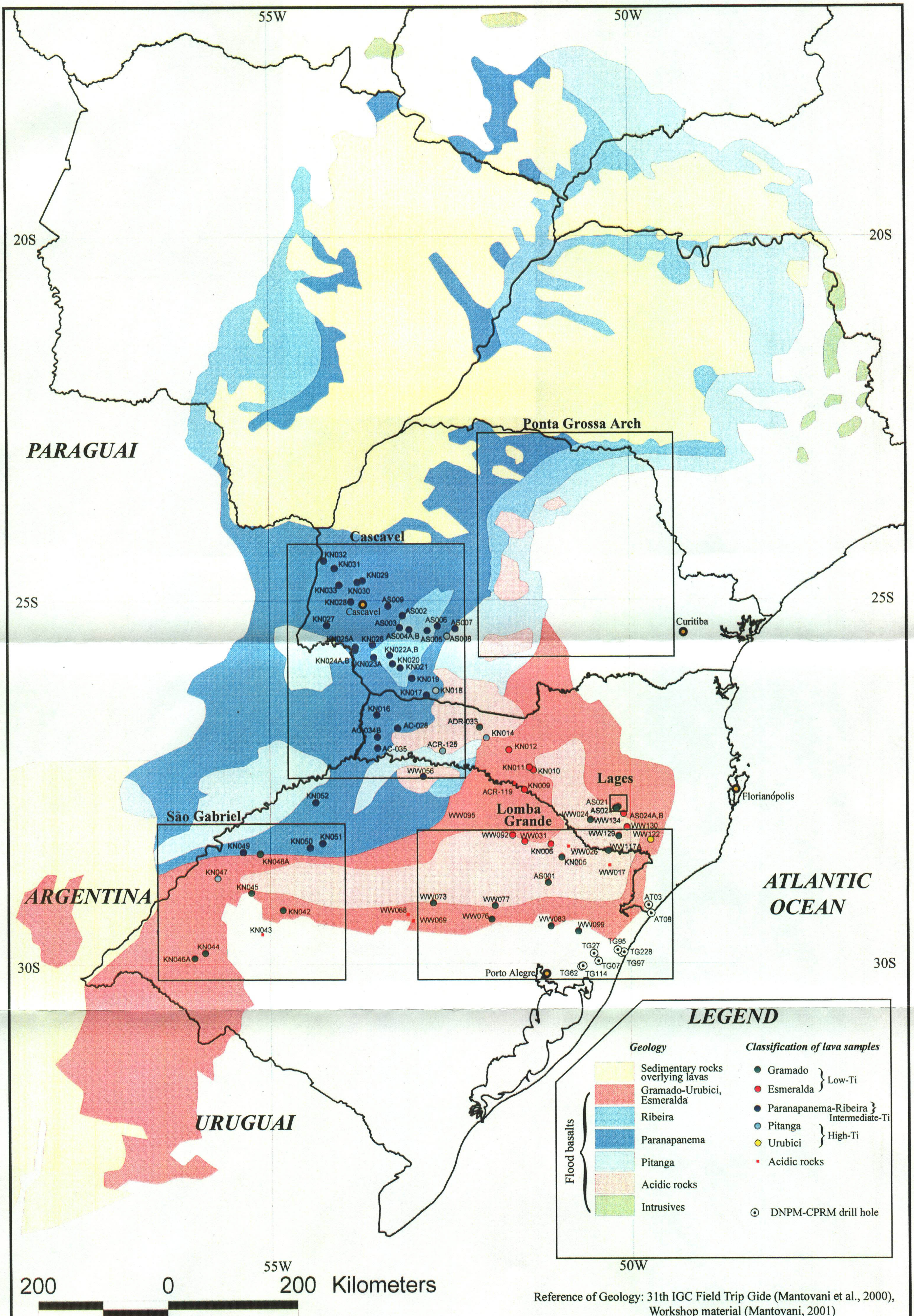


Fig. II-3-3-1 Distribution of classified lava samples and Paraná flood basalts

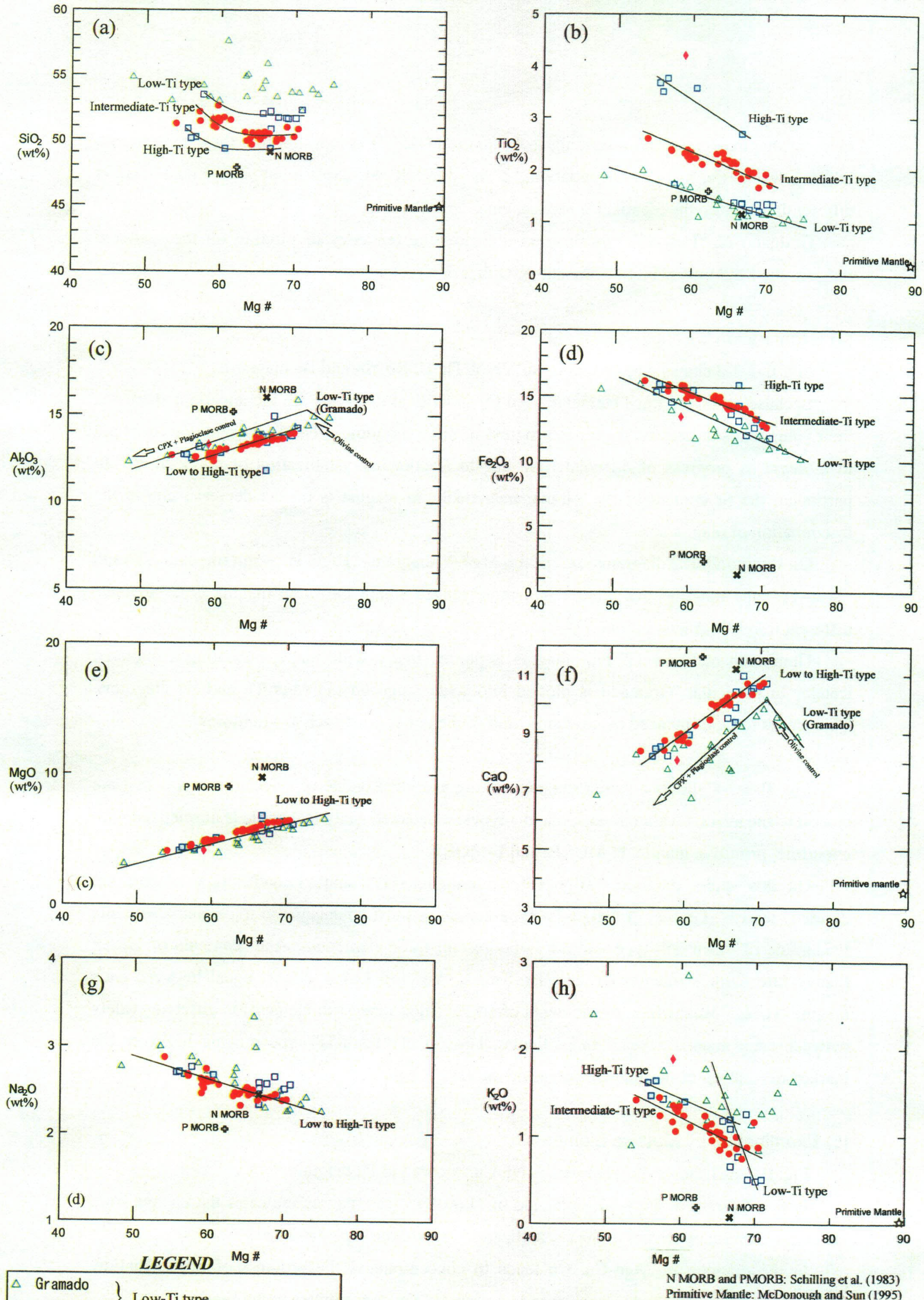


Fig. II-3-3-2 Selected variation diagrams of major elements for lava samples

(a) Mg# vs SiO2, (b)Mg# vs TiO2, (c)Mg# vs Al2O3, (d)Mg# vs Fe2O3, (e)Mg# vs MgO, (f)Mg# vs CaO, (g)Mg# vs Na2O, (h)Mg# vs K2O.

types of magmas classified according to Peate et al. (1992) are plotted into three ranges with keeping each trend in differentiation, it is difficult to explain by the crystallization differentiation from the identical source magma.

