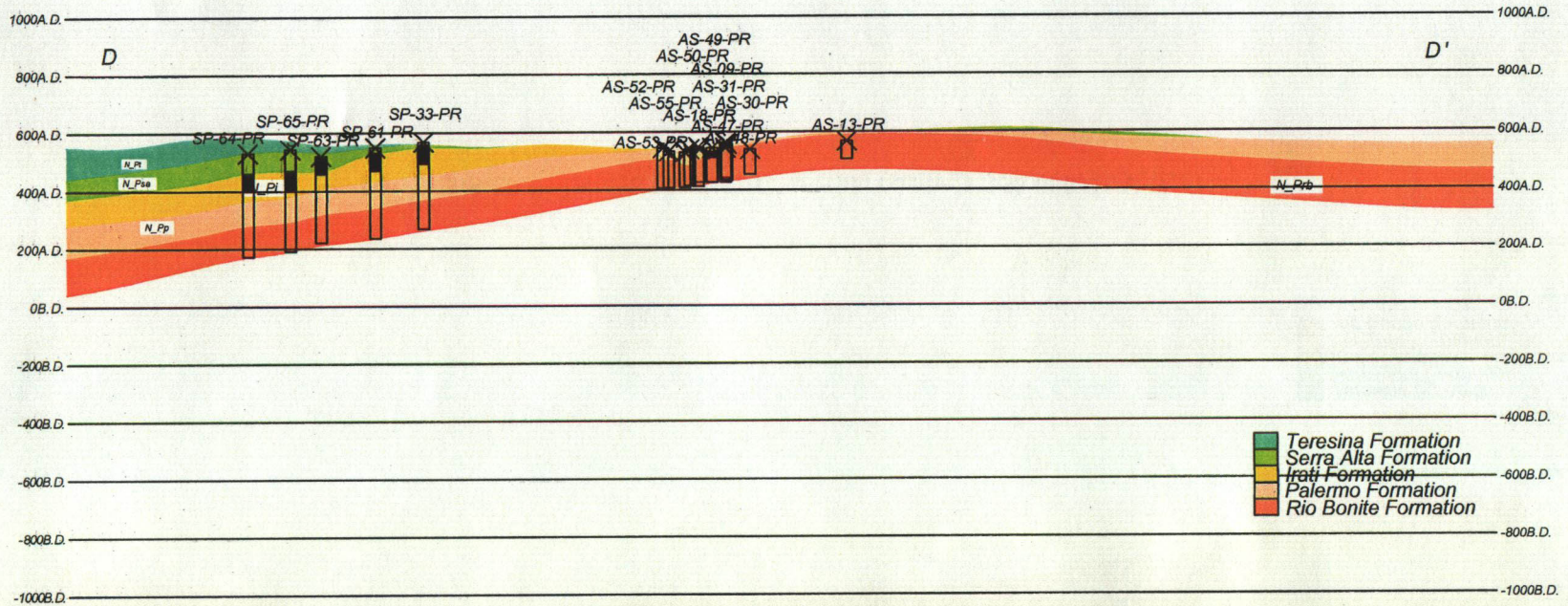

Fig. II-3-8-21 North block D-D' section (scale; 1:150,000, H/V; 1:6)

Table II-3-8-1 Samples collected from intrusions

・Northern part of the survey area (Ponta Grossa Arch)		
・Ponta Grossa Arch	Sill : 7 samples	outcrop
	Dike : 8 samples	outcrop
・Southern part of the survey area (Lomba Grande Area)		
・Northeastern Lomba Grande Sill	Sill : 22 samples	drill core:AT03, AT08
・Eastern Lomba Grande Sill	Sill : 26 samples	drill core:TG95, TG97, TG228
・Central Lomba Grande	Sill : 38 samples	outcrop and drill core:TG07, TG27 TG62, TG114
	Dike : 1 samples	outcrop (feeder dike)
・Lages Area	Dike : 1 samples	outcrop(feeder dike)

The samples of sills and dikes were collected from the outcrops along the line of the NE - SW direction which crosses the Ponta Grossa Arch in the northern part of the survey area. Most of the sills and dikes of the Ponta Grossa Arch were observed doleritic, part of which containing a coarse-grained gabbro. Secondary pyrite (or pyrrhotite) in scaly texture was found along the crack; however, fine-grained pyrite, considered as primary, was rarely seen in the matrix. The sills and dikes of the entire Ponta Grossa Arch are markedly homogeneous, indicating poor change in lithology. Regarding the sampling from outcrops, plural samples corresponding to the facies were collected for analysis in case more than one rock facies were observed in an outcrop; however, a sample collected from the most typical rock facies was utilized for petrochemical analysis. Generally, part of the coarse-grained gabbro was found in fine- to medium-grained dolerite in an outcrop. In this case, more homogeneous doleritic part was judged most typical, to which petrochemical analysis was made using the above sample.

As mentioned above, extensive two sills were recognized by drilling data analysis in the Lomba Grande area in the southern part of the survey area. Two drill cores (AT03 and AT08) in the northeastern part of the Lomba Grande Area and three drill cores (TG95, TG97 and TG228) in the eastern part of the Lomba Grande Area are considered to have intersected the "Northeastern Lomba Grande Sill" and the "Eastern Lomba Grande Sill", respectively. The samples collected in these two sills are fine- to medium-grained doleritic rocks partly containing coarse-grained gabbroic layers. Aphyric quenched part was recognized in the contact part with the host rocks in every drill core. Disseminated pyritization was also observed in the "Northeastern Lomba Grande Sill" including in the host rock. Moreover, course-grained

native copper was found within a cavity in the contact part of the sill and the upper shale at the AT03 drill core. Pyritization was also recognized in the "Eastern Lomba Grande Sill"; however, the pyritization was weaker than in the "Northeastern Lomba Grande Sill. Samples were collected from these sills at 10 to 20 m intervals.

Samples of TG62 and TG114 drill cores in the central part of Lomba Grande Area include picritic part in their characteristics; they were kept in the Porto Alegre branch office of CPRM. Besides these samples, four samples were collected from outcrops; two from Lomba Grande Complex and the other two from the dikes that went through the flood basalt.

(4) Petrochemistry of Intrusions

a) Compositional Variations with Differentiation

Fig. II-3-8-22 shows the compositional variations of major elements. As pointed out in the cooperative survey report of Canada-Brazil, compositional variations in Al_2O_3, CaO, and MgO indicate that the fractionation of olivine played the major role in the differentiation of magma in the early stage of differentiation (until Mg# becomes approximately 70 to 80), followed by fractionations of clinopyroxene and plagioclase, which also played the major role in the subsequent differentiation of the magma. According to the variation of TiO_2, the samples of the Ponta Grossa Arch and the Lomba Grande Area showed a clear division into "High-Ti" type and "Low-Ti" type, respectively. The sills of the Lomba Grande Area show compositional range from picritic to basaltic. On the other hand, the compositions of the sills in the Ponta Grossa Arch concentrate to basaltic.

Fig. II-3-8-23 shows the compositional variations of trace elements. The samples collected from the Lomba Grande Area tend rich in Th, U, and Rb contents compared with the samples collected from the Ponta Grossa Arch. This may indicate the addition of the upper crustal materials into the sills of the Lomba Grande Area. In addition, the samples of the Ponta Grossa Arch tend rather rich in Nb, Zr, and Y. These tendencies are in harmony with the fact that the Lomba Grande Area and the Ponta Grossa Arch respectively belong to the "Low-Ti" type area and "High-Ti" type area, which are indicated in their respective lavas.

Fig. II-3-8-24 shows the compositional variations of chalcophile elements. As the cooperative survey report of Canada-Brazil pointed out, a gap in Pt and Pd concentrations is recognized. It seems that some samples are depleted in Pt and Pd while the other are not. Picritic to dacitic sills are distributed in the central part of the Romba Grande Area, forming association of similar to that found in the Noril'sk region. However, the concentrations of Pt and Pd are very low. Meanwhile the concentrations of Pt and Pd were found high in two large-scale sills recognized in the eastern and in the northeastern part of the Lomba Grande. In particular, the content of Pt is high in the "Northeastern Lomba Grande Sill" which contains abundant pyrite. Some samples exceed 20 ppb in Pt content.

