4. Himalaya-Bengal area

4-1. Historical review

The stratigraphy of Bangladesh has been compiled by some authors. Alam (1989) divided the strata in the Bangladesh into five groups, namely Jaintia (Tura Sandstone, the Sylhet Limestone and the Kopili Formation), Barail (the Jenam Formation), Surma (the Bhuban and Boka Bil Formations), Tipam (the Tipam Formation and Girujan Clay) and Madhupur (the Dupi Tila Formation and the Madhupur Clay) Groups in ascending order. Johnson and Nur Alam (1991) and Uddin and Lundberg (1998b) divided the strata in the Sylhet Trough, northeast Bangladesh, into the Sylhet Limestone, the Kopili Formation, the Barail Formation, the Surma Group, the Tipam Sandstone and the Dupi Tila Formation in ascending order. Reimann (1993) divided the strata in the Sylhet Trough into the Sylhet Limestone Formation, the Renji Formation, the Bhuban Formation, the Boka Bil Formation, the Tipam Sandstone, the Girujan Clay and the Dupi Tila Formation in ascending order. Gani and Alam (2003) divided the strata in the southeastern part of Bangladesh into the Surma Group, the Tipam Group and the Dupi Tila Formation in ascending order.

Few fossil data have been reported from Bangladesh. The Sylhet Limestone yields Nummulites (Alam, 1989). Mannan (2002) reported pollen fossils from the Surma Group. Before his study, the age of the strata in Bangladesh was inferred from the fossils from the equivalent strata in India.

There are some papers of sedimentary petrological study in Bangladesh and Bengal Fan. Ingersoll and Suczek (1979) studied the modal composition of sands from the Deep Sea Drilling Program (DSDP) Site 211. Johnson and Alam (1991) and Uddin and Lundberg (1998b) studied modal composition of sandstones in Bangladesh and reconstructed the paleogeography of Himalaya-Bengal system. Yokoyama et al. (1990), Bouquillon et al. (1990) and Amano and Taira (1992) studied the mineralogy of silt obtained from the Ocean Drilling Program (ODP) Leg 116 cores, and Amano and Taira (1992) inferred that there is two-phase uplift of Higher Himalayas since 17 Ma. Corrigan and Crowley (1990) reported the fission-track age of detrital apatites from the ODP Leg 116 cores. Copeland and Harrison (1990) and Rahman and Faupl (2003a) measured the $^{40}Ar/^{39}Ar$ age of detrital muscovites and K-feldspars from the ODP Leg 116 cores and the Surma Group in Bangladesh, respectively. Uddin and Lundberg (1998a) studied the quantitative analyses and temporal variations in detrital heavy minerals assemblages from the Sylhet area, northeast Bangladesh. Rahman and Faupl (2003b) measured the major and trace elements of shales from the Surma Group in the Sylhet Trough.

4-2. Outline of stratigraphy in Bangladesh

In this section, the outline of stratigraphy in Bangladesh is summarized based on Uddin and Lundberg (1998b). The Tertiary sediments are distributed in the northeastern and southeastern parts of Bangladesh (Fig. 57). Uddin and Lundberg (1998b) divided the strata in Bangladesh into two groups and five formations, namely the Sylhet Limestone, the Kopili Formation, the Barail Formation, the Surma Group (the Bhuban and Boka Bil Formations), the Tipam Group and the Dupi Tila Formation in ascending order (Fig. 58).

The Sylhet Limestone is the oldest stratigraphic unit exposed in Bangladesh. This is composed of middle Eocene nummulitic limestone and attains to a thickness of about 250 m. The Kopili Formation overlies the Sylhet Limestone conformably. The Kopili Formation consists mostly of late Eocene argillaceous and fossiliferous materials. This formation is 40 to 90 m in thickness. These Eocene strata are exposed at two localities along the northeastern national boundary between Bangladesh and India (Alam et al., 1990).