Gramado of "Low-Ti" type magma indicates the tendency of plotting on the scattered range in the Mg# versus SiO_2, TiO_2, and K_2O diagram.

(4) Examination by Trace Elements

Fig. II-3-3-3 shows a Mg# versus Nb, Zr, Y, Th, U, Rb, Sr, and Ba diagrams.

Because all of the trace elements used for individual diagrams are incompatible elements, their value tends to become higher as progress of differentiation. The Sr content does not tend to increase as progress of differentiation due to fractional crystallization of plagioclase. In particular, the Sr content of the Paranapanema-Ribeira magma is on the decrease due to the fractionation of plagioclase.

On the individual diagrams except the Mg#-Y diagram, "High-Ti", "Intermediate-Ti" and "Low-Ti" type magmas are plotted into three ranges where the three magma types indicate different trends in fractionation.

Gramnodo of "Low-Ti" type magma is plotted into a wide range, indicating a scattered trend. In particular, Gramado is plotted into wide range on the Mg#-Th and -U diagrams. This means to be influenced by contamination of the upper crust such as granitoids.

Fig. II-3-3-4 shows a spider diagrams using analytical value of selected samples that are closest to the average value of each magma types. Selected analytical value is normalized with chondrite, primitive mantle, N-MORB, and E-MORB.

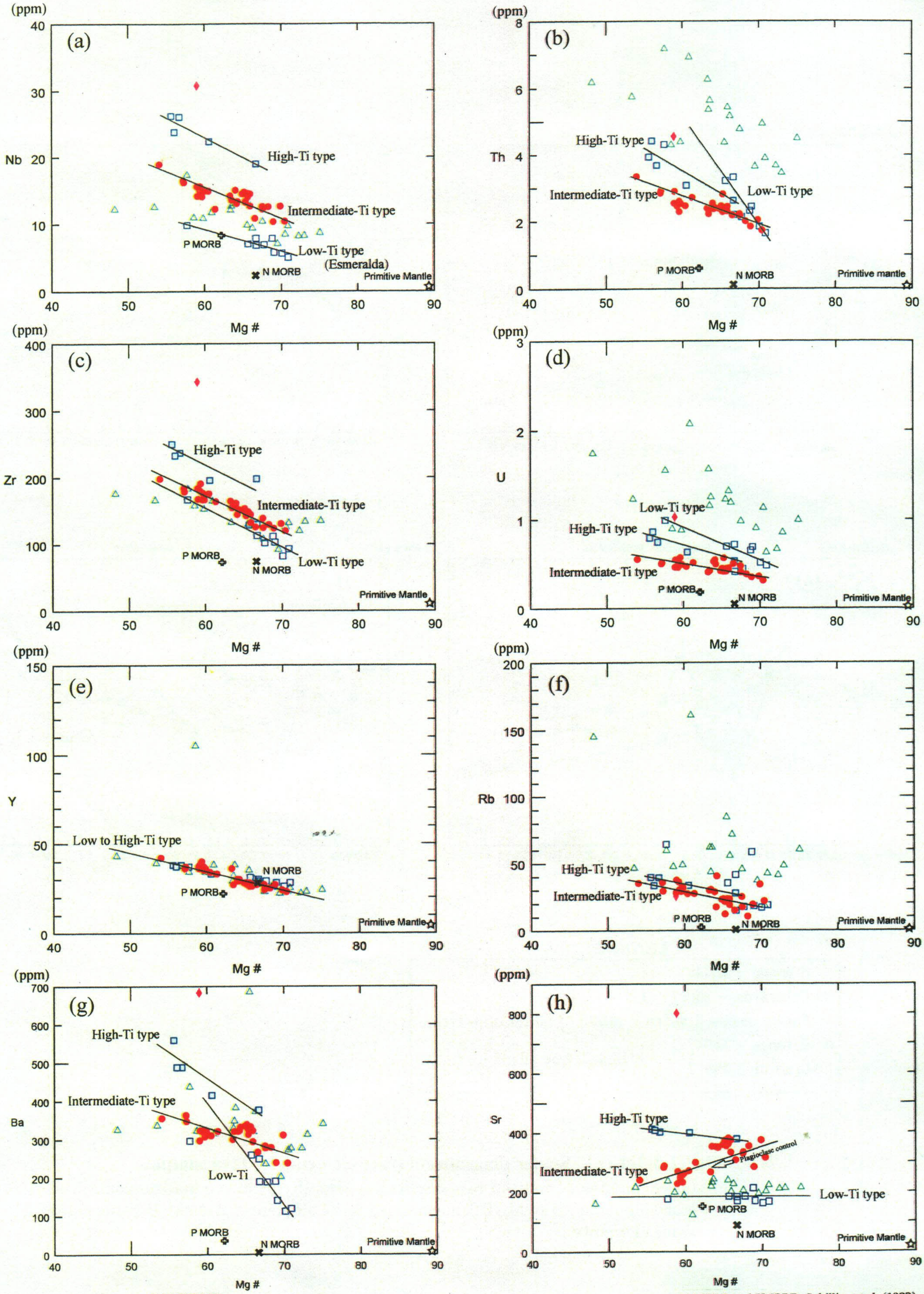
On this spider diagram, "High-Ti", "Intermediate-Ti", and "Low-Ti" type magma are divided clearly. Urubicí of "High-Ti" type magma is most abundance in trace elements while Esmeralda of "Low-Ti" type magma is poorest in trace elements. And, contents of HREE (heavy rare earth elements: Dy, Ho, Er, Tm, Y, Yb, and Lu) is almost equal between each magma types. Meanwhile, the contents of LREE (light rare earth element) is different widely between each magma types. In particular, Urubicí of "High-Ti" type magma indicates the marked decreasing of normalized values on the HREE part.

(5) Examination by Metallic Elements

Fig. II-3-3-5 shows the Mg# versus Ni, Cu, Au, Pt and Pd diagram.

In the diagram of Mg#-Ni, Gramado of "Low-Ti" type magma indicates the change from the crystallization of olivine to the crystallization of pyroxne + plagioclase.

In the diagram of Mg#-Cu, Cu tends to concentrate as the progress of differentiation. Because Cu is not captured by rock-forming minerals, Cu concentrates in the liquid.