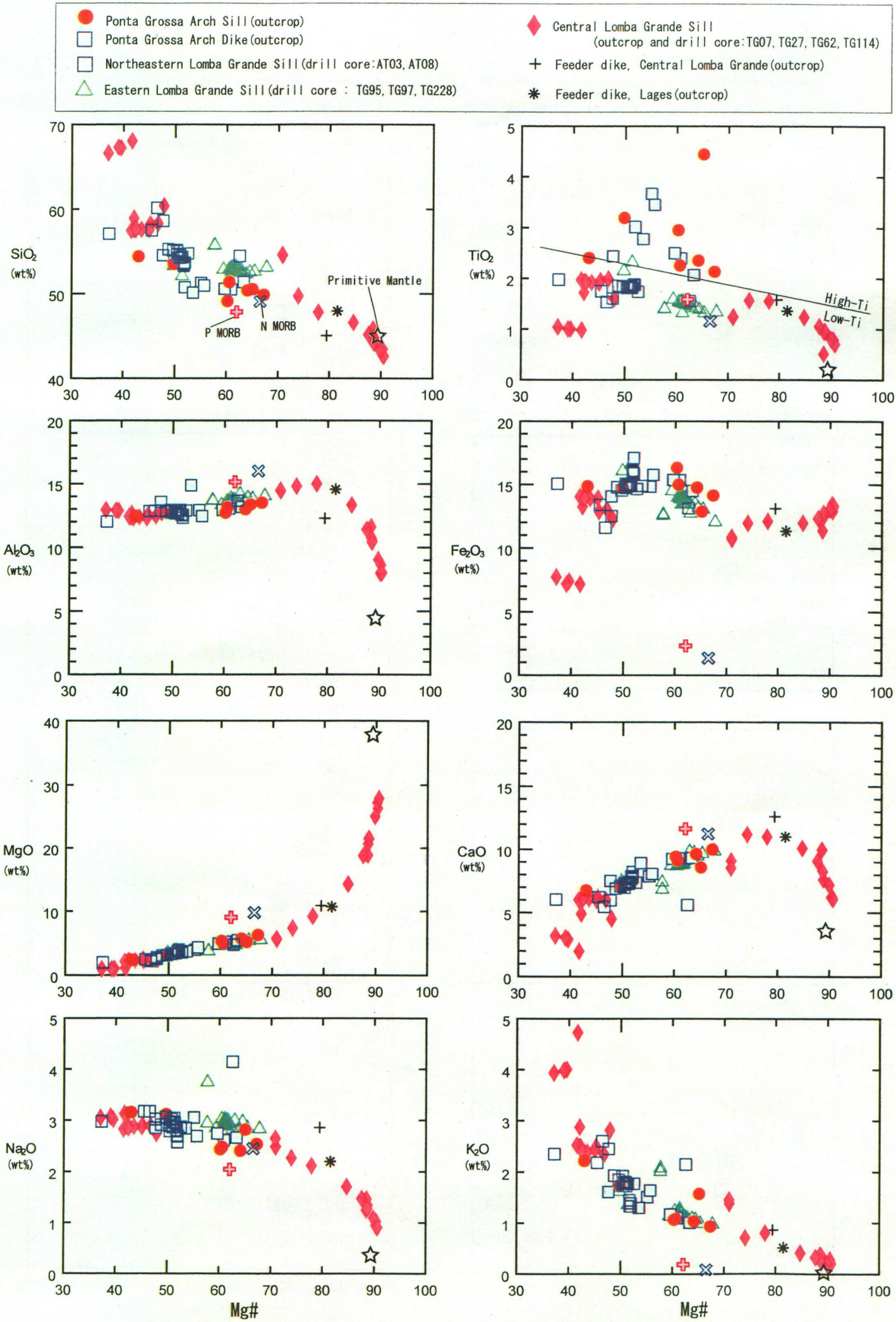

Fig. II-3-8-22 Mg# - major element diagrams for intrusive rocks

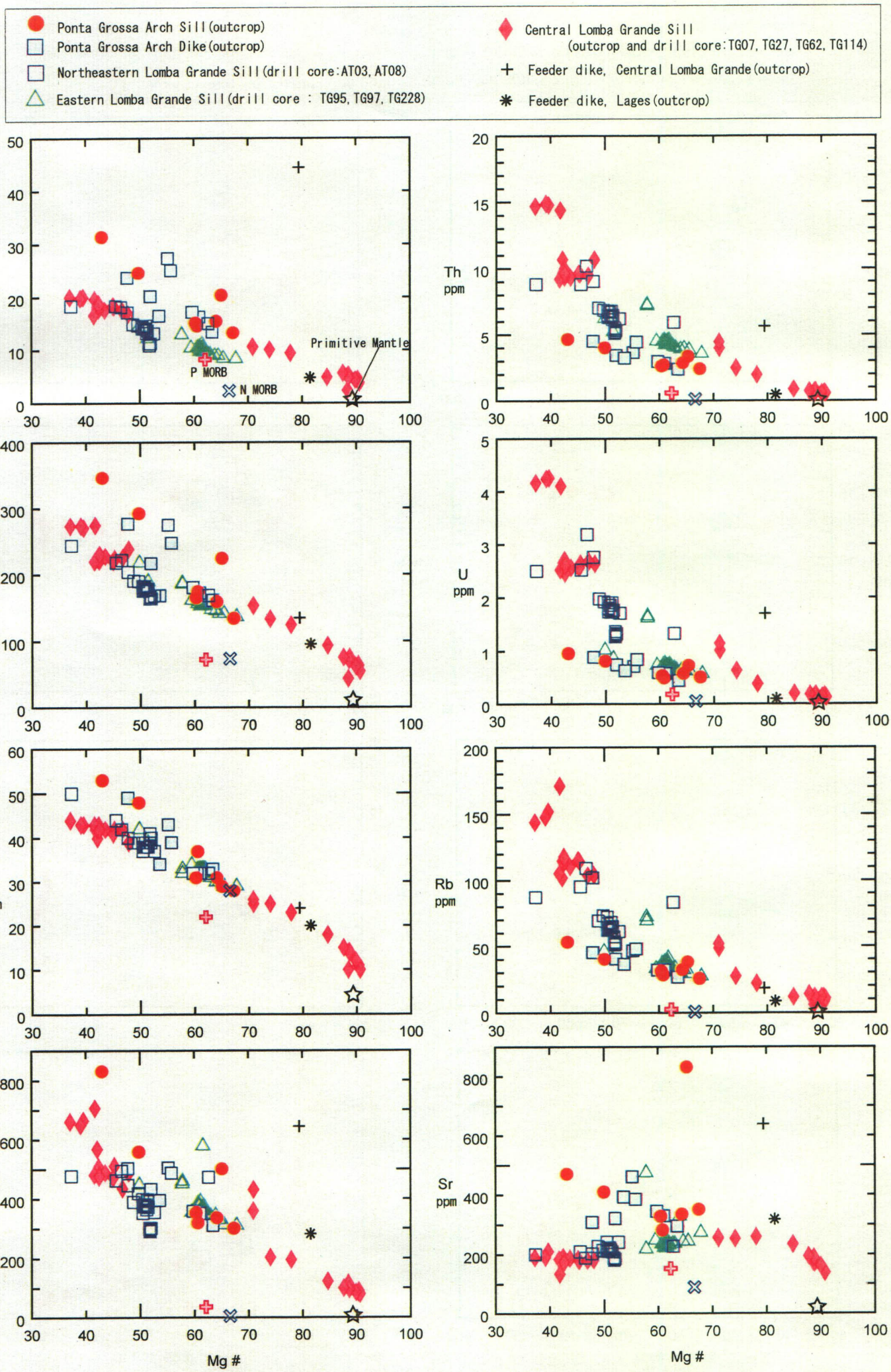

Fig. II-3-8-23 Mg# - trace element diagrams for intrusive rocks

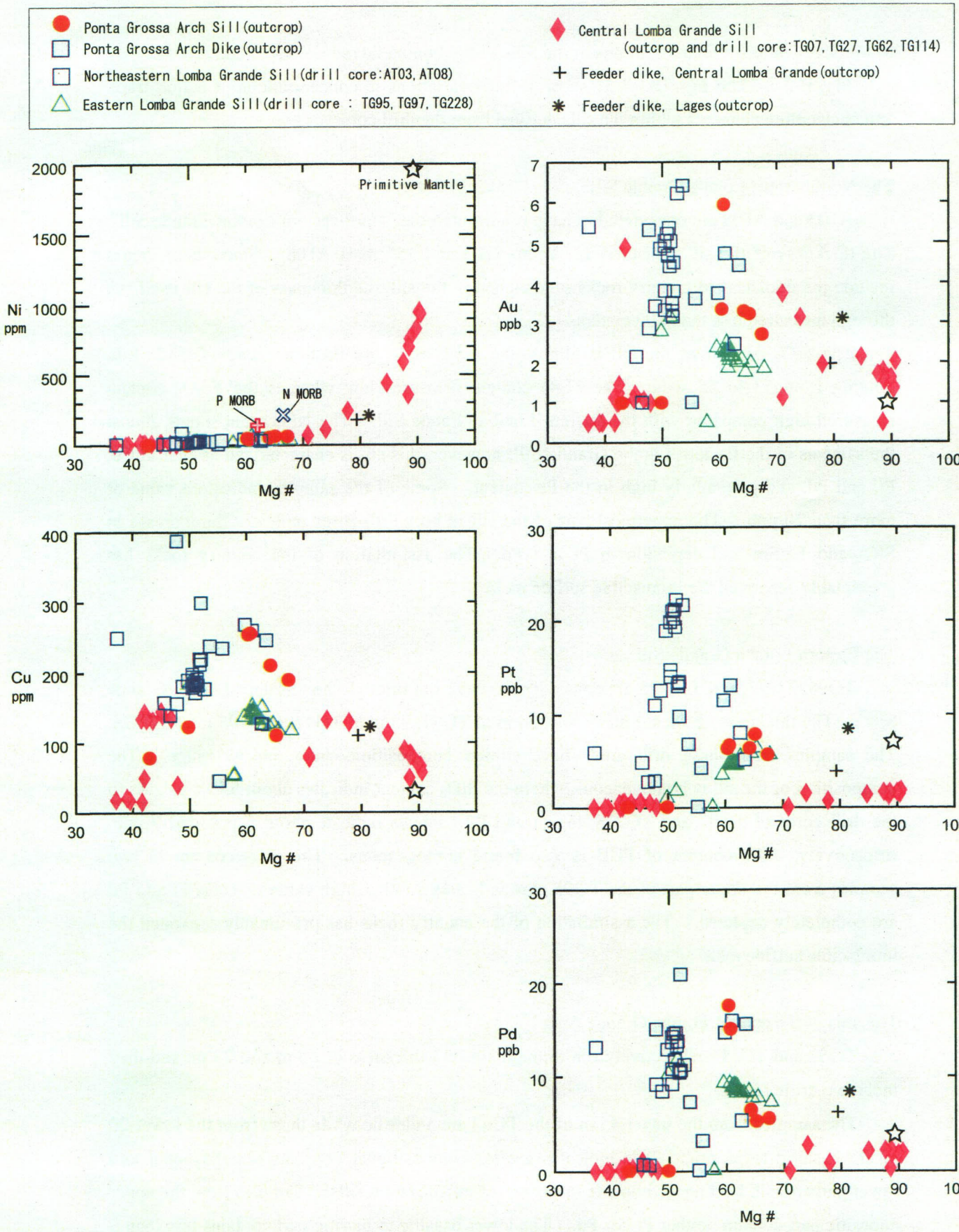

Fig. II-3-8-24 Mg# - chalcophile element diagrams for intrusive rocks

b) Vertical Compositional Variations of the Sills in the Lomba Grande Area

Fig. II-3-8-25 to Fig. II-3-8-31 show vertical variations in concentrations of major, trace, and chalcophile elements within the sills derived from the drill cores.