The Barail Formation consists mostly of massive to bedded sandstone and was

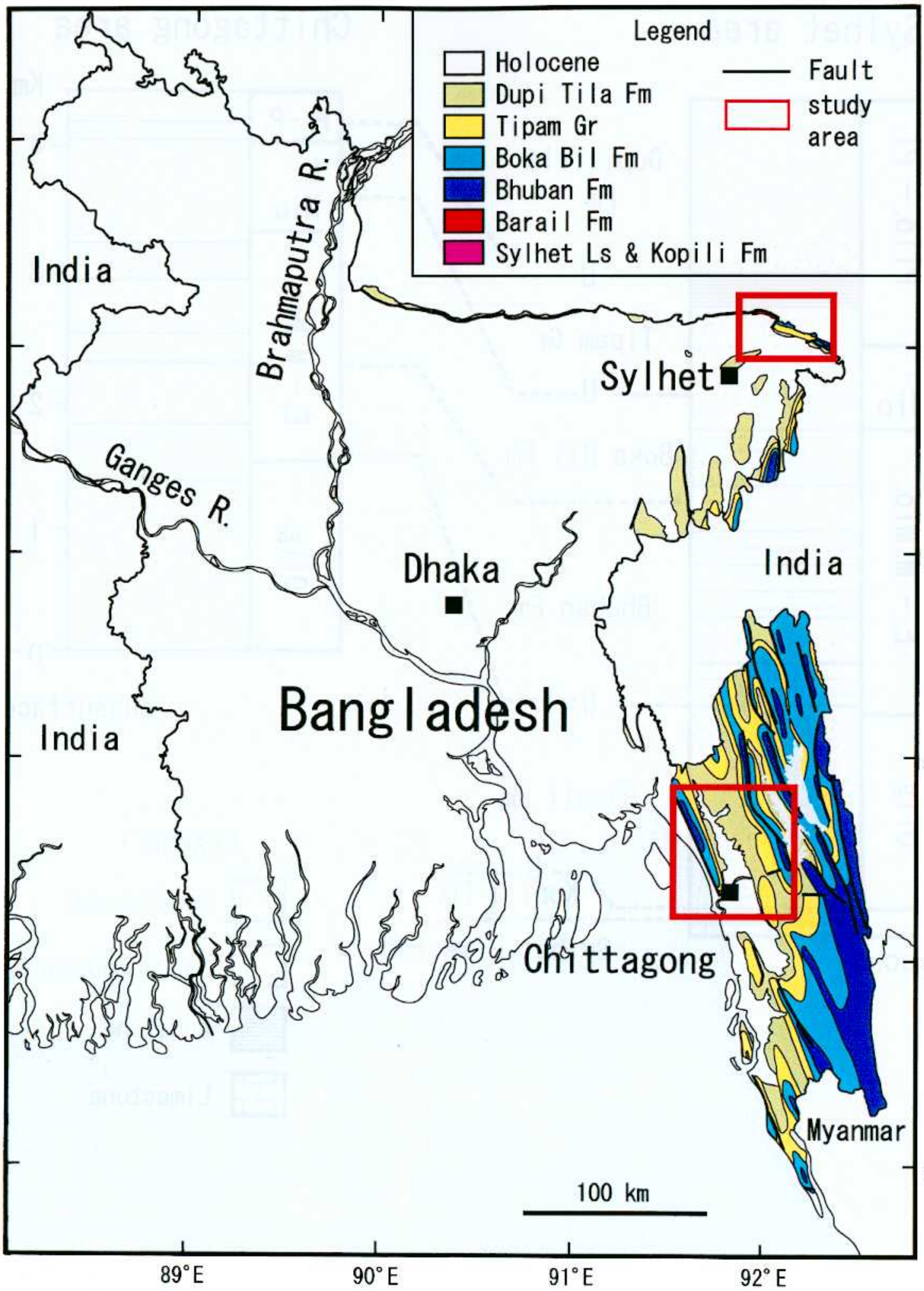


Fig. 57. Geologic map of Bangladesh.(Simpified from Alam et al., 1990)