N MORB and PMORB: Schilling et al. (1983)
Primitive Mantle: McDonough and Sun (1995)

LEGEND

△ Gramado	} Low-Ti type	
□ Esmeralda		
● Paranapanema-Ribeira	} Intermediate-Ti type	
□ Pitanga	} High-Ti type	
♦ Urubici		

Fig. II-3-3-3 Selected variation diagrams of trace elements for lava samples

(a) Mg# vs Nb, (b) Mg# vs Th, (c) Mg# vs Zr,
(d) Mg# vs U, (e) Mg# vs Y, (f) Mg# vs Rb,
(g) Mg# vs Ba, (h) Mg# vs Sr.

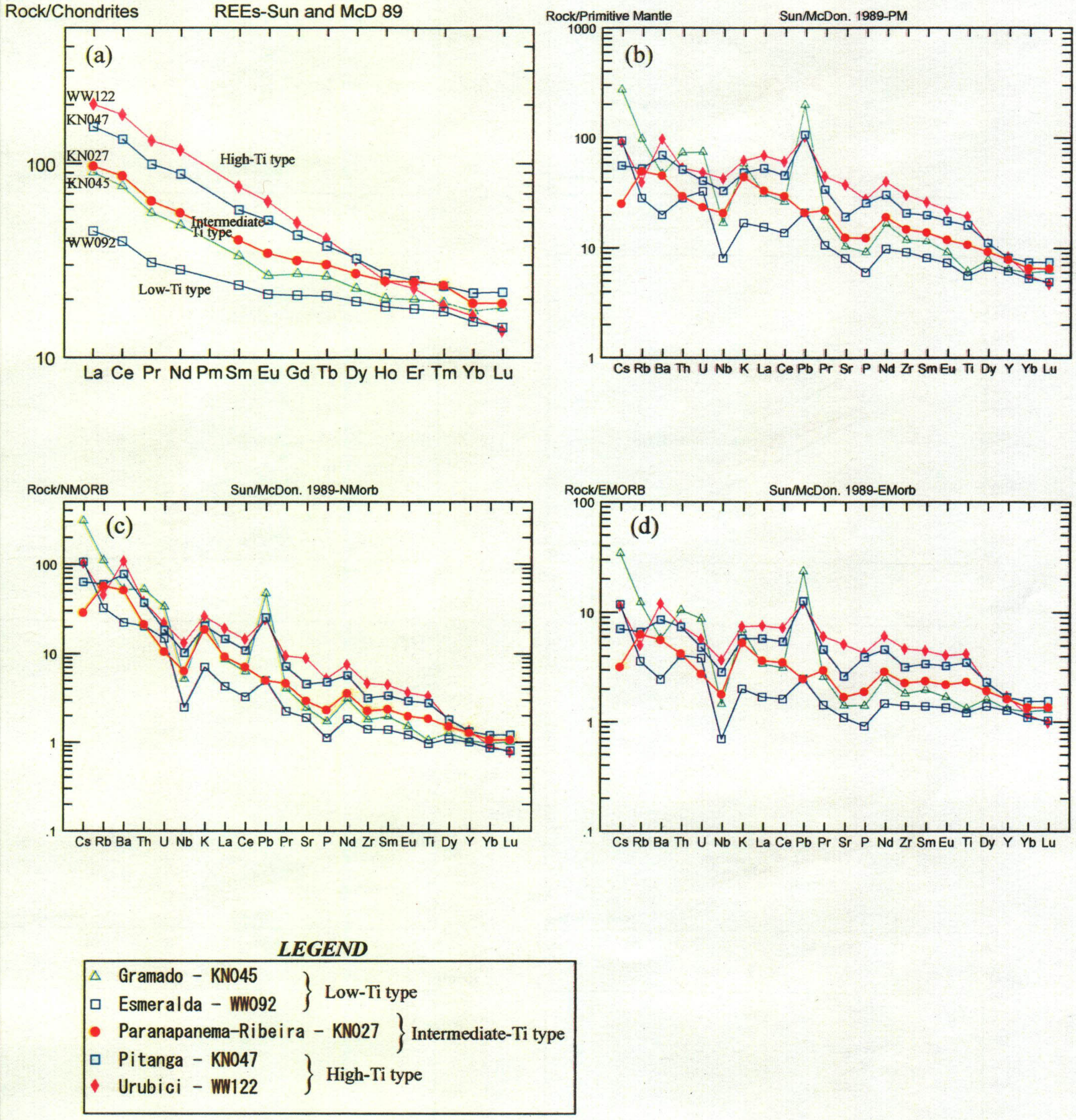


Fig. II-3-3-4 Spider diagrams of trace elements for lava samples

(a) chondrites-nomalized rare earth elements, (b) primitive mantle-nomalized trace elemens, (c) N-MORB-normalised trace elements, (d) E-MORB-normalized trace elements.