The Northeastern Lomba Grande Sill

AT03 and AT08 are considered to have run through the "Northeastern Lomba Grande Sill". The thickness of the sill measured 131 m at AT03 and 155 m at AT08. Since these values include the thickness of country rocks sandwiched in the sill, the thickness of the sill itself run through measured less than 100 meters.

The SiO_2 content of the sill is almost the same as in the Eastern Lomba Grande Sill, ranging from 53 to 55 wt%. The MgO content measures low whereas the Fe_2O_3 content measured high compared with the Eastern Lomba Grande Sill. The Ni content stands almost the same as in the Eastern Lomba Grande Sill; however, this sill is characterized as rich in Cu, Pt, and Pd, and particularly high in the Pt content. Some of the samples indicate a value of more than 20 ppb. The uppermost part of the sill in both drill cores indicates the increase in SiO_2 and La/Sm and depletion in Pt and Pd. The assimilation of the country rocks has presumably separated the immiscible sulfide melt.

The Eastern Lomba Grande Sill

TG95, TG97, and TG 228 are considered to have run through the "Eastern Lomba Grande Sill". The thickness of the sill measures 134 m at TG95, 95 m at TG97, and 105 m at TG228. The samples from these drill cores have similar compositions in a narrow range. The composition of the sill is homogeneous, where the SiO_2 content indicates about 53 wt%. As to the drill cores of TG97 and TG228, the Pt and Pd contents indicate about 5 ppb and 9 ppb, respectively. The content of PGE is also found homogeneous. The SiO_2 content in two samples from the upper part of the TG95 core indicates a rather high value whereas Pt and Pd are completely depleted. The assimilation of the country rocks has presumably separated the immiscible sulfide melt.

The sills of the central Lomba Grande Area

TG62 and TG114 respectively run through sill of a thickness of 65 m and 23 m, and they include picritic rocks.

The samples from the upper 45 m of the TG62 are andesitic while those from the lower 20 m are basaltic to picritic. This indicates a clear compositional gap between the upper and lower parts of sill, leading to probable intrusions of two different sills. Samples from the upper andesitic part contain neither Pt nor Pd. The lower basaltic to picritic part contains less than 3

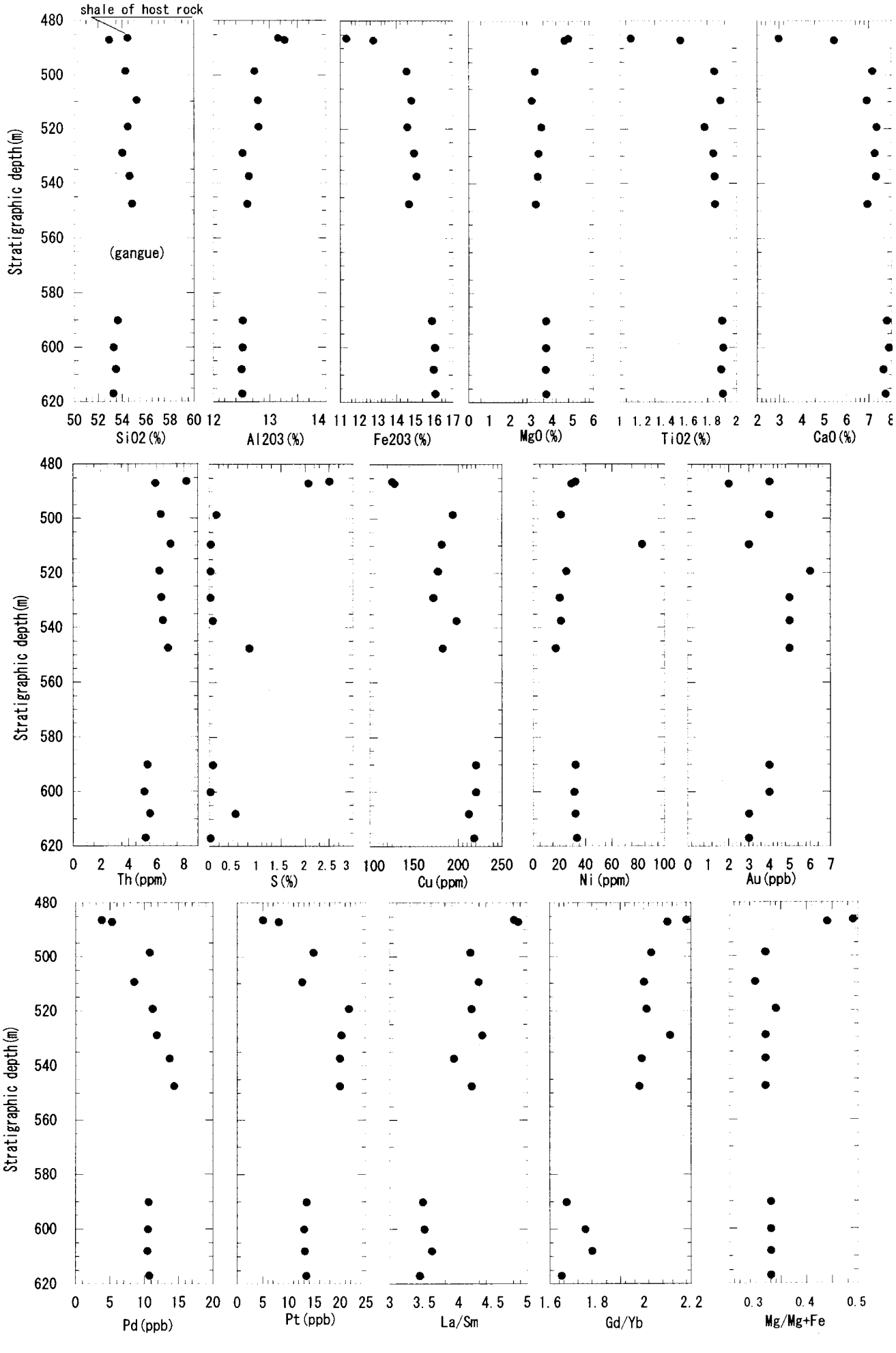

Fig. II-3-8-25 Vertical variations in major and trace-element in sill intersected by drill (AT03)