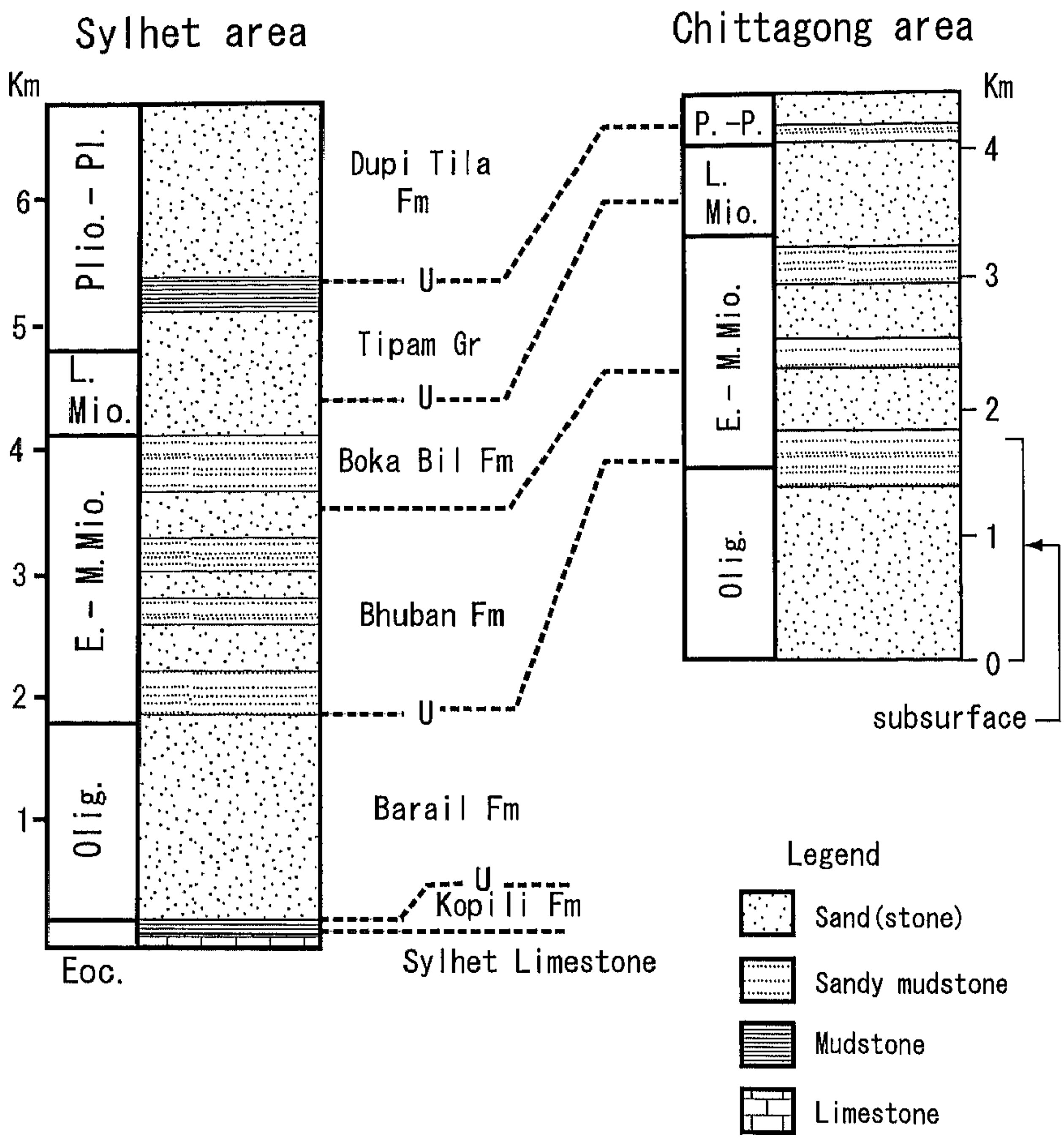


Fig. 58. Stratigraphy of the Sylhet and Chittagong areas.
(Udding & Lundberg, 1998)

deposited in the Oligocene. Banerji (1984) interpreted this formation as estuarine and deltaic deposits. This formation is 800 to 1600 m in thickness and is exposed only in the northernmost part of the Sylhet area (Alam et al., 1990).