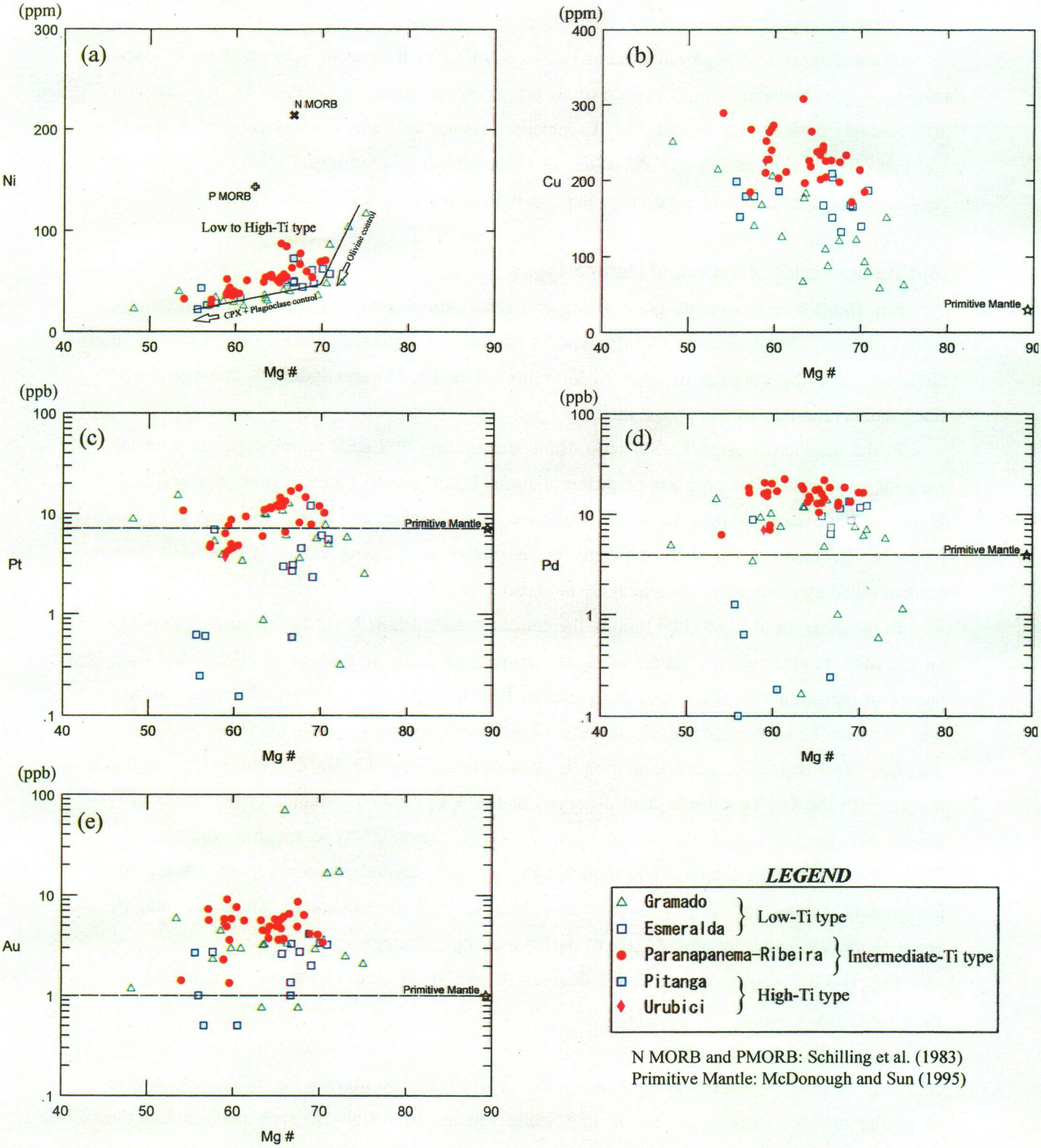


Fig. II-3-3-5 Selected variation diagrams of metallic elements for lava samples

(a) Mg# vs Ni, (b) Mg# vs Cu, (c) Mg# vs Pt, (d) Mg# vs Pd, (e) Mg# vs Au.

"Intermediate-Ti" type magma is most abundance in Cu.

In the diagrams of Mg#-Au, Pt and Pd, Paranapanema-Ribeira of "Intermediate-Ti" type magma is most abundance in Pt and Pd of all magma types, meanwhile "High-Ti" type magma are relatively poor in Au, Pt and Pd. Especially, Pitanga indicates the low content of Au, Pt and Pd. In addition, the Pt and Pd values of Gramado are plotted into a wide range with no relation to fractionation, and are divided into the PGE rich type and PGE poor type.

(6) Characteristics of Individual Magma Types

Fig. II-3-3-6 shows the diagram of Mg # -La/Sm ratio which represents LREE (light rare earth elements), the diagram of the Mg#-Gd/Yb ratio which represents HREE (heavy rare earth elements), and the diagram of Mg#-Nb/Zr ratio. The Nb/Zr ratio indicates the degrees of fractional crystallization and partial melting.

In the diagram of Mg#-La/Sm ratio, the concentration of LREE varies depending on the each magma types. As progress of differentiation, LREE concentrates. Thus, Esmeralda of "Low-Ti" type magma may be most primitive magma relatively in the all magma types. Likewise, Gramado of "Low-Ti" type magma is plotted into a wide range, it may have been contaminated by crust materials which are abundance in LREE.

In the diagram of Mg#-Gd/Yb ratio, the concentration of HREE varies distinctly depending on the each magma types. "High-Ti" type magma tend to be abundance in HREE, and their degree of partial melting may have been smaller than those of "Low-Ti" type magma. In this way, Nb and Zr have a different distribution coefficient between mantle materials and basalt magma. The degree of partial melting is well indicated by the Nb/Zr ratio. The similar tendency to the Gd/Yb ratio is also observed at the Nb/Zr ratio. Magma types presumably having the largest degree of partial melting are of "Low-Ti" type magma, followed by "Intermediate-Ti" type magma, and then "High-Ti" type magma. In our survey, the magma presumably having the largest degree of partial melting is Esmeralda while the magma presumably having the smallest degree of partial melting is Pitanga.

Fig. II-3-3-7 shows a diagram of degrees of partial melting, estimated by applying the Ba/Ca and Sr/Ca ratios.

In this diagram, the degree of partial melting are distinctly divided into three groups, covering "High-Ti" to "Low-Ti" type magmas. "Low-Ti" type magma had the largest degree of partial melting, ranking on 30 % line while Pitanga of "High-Ti" type magma had the smallest degree of partial melting, ranking on 10 % line. Paranapanema-Ribeira of "Intermediate-Ti" type magma placed middle, ranking on some 20% line. The results match the examination which rare earth elements were used.

Fig. II-3-3-8 shows a diagram which studied characteristics of the magmas, using the Ta/Yb and Th/Yb ratios and the Zr/Nb and Y/Nb ratios.