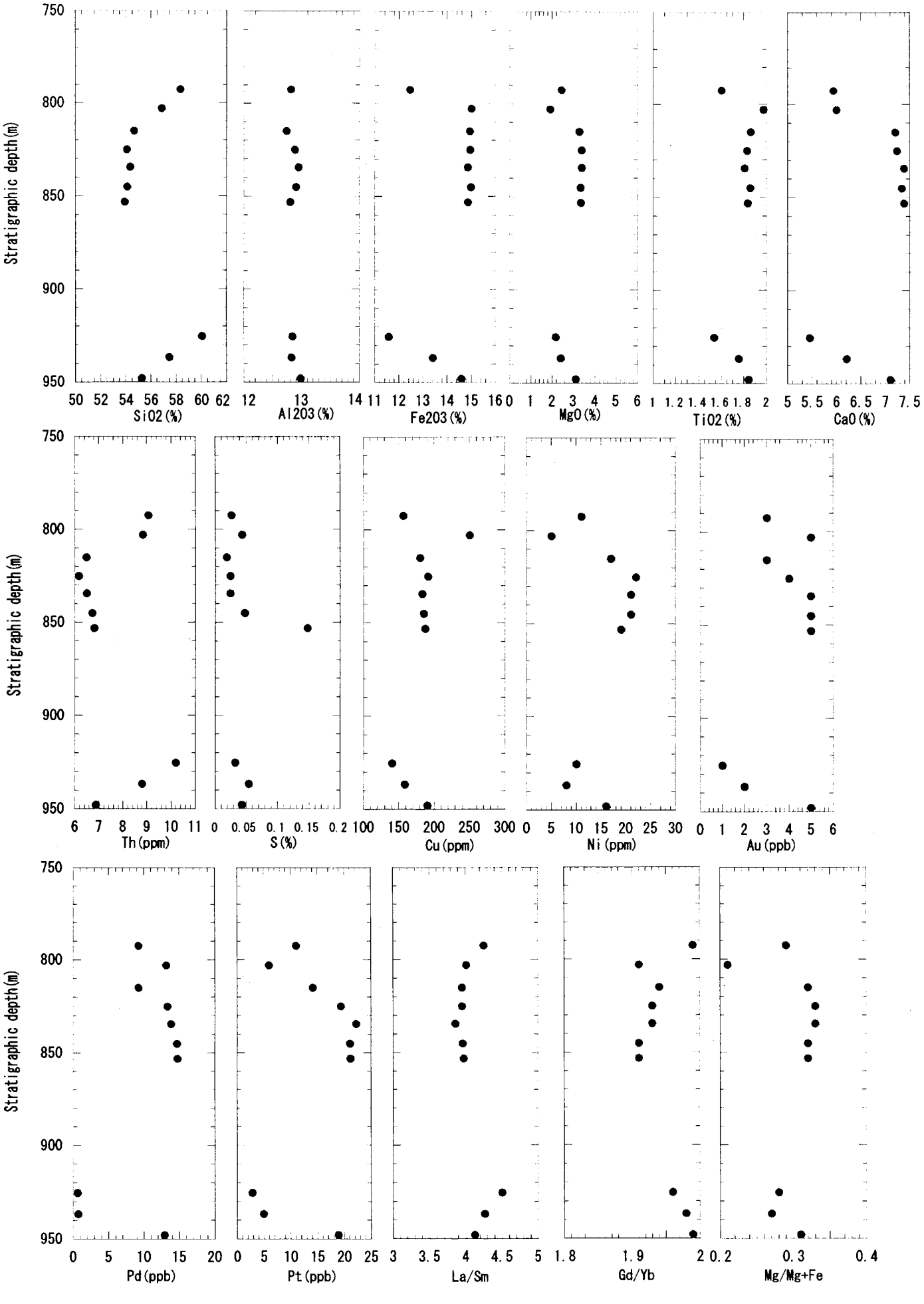

Fig. II-3-8-26 Vertical variations in major and trace-element in sill intersected by drill (AT08)

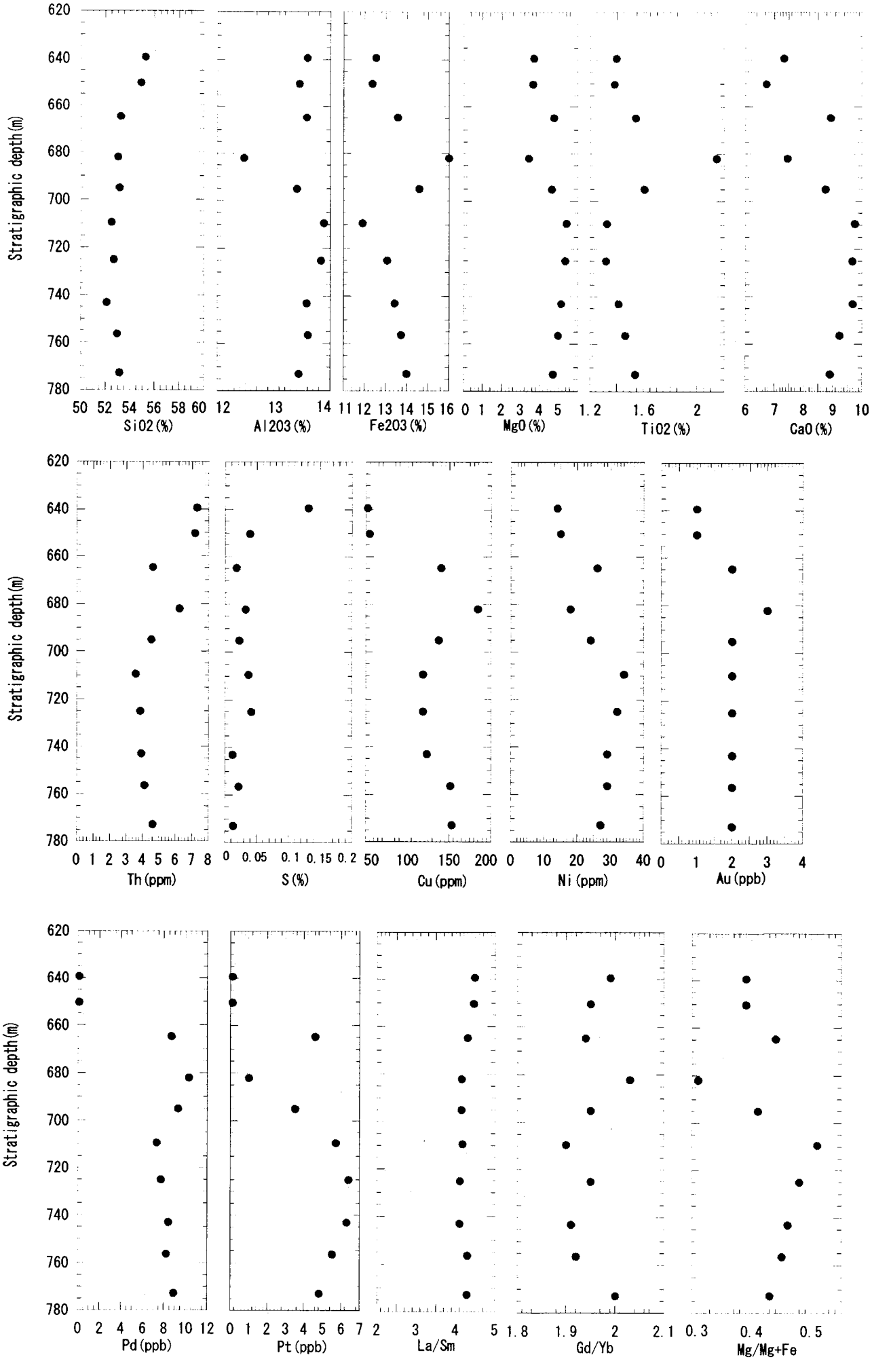

Fig. II-3-8-27 Vertical variations in major and trace-element in sill intersected by drill (TG95)

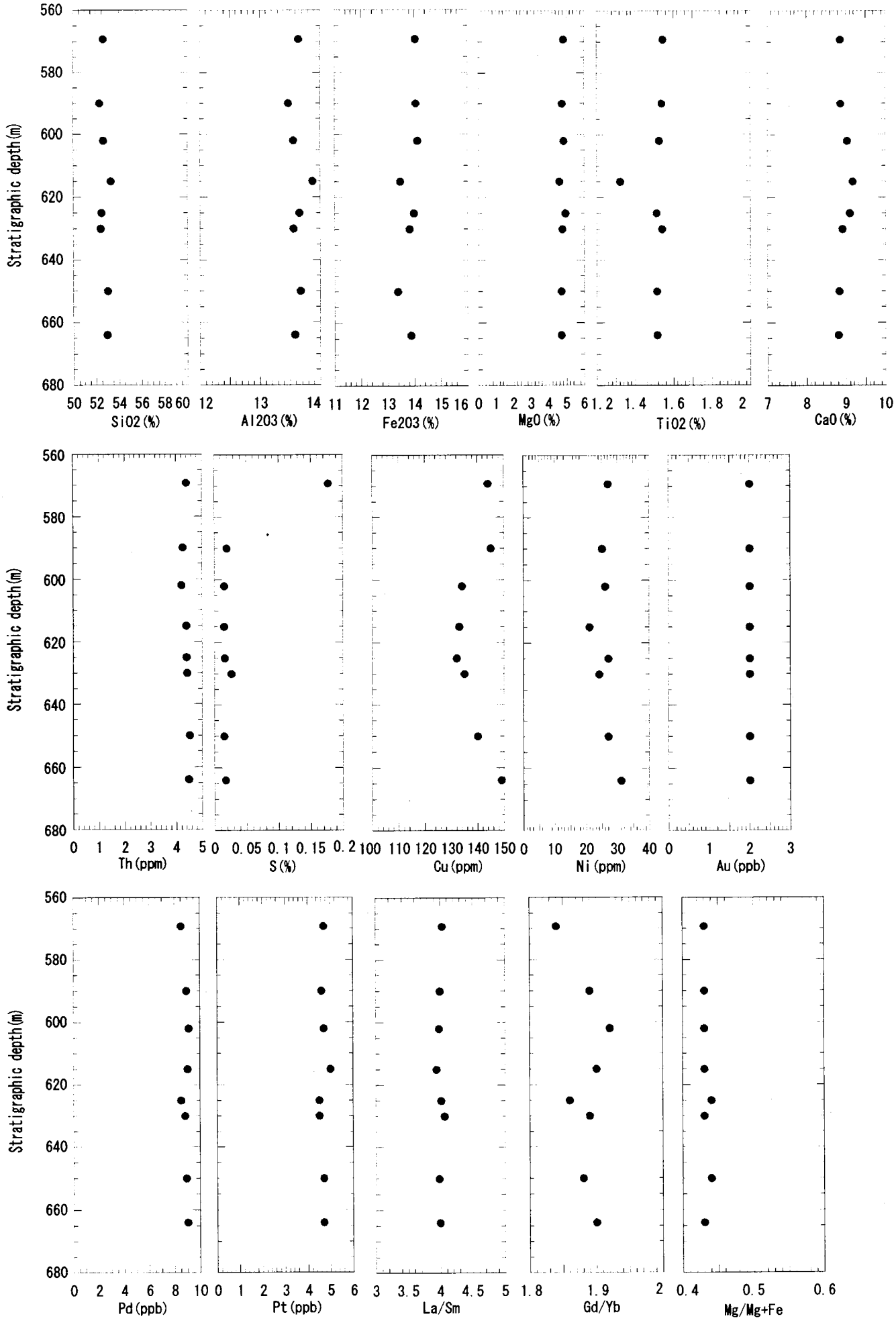

Fig. II-3-8-28 Vertical variations in major and trace-element in sill intersected by drill (TG97)