The Surma Group overlies the Barail Formation unconformably. This Group consists of the Bhuban and Boka Bil Formations and was deposited in the early to late Miocene. The Bhuban Formation is composed mainly of sandstone, siltstone, muddy sandstone and mudstone. The Boka Bil Formation is generally composed of mudstone, siltstone and sandstone. These formations are interpreted as deposits during repeated transgressions and regressions. A muddy upper member of the Boka Bil Formation was designated by Holtrop and Keizer (1970) as the "Upper Marine Shales," representing the last Miocene transgression. Total thickness of the Surma Group is about 4.5 km in the northern Chittagong Hill and the Sylhet Trough, though the lower part of the Bhuban Formation is not exposed in the Chittagong Hill.

The Surma Group is unconformably overlain by the Tipam Group. The Tipam Group consists of the Tipam Sandstone Formation and Girujan Clay Formation, and was deposited in the late Miocene to Pliocene. The Tipam Sandstone Formation is composed mostly of weathered, medium- to coarse-grained, cross-bedded and massive sandstone, and was interpreted to have been deposited in bedload-dominated braided-fluvial environments (Johnson and Nur Alam, 1991). Maximum thickness of this formation is about 2.5 km. The Girujan Clay is loccaly as thick as 1 km, and is composed mainly of mudstone deposited in lacustrine, flood-plain and overbank environments (Khan and Muminullah, 1980).

The Tipam Group is unconformably overlain by the Dupi Tila Formation which was deposited in the Pliocene to Pleistocene. The Dupi Tila Formation is composed mostly of massive cross-bedded coarse to pebbly sandstone, and is 2.3 km in thickness in the Sylhet Trough. This formation contains alternating channel and flood-plain deposits, and was interpreted as a meandering-river deposit (Johnson and Nur Alam, 1991).

In the Sylhet area, the whole stratigraphy mentioned above is observable (Figs.

58 and 59). On the other hand, the stratigraphic units above the middle Bhuban Formation can be observed in the Chittagong area, southeastern part of Bangladesh (Figs. 58 and 60).

4-3. Description of the piston cores

In this study, sand samples of piston cores from the central part of the Bengal Fan were used to know the characteristics of detritus of late Quaternary from the Himalayas. The cores were collected during Leg 4 of KH-00-5 of the Hakuho-maru (the Oceanic Research Institute, the University of Tokyo). Five piston cores were recovered during Leg 4 of KH-00-5 and sand samples of three cores, namely BP1, BP3 and BP4, were studied. These cores were collected in an active deep-sea channel and its channel levee, and an old channel. The shape of active and old channels on the Bengal Fan has been described by Thu et al. (2001). An outline of lithology of these cores is described in this section after Kuroda (pers. comm.).

Core BP1, about 740 cm long, was recovered at 9°55.82' N, 86°07.96' E in an old deep-see channel on the Bengal Fan. This core is composed mainly of massive clay and alternation of massive clay and parallel laminated very fine- to fine-grained sand (Fig. 61). There are four relatively thick (more than 15 cm) parallel laminated sand beds. One sand sample was collected from parallel laminated very fine- to fine-grained sand bed near the bottom of this core (Fig. 61).

Core BP3, about 880 cm long, was recovered at 12°03.40' N, 87°24.82' E in an active deep-sea channel on the Bengal Fan. Its lower to middle part is composed of massive medium-grained sand, and its upper part is composed mainly of massive clay and alternation of silt and clay (Fig. 61). Many patches were observed in the clay of the uppermost part. Four samples were collected from the massive medium-grained sand in the lower to middle part of this core (Fig. 61).