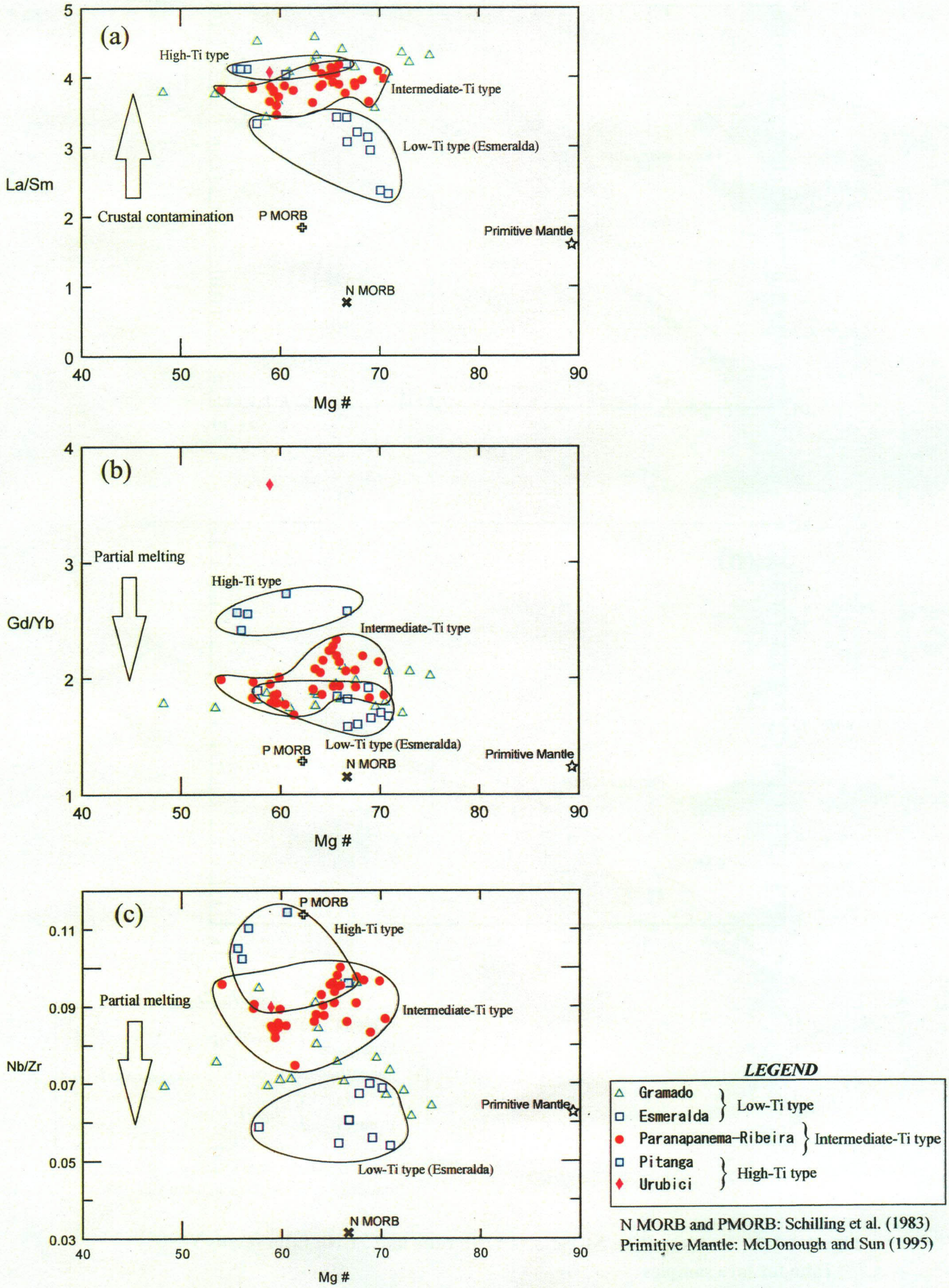
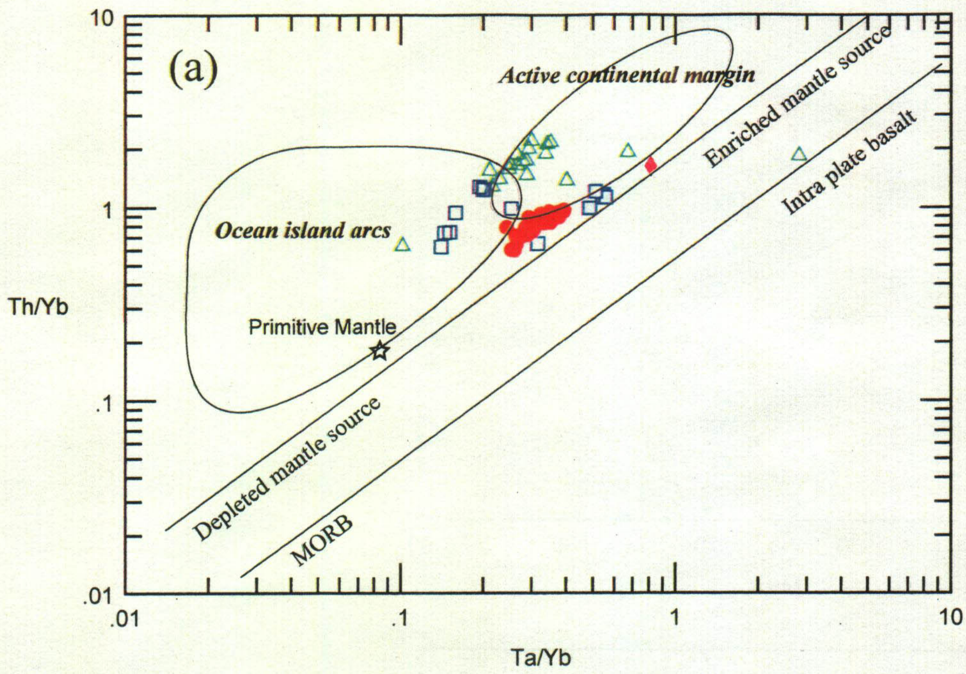
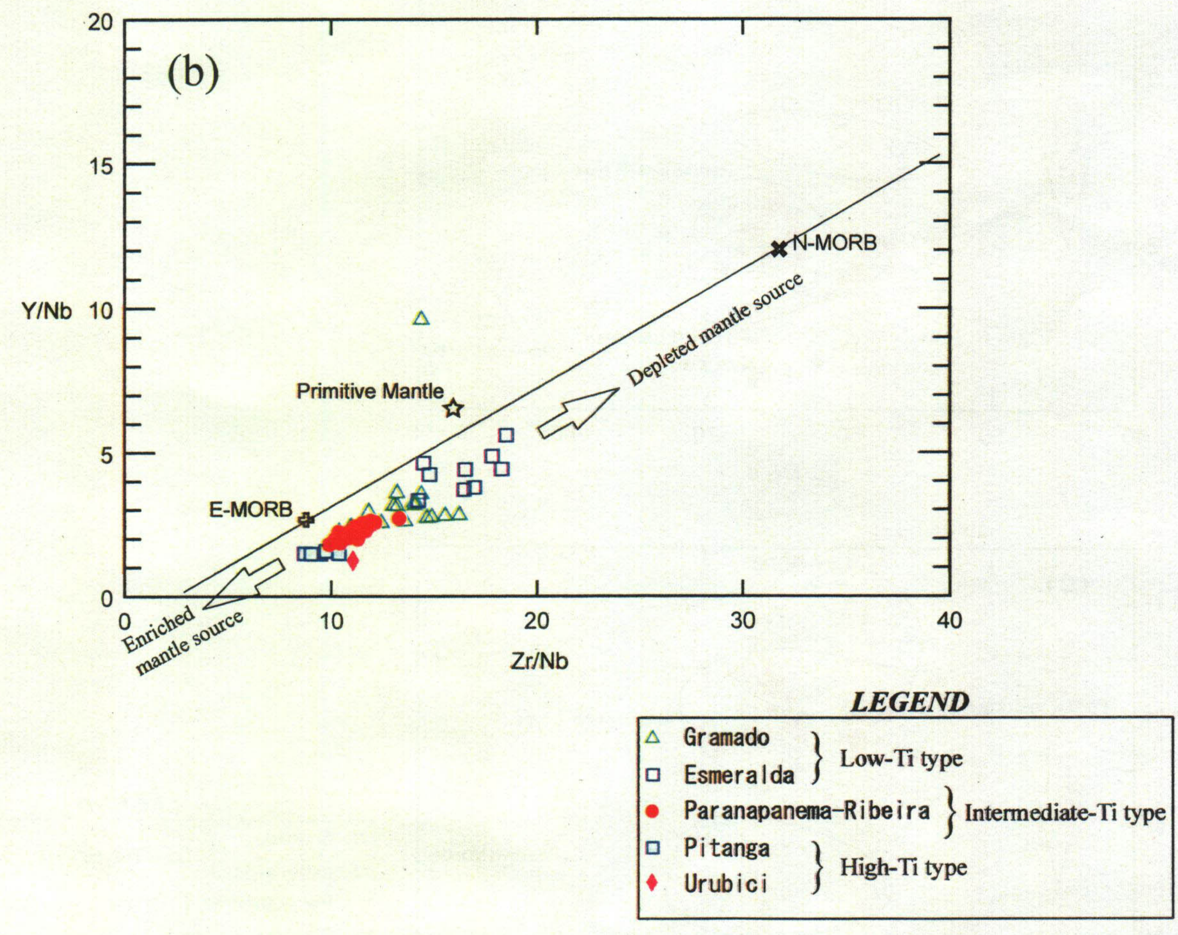