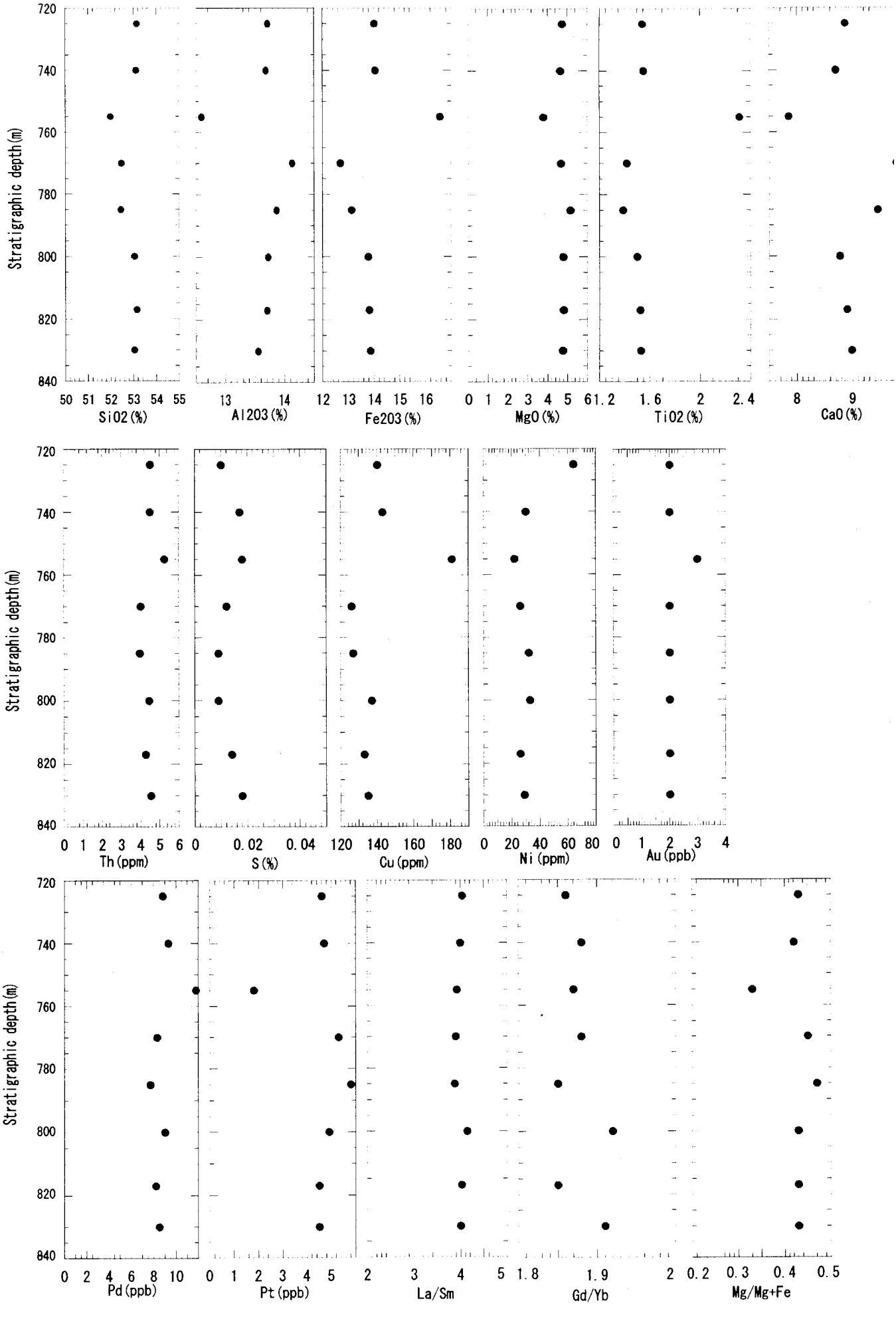

Fig. II-3-8-29 Vertical variations in major and trace-element in sill intersected by drill (TG228)

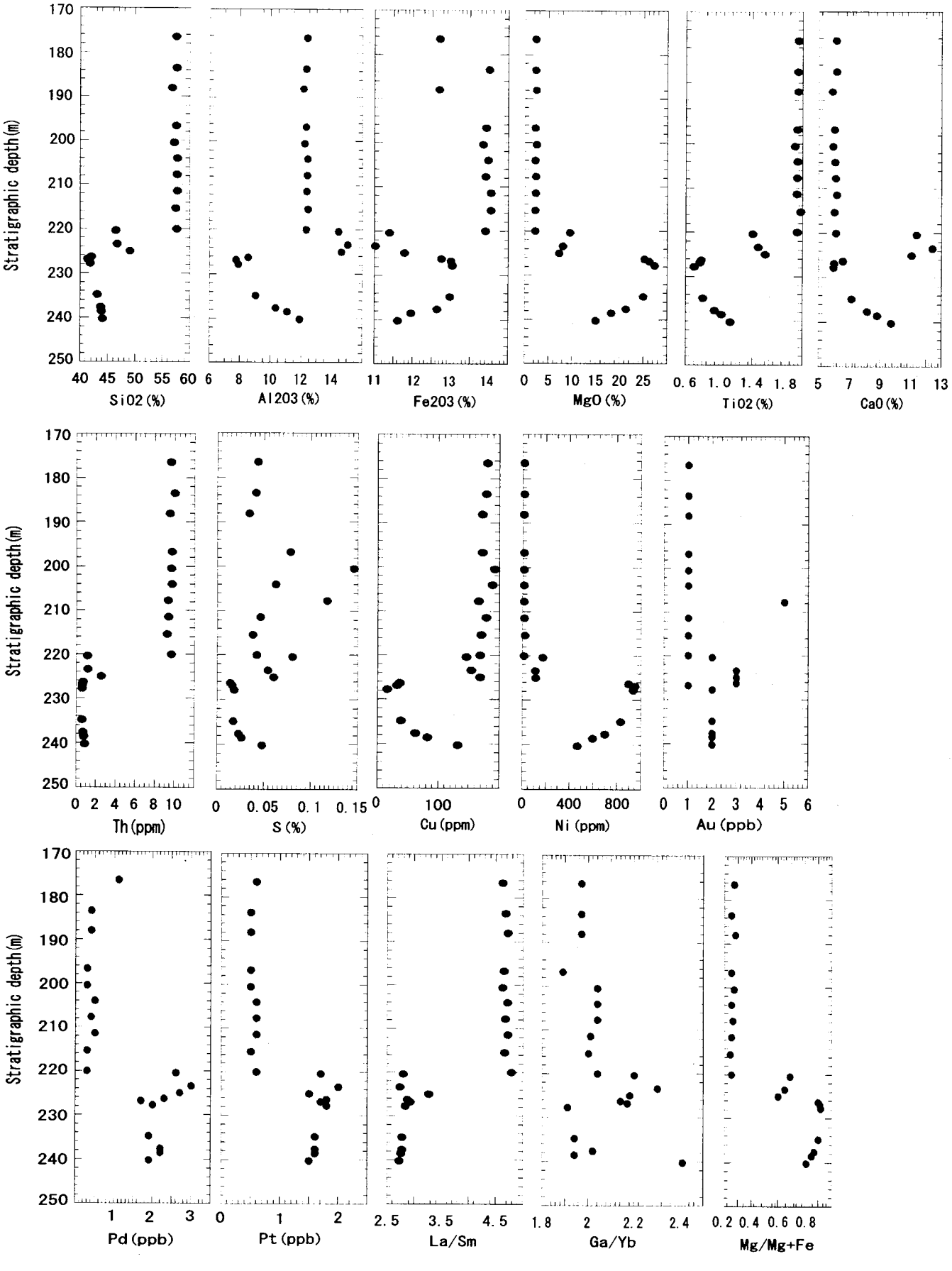

Fig. II-3-8-30 Vertical variations in major and trace-element in sill intersected by drill (TG62)