Core BP4, about 940 cm long, was recovered at 12°03.39' N, 87°24.31' E on a

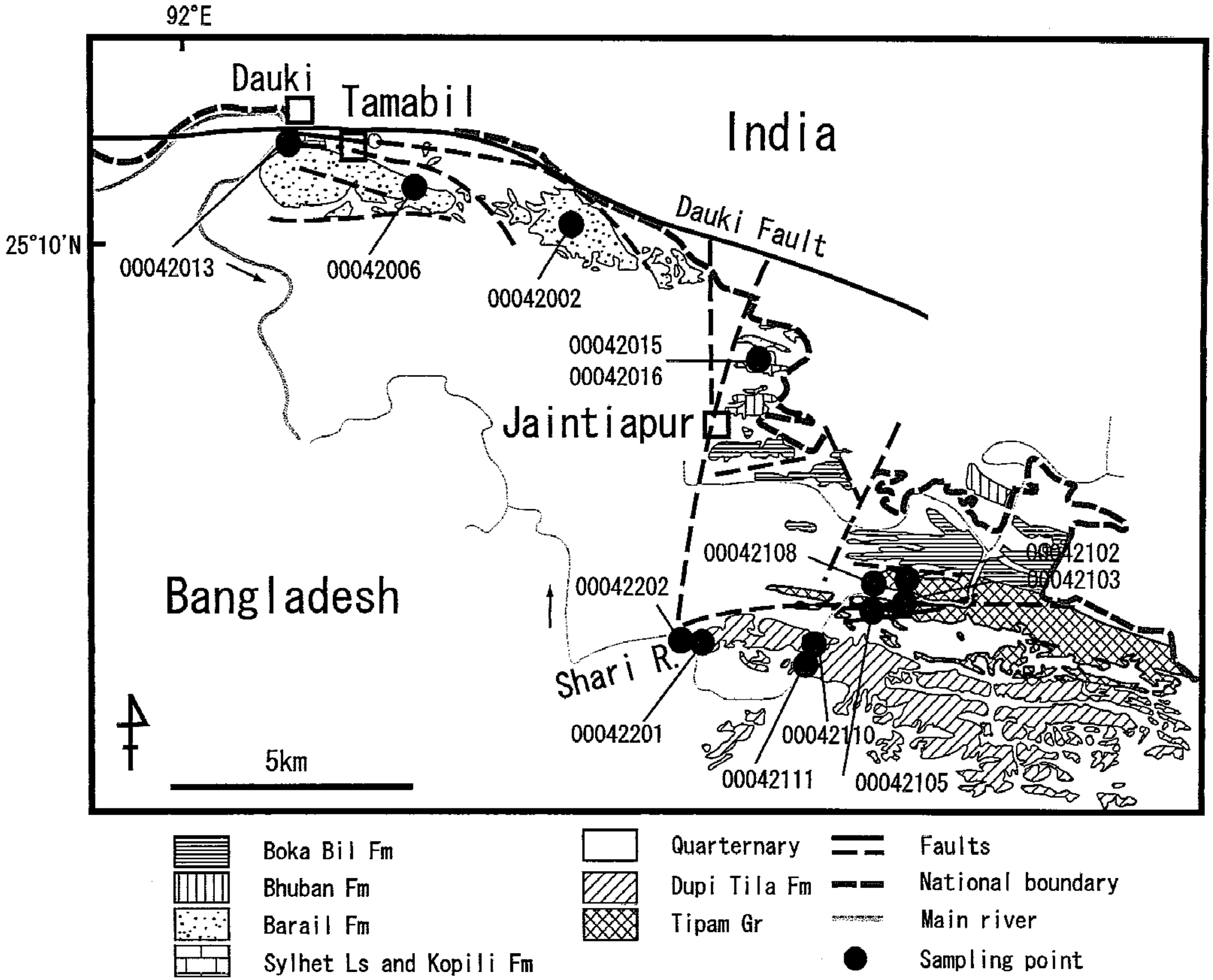


Fig. 59. Geological map of the northern part of the Sylhet area (Reimann, 1993).