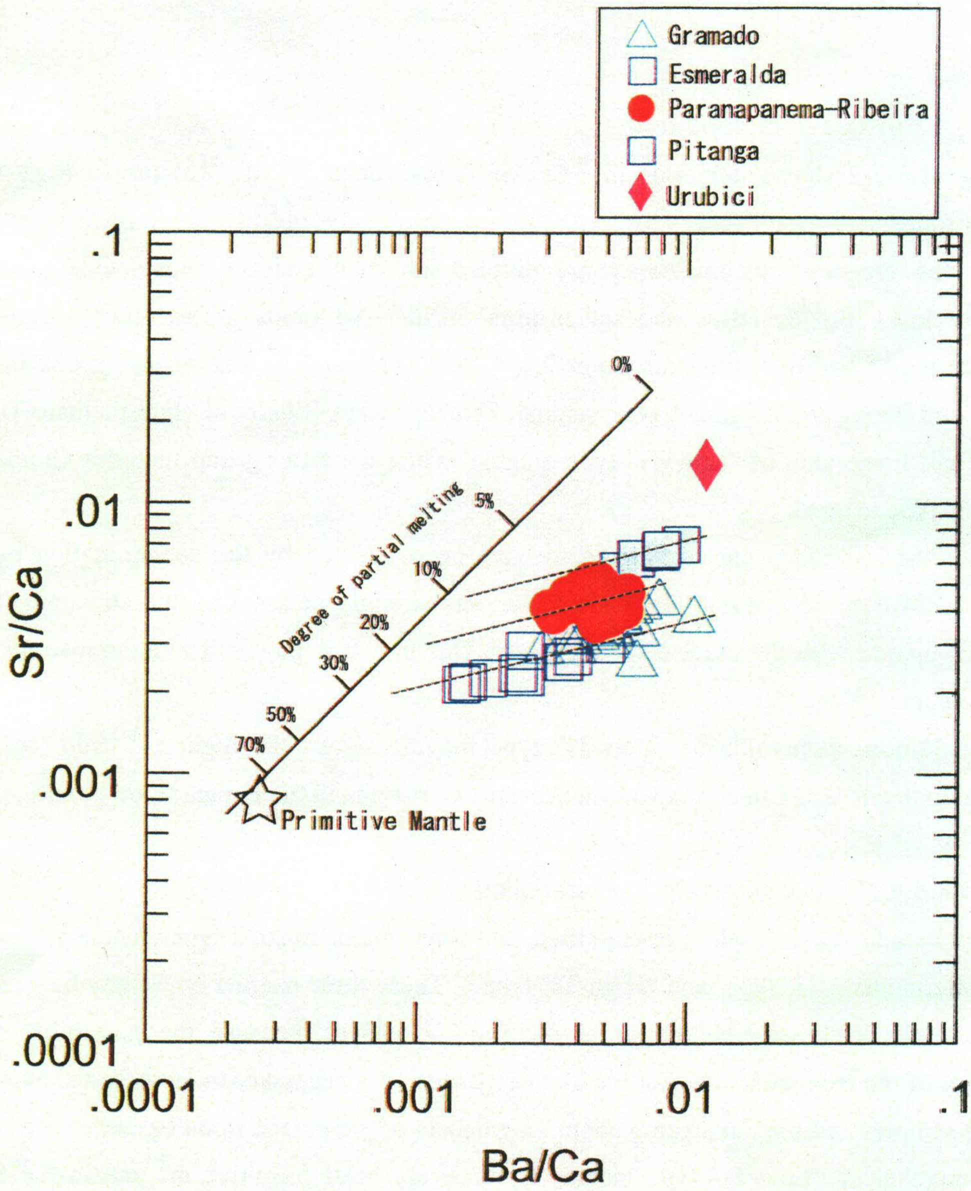
Fig. II-3-3-6 Plots of Mg# vs La/Sm ratio, Mg# vs Gd/Yb ratio and Mg# vs Nb/Zr ratio for lava samples





N MORB and PMORB: Schilling et al. (1983)
Primitive Mantle: McDonough and Sun (1995)

Fig. II-3-3-7 Plots of Ta/Nb ratio vs Y/Nb ratio and Zr/Nb ratio versus Y/Nb ratio for lava samples



(From Onuma and Montoya, 1984)

Fig. II-3-3-8 Plots of Ba/Ca vs Sr/Ca for lava samples

According to these diagrams, Pitanga of "High-Ti" type magma is characterized by most enriched source, whereas Esmeralda of "Low-Ti" type magma is characterized by most depleted source.

(7) Characteristics of Isotope ratios

Fig. II-3-3-9 shows diagrams of $^{87}Sr/^{86}Sr$ ratios versus $^{143}Nd/^{144}Nd$ ratios, Mg# versus $^{87}Sr/^{86}Sr$ ratios and $^{143}Nd/^{144}Nd$ ratios.

On the diagrams, magma types are divided into two major groups. One group has relatively low $^{87}Sr/^{86}Sr$ ratios and rather high $^{143}Nd/^{144}Nd$ ratios. The other groups have relatively high $^{87}Sr/^{86}Sr$ ratios and rather low $^{143}Nd/^{144}Nd$ ratios. The former group includes Urubicí and Pitanga of "High-Ti" type magma, Paranapanema-Ribeira of "Intermediate-Ti" type magma and Esmeralda of "Low-Ti" type magma, while the latter group includes Gramado of "Low-Ti" type magma.

The $^{87}Sr/^{86}Sr$ ratios are considered to have been affected by the contamination of crust materials. We could say that Gramado alone was strongly affected by the contamination of crusts, compared with the other magma types. This matches the result of examinations using trace elements.

In addition, Esmeralda of "Low-Ti" type magma shows the highest $^{143}Nd/^{144}Nd$ ratio. This may indicate that Esmeralda was most primitive magma in the Paraná flood basalt.

(8) Summary of Geochemical Characteristics

The Paraná flood basalts are classified into three major magma types, namely "Low-Ti" type, "Intermediate-Ti" type, and "High-Ti" type. These three magma types may be generated by difference of the degree of partial melting. However, because the possibility of the differance of the magma source can not be disregarded, it is necessary to increase the number of analysis samples and keep analyzing about magmatism of the Paraná flood basalt.

Esmeralda of "Low-Ti" type magma is relatively most primitive magma in the Paraná flood basalts. Likewise, Gramado of "Low-Ti" type magma indicates the effection of contamination of continental crusts larger than the other magma types in Paraná flood basalt.

Among the magma types, Paranpanema-Ribeira of "Intermediate-Ti" type magma is relatively abundant in Cu, Au, Pt and Pd, while "High-Ti" type magmas are relatively poor in these elements. Gramado of "Low-Ti" type magma is subdivided into two groups. one group is characteristics by enrichment of Pt and Pd, and another group is characteristics by depletion of Pt and Pd. This may indicate PGE segregation by the effection of contamination of crust materials.