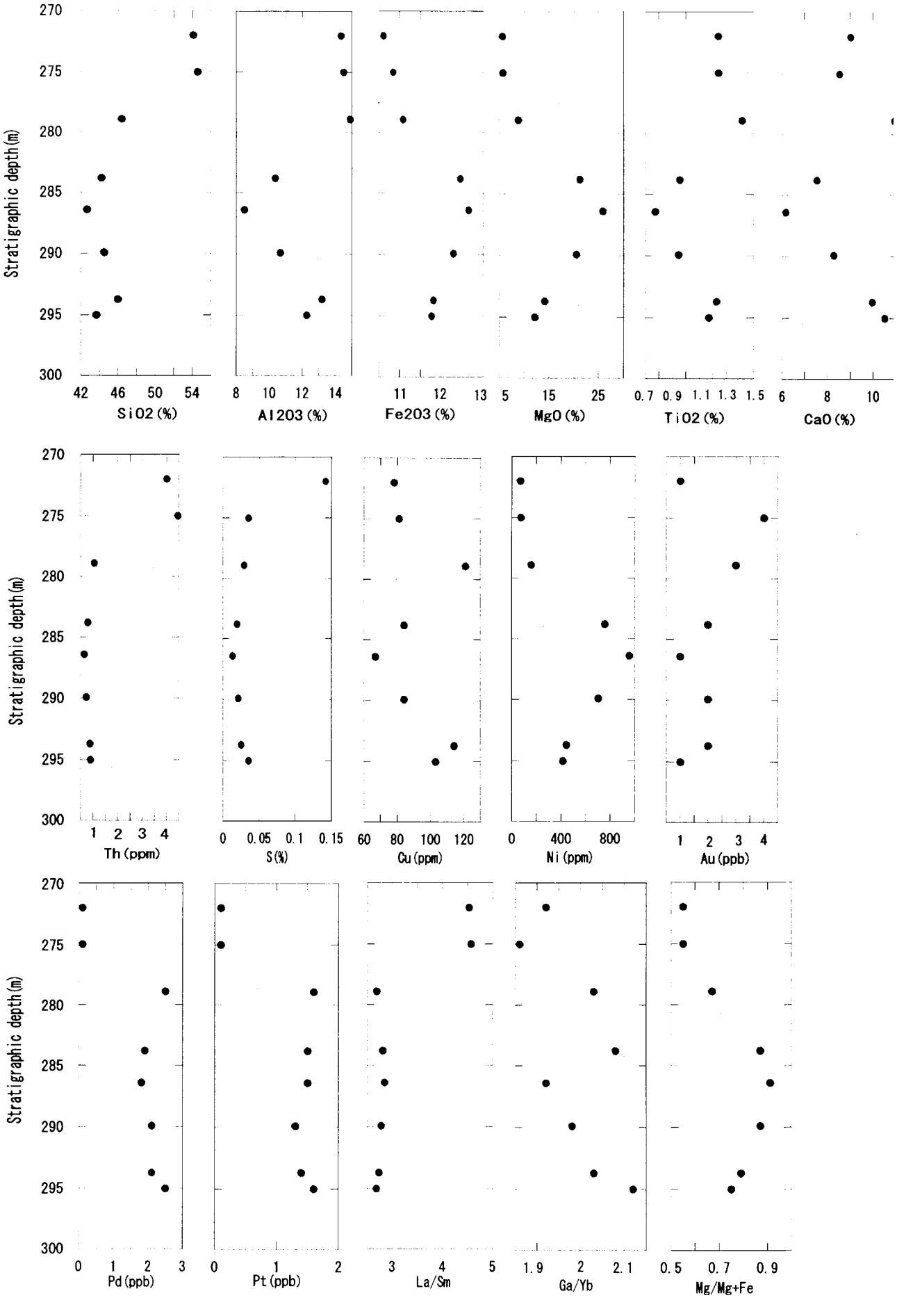

Fig. II-3-8-31 Vertical variations in major and trace-element in sill intersected by drill (TG114)

ppb of Pt and Pd. In the basaltic to picritic parts, Cu content increases according to decrease in Ni content that indicates differentiation of olivine, whereas the contents of Pt and Pd remain unchanged. These facts suggest that the basaltic to picritic magma have hardly separated the immiscible sulfide melt. Therefore, the initial contents of Pt and Pd are thought to have been low in the original magma of this sill.

Almost all parts of the TG 114 drill core are basaltic to picritic except the uppermost part, which indicates differentiated composition. The variations in chalcophile elements show the same pattern as in TG62 drill core. The differentiated composition in the uppermost part is considered as contaminated by the country rocks overlying the sill.

c) PGE Content of Intrusions

Fig. II-3-8-32 shows the relationship between Pt and Pd concentrations in the intrusions. The Northeastern Lomba Grande Sill indicates high concentrations of Pt and Pd, and particularly high Pt concentration. Its high Pt/Pd is characterized as a primitive mantle. The high Pt/Pd of the intrusion contrasts to that of the lavas, which indicate higher Pt concentrations than the Pd concentrations and have non-chondritic characteristics. The Pt and Pd concentrations of the Eastern Lomba Grande Sill measured 5 to 7 ppb and 8 to 9 ppb, respectively, indicating an almost homogeneous composition. The Pd content measured rather high in value. The Pt and Pd concentrations in the sills and dikes of the Ponta Grossa Arch vary in a wide range. The Pd concentrations are plotted in a region higher than the Pt concentrations. Some of the samples indicate that Pt and Pd are depleted. However, the indication is not so distinctive unlike the result indicated by the cooperative survey of Canada and Brazil.

Fig. II-3-8-33 shows relationship between Cu and Pd concentrations in the intrusions. The figure indicates whether magmas were sulfur saturated or not (see Chapter II, 3-4-3). The data of the intrusions ranged almost same as the lavas shown in Fig. II-3-4-2, indicating that the Cu concentrations are generally higher than those in the Noril'sk region. The sills and dikes of the Ponta Grossa Arch are widely distributed in the fields of sulfur saturated and undersaturated magmas. The Northeastern Lomba Grande Sill measured high in the Pd concentrations, which are plotted in the field of sulfur undersaturated magmas. As mentioned above, however, some samples from the uppermost part of the sill are depleted in Pd and plotted in the field of sulfur saturated magmas. The fact suggests a segregation of immiscible sulfide melt. All of the samples from the sills of the central Lomba Grande Area stand low in the Pd concentration. Some of these are plotted on the boundary of sulfur saturated and undersaturated fields while others hardly contain Pd (<0.01 ppb).

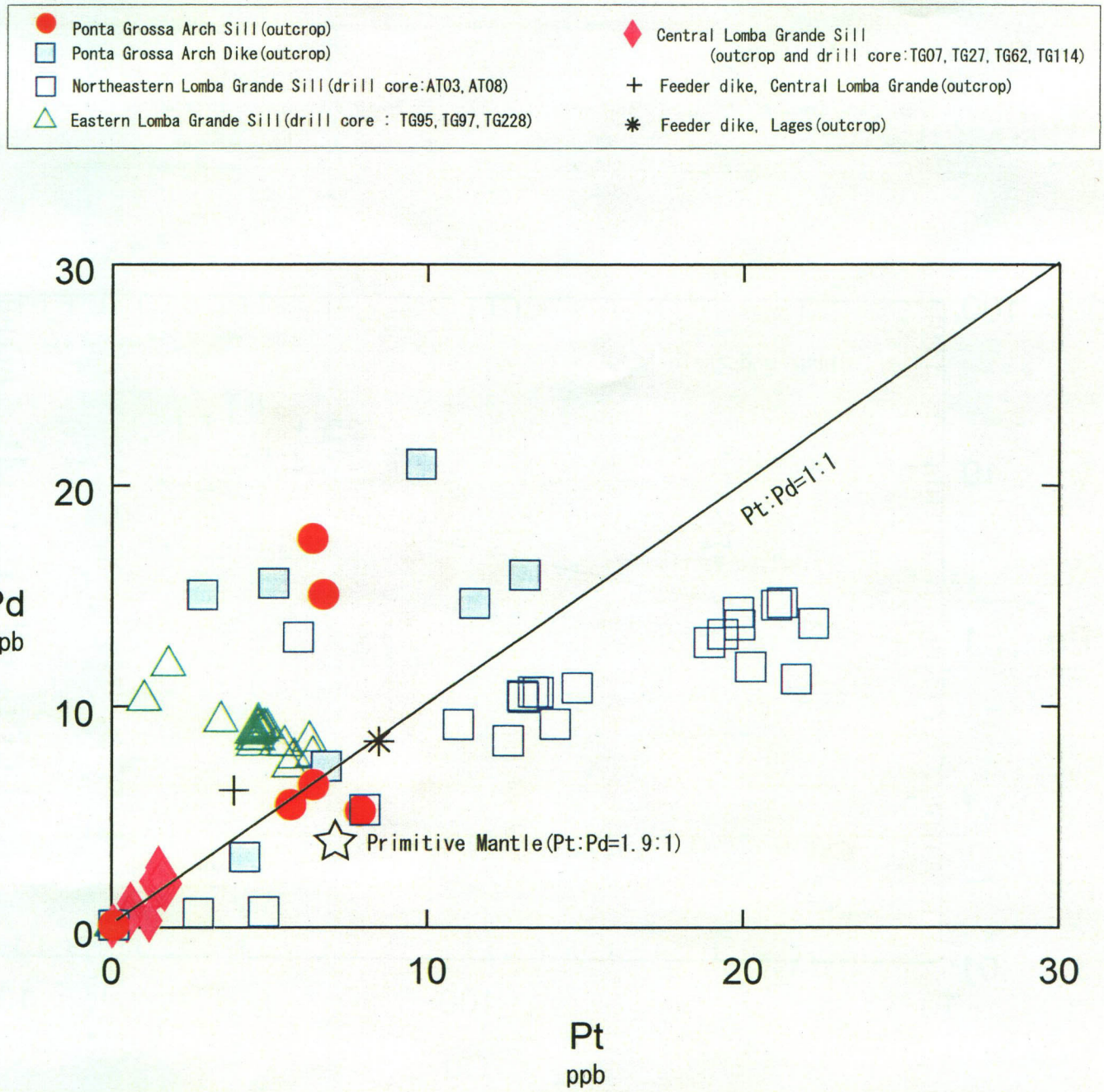

Fig. II-3-8-32 Pt - Pd correlation diagram for intrusive rocks

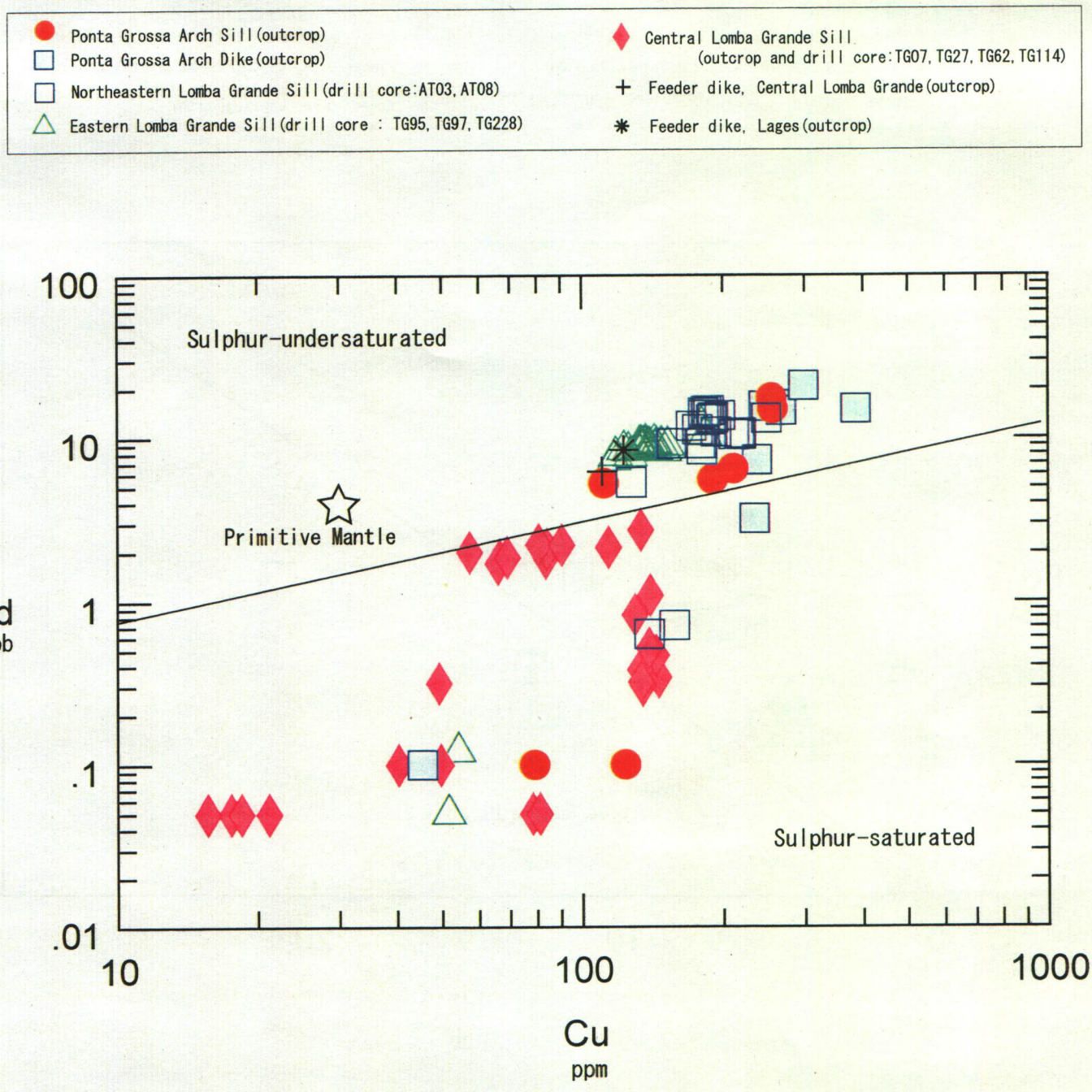

Fig. II-3-8-33 Cu - Pd discriminant diagram for intrusive rocks between the field of rocks formed by sulphur-saturated magmas and the field of rocks formed by sulphur undersaturated magmas

d) Influence of Crustal Contamination

Fig. II-3-8-34 and Fig. II-3-8-35 respectively indicate the relationship between Th/Nb and Pd, and the relationship between La/Sm and Gd/Yb. The Th/Nb in Fig. II-3-8-34 is the value hardly changes in fractional crystallization; however, the ratio is considered to make a marked increase in the contamination of the upper continental granitic materials (see Chapter II: 3-4-3). The La/Sm shown in Fig. II-3-8-35 is considered to increase in fractional crystallization, while increase in La/Sm under a constant Gd/Yb is considered to indicate crustal contamination (Naldrett, 1992).

According to these figures, all of the sill samples in the Lomba Grande Area except the picritic rocks suggest the influence of crustal contamination. The fact presumably points out some relationship to the distribution of Gramado type flood basalt that shows crustal contamination and acidic rocks in the Lomba Grande Area. In the central part of the Lomba Grande Area, basaltic to picritic sills and andesitic sills exist meanwhile the La/Sm and Th/Nb of these sills are completely different; the former cannot generate the latter in fractional crystallization. The andesitic sills presumably have been generated from the magmas which were contaminated by crustal materials.

The La/Sm and Th/Nb of the sills and dikes in the Ponta Grossa Arch stand lower than those of the sills in the Lomba Grande Area, concentrating in a narrow region. These rocks were presumably generated from the magmas which were not contaminated by crustal materials. However, some samples from the Ponta Grossa Arch are depleted in Pd. As a possibility, the sulfur-rich sedimentary rocks presumably supplied sulfur to the magma, causing segregation of immiscible sulfide melt.

Sr isotope ratio ($^{87}Sr/^{86}Sr$) and Nd isotope ratio ($^{143}Nd/^{144}Nd$) were measured for 11 intrusion samples. All of the isotope ratios measured were converted to the initial ratios (130 Ma), which are then plotted in Fig. II-3-8-36. The samples of the "Northeastern Lomba Grande Sill" and the "Eastern Lomba Grande Sill" were high in the Sr isotope ratios and low in the Nd isotope ratios, suggesting crustal contaminations. The influence of the crustal contamination is considered as weak in the picritic sills of the central Lomba Grande Area and in the sills and dikes of the Ponta Grossa Arch. These isotopic characteristics are consistent with the results observed in the study using trace elements.

e) Sulfur Isotope Ratio

In order to consider the origin of sulfur in the intrusions, sulfur isotope ratios were determined for the intrusions and a Paleozoic sedimentary rock, which is a possible sulfur supplier to the intrusions. 3 samples are selected from a sill and a dike of the Ponta Grossa Arch, and from the Northeastern Lomba Grande Sill. A pyrite rich coal sample from the operating coal mine of Rio Grande do Sul was chosen as a sulfur rich sedimentary rock. The