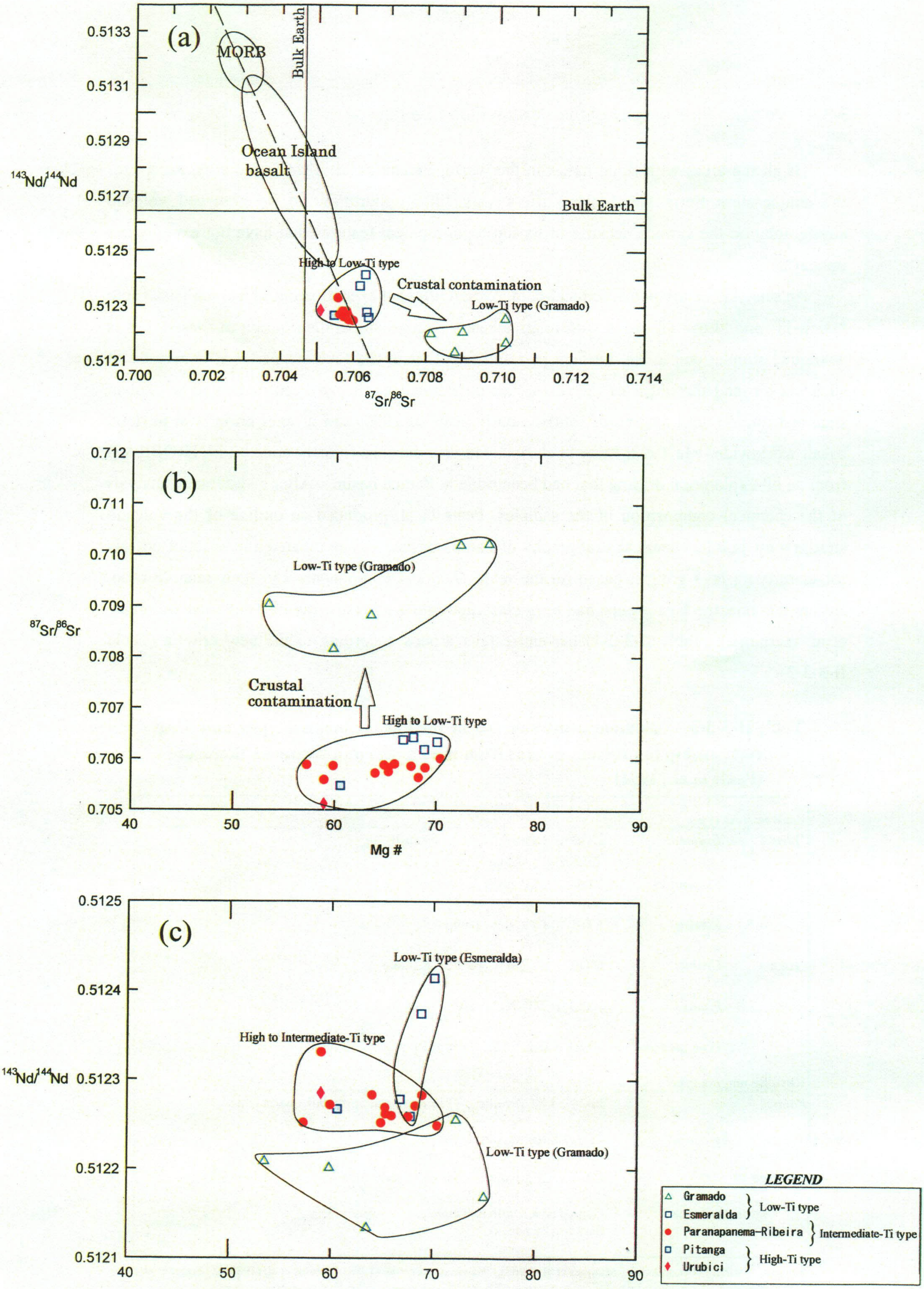


Fig. II-3-3-9 Plots of $^{87}Sr/^{86}Sr$ ratio and $^{143}Nd/^{144}Nd$ ratio for lava samples

(a) $^{87}Sr/^{86}Sr$ vs $^{143}Nd/^{144}Nd$, (b) Mg# vs $^{87}Sr/^{86}Sr$, (c) Mg# vs $^{143}Nd/^{144}Nd$.

3-3-2 Volcano Stratigraphy of the Paraná Flood Basalt

Of all the areas with flood basalt in the world, Paraná basalt distribution area, except for the southeastern Serra Geral area, offers very little opportunity to be observed volcano stratigraphy on the surface because of its flat topographical features that have not experienced upheaval.

An analysis of the petrochemical composition allowed classification of Paraná basalt into "High-Ti" and "Low-Ti" types with relative ease. Geographical distribution of these types is also quite simple: one in the northern part and the other in the southern part. It is because of such background that most of the researches on Paraná basalt had been dedicated to explain such distribution until the end of 1980s. Early years of 1990s saw a renewed interest in flood basalt worldwide. In 1992, Peate et al. obtained drill cuttings (mostly done by PETROBRAS) from an oil exploration drilling that had been done in Paraná basin. After a systematic analysis of the chemical composition of the samples, Peate et al. produced an outline of the volcano stratigraphy, that is, chemical stratigraphy of Paraná basalt. They created a new set of criteria for classifying lava groups, based on the main chemical components and their relative ratio. Before this one, the lava groups had been classified into a diverse array of categories, but Peate et al. rearranged (Table II-3-3-1) the entire lava groups according to the new criteria (Table II-3-3-3).

Table II-3-3-3 Nomenclature scheme for the Paraná magma types, and their relationship to previous groups from the Paraná and Etendeka literature (Peate et al., 1992)

Bsalt magma types		
"Low-Ti"	*Gramado*	LTiB[1], LTi(S)[2], LPT[3], sector II[5], Tafelberg[9], Albin[9]
	Esmeralda	LTiB[1], LTP upper[4], sector I[5]
	Ribeira	LTiB[1], LTi(N)[2], group A[6]
"High-Ti"	*Urubici*	HTiB[1], HTi(S)[2], HPT[3], Khumib[10]
	Pitanga	HTiB[1], HTi(N)[2], HPT[3],
	Pranápanema	HTiB[1], IPT[3], ITi[7], sector III[5]
Rhyolite magma type		
Palmas		PAV[8], LPT rhyolite[3], Taferberg and Springbok quartz latite[9],
new subgrouops:		Santa Maria, Caxias do Sul
Chapecó		CAV[8], HPT ryolite[3], Sarusas quartz latite[10]
new subgrouops:		Guarapuava, Ourihos (Paraná); Sarusas (Etendeka)

Sources: [1] Bellieni et al. (1984a), [2] Marques et al. (1988), [3] Hawkesworth et al. (1988), [4] Peates et al. (1988b), [5] Fodor et al. (1985), [6] Petrini et al. (1987), [7] Mantovani et al. (1988), [8] Bellieni et al. (1986), [9] Erlank et al. (1984), [10] Duncan et al. (1988)

The chemical stratigraphy by Peate et al. is based on the chemical analysis of the drilling core, however, they disclosed only a portion of the analysis. Therefore we have not been able to verify the new criteria with certainty. We acquired samples and conducted classification according to the new criteria and found that the criteria allowed us to classify approximately 80% of the lava group. We still have to verify the appropriateness of stratigraphic classification and improve the accuracy of the stratigraphy criteria. In order to do so, we will need a three-dimensional analysis that uses not only surface samples but also more of borehole. And we believe that it is desirable that trace elements included in chemical analysis.

Fig. II-3-3-10 shows the distribution of lava types in the eight drill holes in Paraná basin. This information is based on the data supplied by Peate et al. (1992). Please note that the vertical axis of the diagram represents 1.5 km in length and the horizontal axis that links eight drills extends 700 km. At the southern rim of the basin, where basement is shallow, Gramado type and Esmeralda type lava, both of which are "Low-Ti" type, spreads towards the northern basin for about 400 to 500 km. Both Pitanga type and Paranapanema type lava overlying Gramado and Esmeralda, which are classified as "High-Ti" type, were tracked 600 km. They occupy the center of Paraná basin and a portion of these flows is over flown to the south.

Stewart et al. (1966) presented the Ar-Ar dating results on the four drill-holes sample in Paraná basin and from the surface. They concluded that the active period of Paraná basalt extended to 10 Ma. According to a three-dimensional distribution of dating data, they concluded that the igneous activity moved toward southeastern part from the northwestern part and led to the forming of the Atlantic Ocean.

Fig. II-3-3-10 also shows all dated results on drill holes based on the paper by Stewart et al. (1996) juxtaposed to the stratigraphy by Peate et al. Compared in this way, it became clear that there were large gaps between the dated results and the stratigraphy, and the number of analysis to be still insufficient.