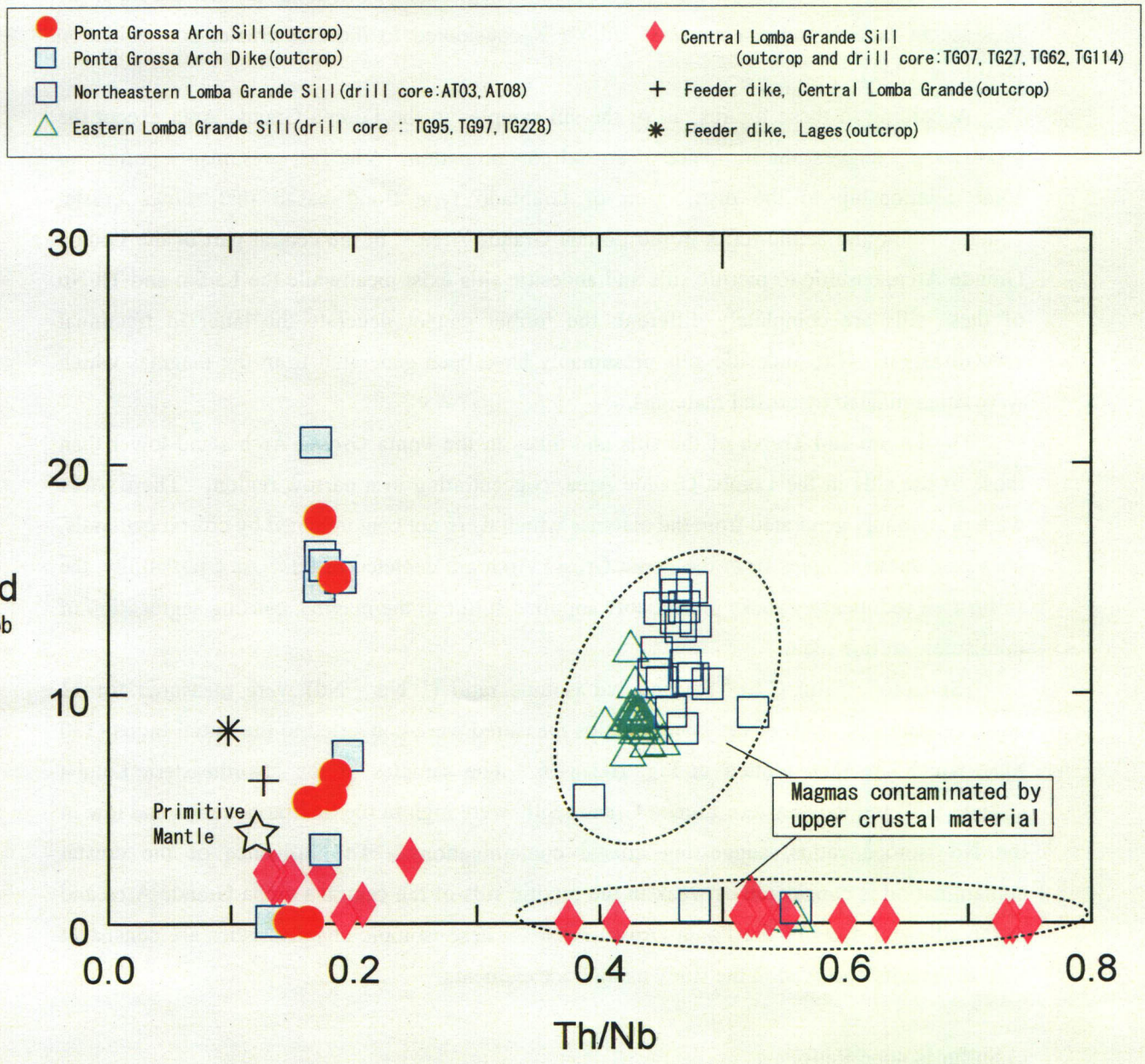

Fig. II-3-8-34 Th/Nb - Pd correlation for intrusive rocks

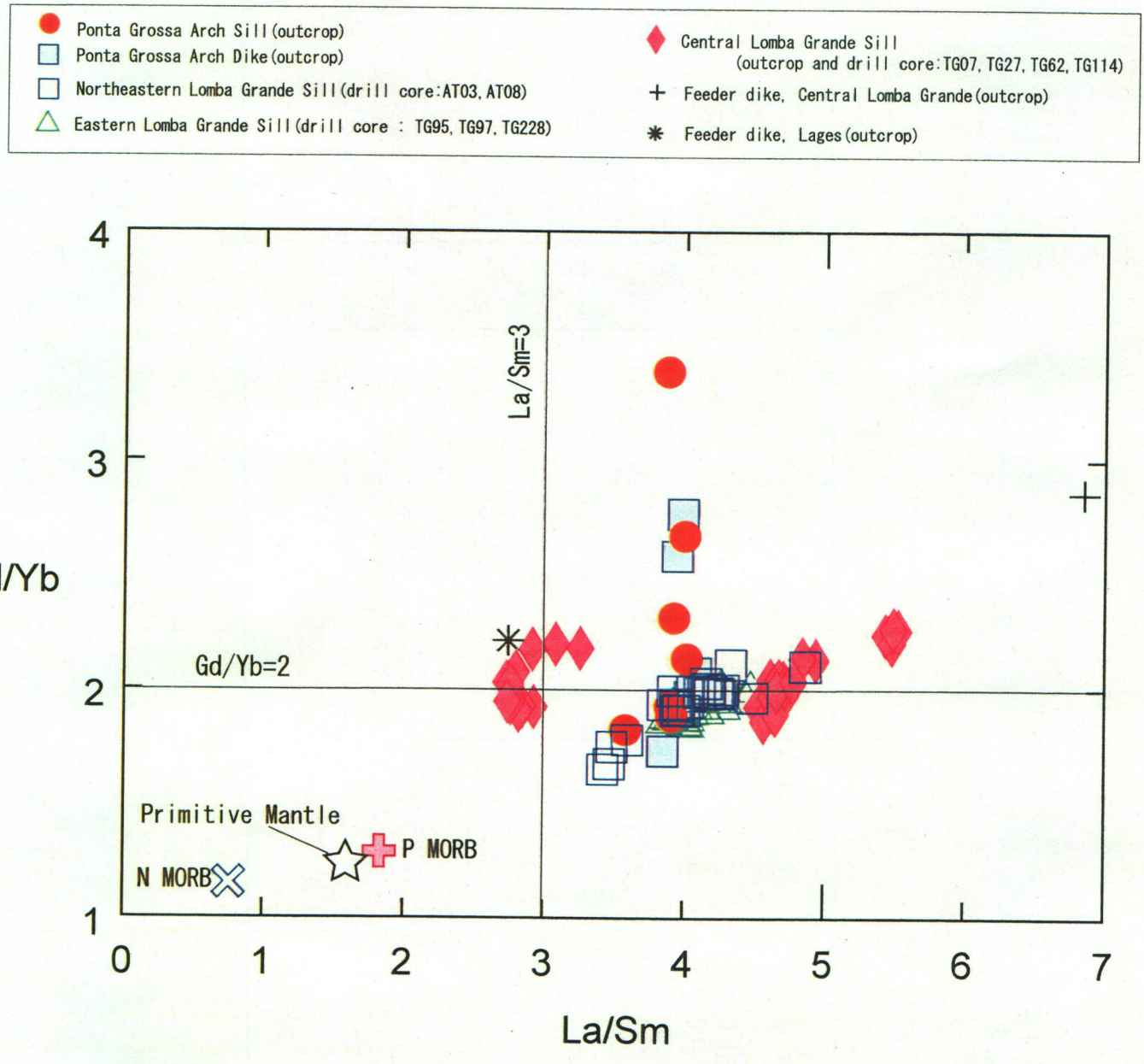

Fig. II-3-8-35 La/Sm - Gd/Yb correlation for intrusive rocks

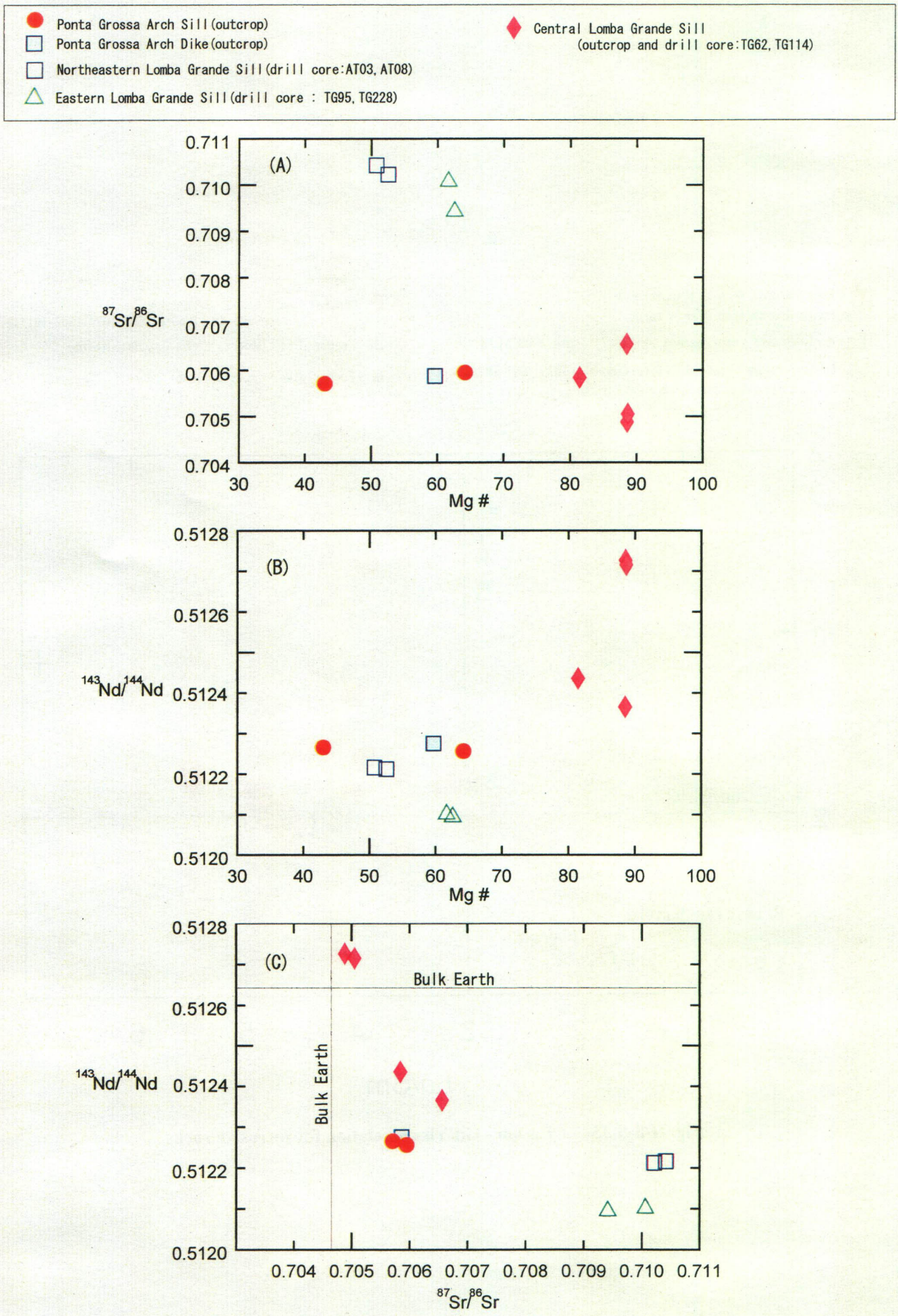

Fig. II-3-8-36 **(A): Mg-number - Sr-isotope initial ratio diagram; (B): Mg-number - Nd-isotope initial ratio diagram; (C): Sr-isotope initial ratio - Nd-isotope initial ratio diagram**

coal horizon belongs to the Rio Bonite formation of the Permian. The measured sulfur isotope ratios are shown in Table II-3-8-2.

Table II-3-8-2 Sulfur isotopic ratios of intrusive rocks

Sample No.	Sample description	$\delta^{34}S$(‰)
KN040B	Doleritic sill from the Ponta Grossa Arch	+10.1
AS010	Doleritic dike from the Ponta Grossa Arch	+ 9.6
AT03-487	Doleritic sill from the northeastern Lomba Grande	+10.5
AS020	Pyrite rich coal ore in the Rio Bonite formation	− 0.6

The ^{34}S of the intrusions showed high values around +10‰. These values are almost same as those of the ores of Noril'sk (+8 to +12‰). In the Noril'sk region, this heavy isotopic sulfur is thought to have been derived by the sulfur supplies from anhydrite in the basement sedimentary rocks.

On the other hand, pyrite of the coal ore from the Rio Bonite formation shows low value of -0.6‰. This value is considered to be normal as a biogenic sulfur.

The values of around +10‰ obtained from the intrusions are abnormally high as those of igneous rocks, therefore, the outer sulfur contribution from the country rocks may be needed in order to explain these high values. Since the value of pyrite in the coal ore from the Rio Bonite formation is too low, another sulfur suppliers may be needed. According to Milani (1998), the Irati formation partly includes anhydrite layer. This is one of the possible sulfur suppliers to the intrusions.