Stewart et al. commented on the discrepancy between stratigraphy and dating results that the diachronous (in the meaning that although a stratum may seem uniform and consistent, it contains fossils showing several epochs). Nature of the basalt was due to the sheer expanse of the distributed basalt. However, just as the cases of Deccan Trap and Columbia River basalt, it is a characteristic of flood basalt that a single lava type flows can be traced 500 km or more. Therefore, for the future discussion on the relationship between volcano stratigraphy and the dated ages, or discussion on a erupted volume change on time scale, we will need to analyze more ages of the rocks and also to evaluate the errors in the existing data. For evaluate the dating data, we need not only discussion on measurement errors, also effect of alteration of the

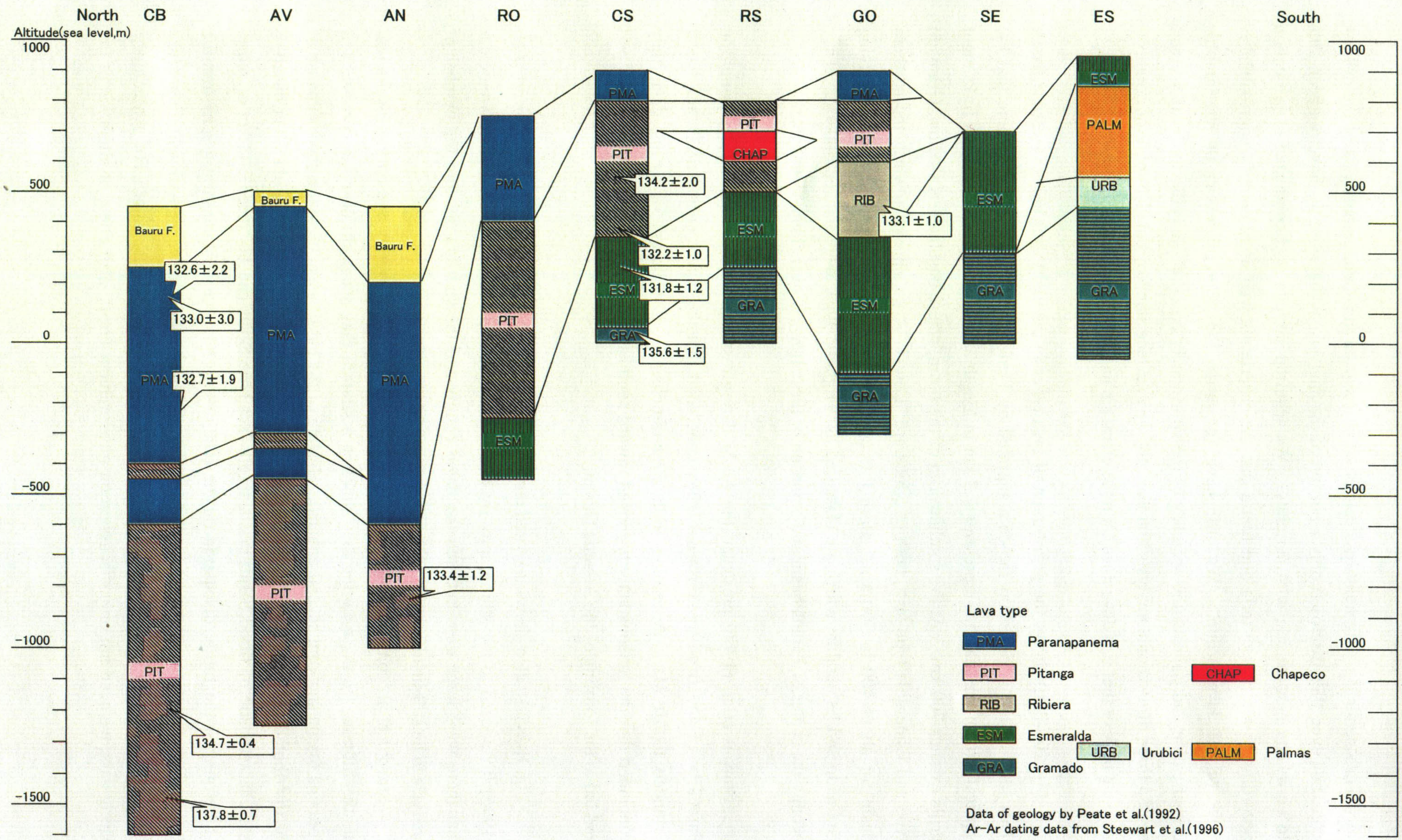


Fig. II-3-3-10 Chemical stratigraphy by drill samples along north-south direction in Paraná basin

sample materials.

Table II-3-3-4 shows the age of the flood basalt eruption, stratigraphical boundaries, and crucial events for the biotic changes/crisis, by Steve Self and Mike Rampino (2000). This table indicates that the major active period for huge amount of flood basalt was during 1Ma or less. However, Madagascar (88.1 ± 1, whole activity period; 6 Ma?) and Serra Geral/Etendeka (132 ± 1, whole activity period;1 or 5?) have question marks attached to their whole active volcanic periods.

As for the event that led to the biotic extinctions, the age of the three cases, namely Deccan, Newark and Siberian flood basalt, match completely. It seems reasonable to assume that other cases are also interrelated to the above mentioned cases.

We conducted Ar-Ar dating in our present survey. When we have the result of dating data including drill hole sample, we will comprehensively evaluate all of the results including past measurement. Estimation of the erupted volume and explosion ratio of various lava types is to be conducted later.

Table II-3-3-4 Flood Basalt Provinces of the last 250 Ma and the estimated ages of stratigraphic boundaries involving significant biotic changes

Flood Basalt Province	Age (Ma)	Volume (10^6 km^3)	Paleolatitude	Duration (Ma)	Stratigraphic Boundary	Age
Columbia River	16 ± 1	0.25	45°N	~ 1 (for 90%)	Early/Mid-Miocene	16.4
Ethiopia	31 ± 1	~ 1.0	10°N	~ 1	Early/Late Oligocene	30
North Atlantic	57 ± 1	>1.0	65°N	~ 1	Paleocene/Eocene	54.8
					(Thanetian/Selandian)	57.9
Deccan	66 ± 1	>2.0	20°S	~ 1	Cretaceous/Tertiary	65.0 ± 0.1
Madagascar	88 ± 1	?	45°S	~ 6?	Cenomanian/Turonian	93.5 ± 0.2
					(Turonian/Coniacian)	(89 ± 0.5)
Rajmahal	116 ± 1	?	50°S	~ 2	Aptian/Albian	112.2 ± 1.1
Serra Geral/ Etendeka	132 ± 1	>1.0	40°S	~ 1 or ~ 5?	Jurassic/Cretaceous	142 ± 2.6
					(Hauterivian/Valangini	(132 ± 1.9)
Antarctica	176 ± 1	>0.5	50-6°S	~ 1?	(Aalenian/Bajocian)	(176.5 ± 4)
Karoo	183 ± 1	>2.0	45°S	0.5 - 1	Early/Middle Jurassic	180.1 ± 4
Newark	201 ± 1	>1.0?	30°N	~ 0.6	Triassic/Jurassic	205.7 ± 4
Siberian	249 ± 1	>2.0	45°N?	~ 1	Permian/Triassic	248.2 ± 4.8

Steve Self and Mike Rampino(2000)

http://www.geolsoc.org.uk/template.cfm?name=fbasalts