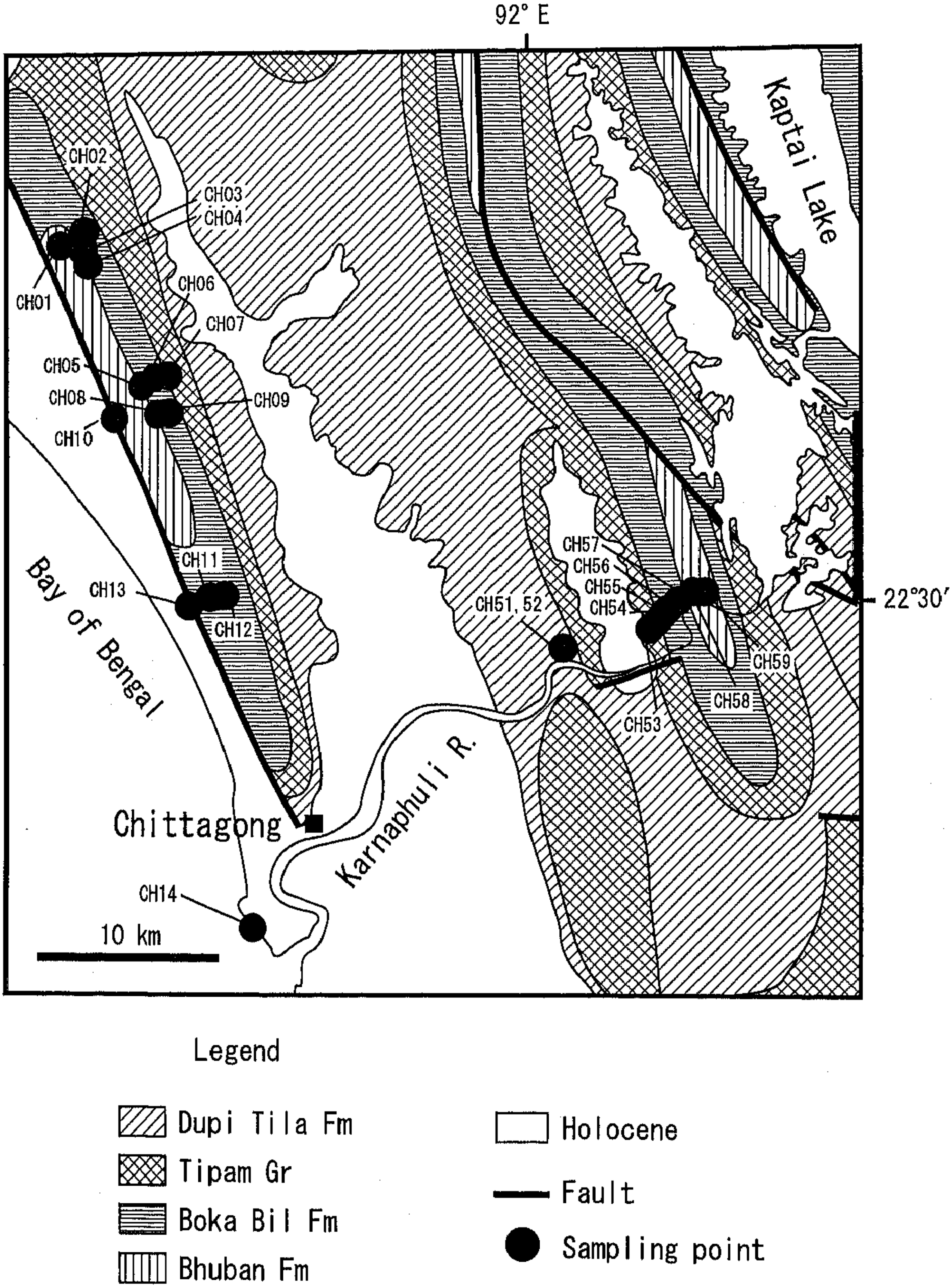


Fig. 60. Geologic map of the Chittagong area.
Simplified from Alam et al. (1990).

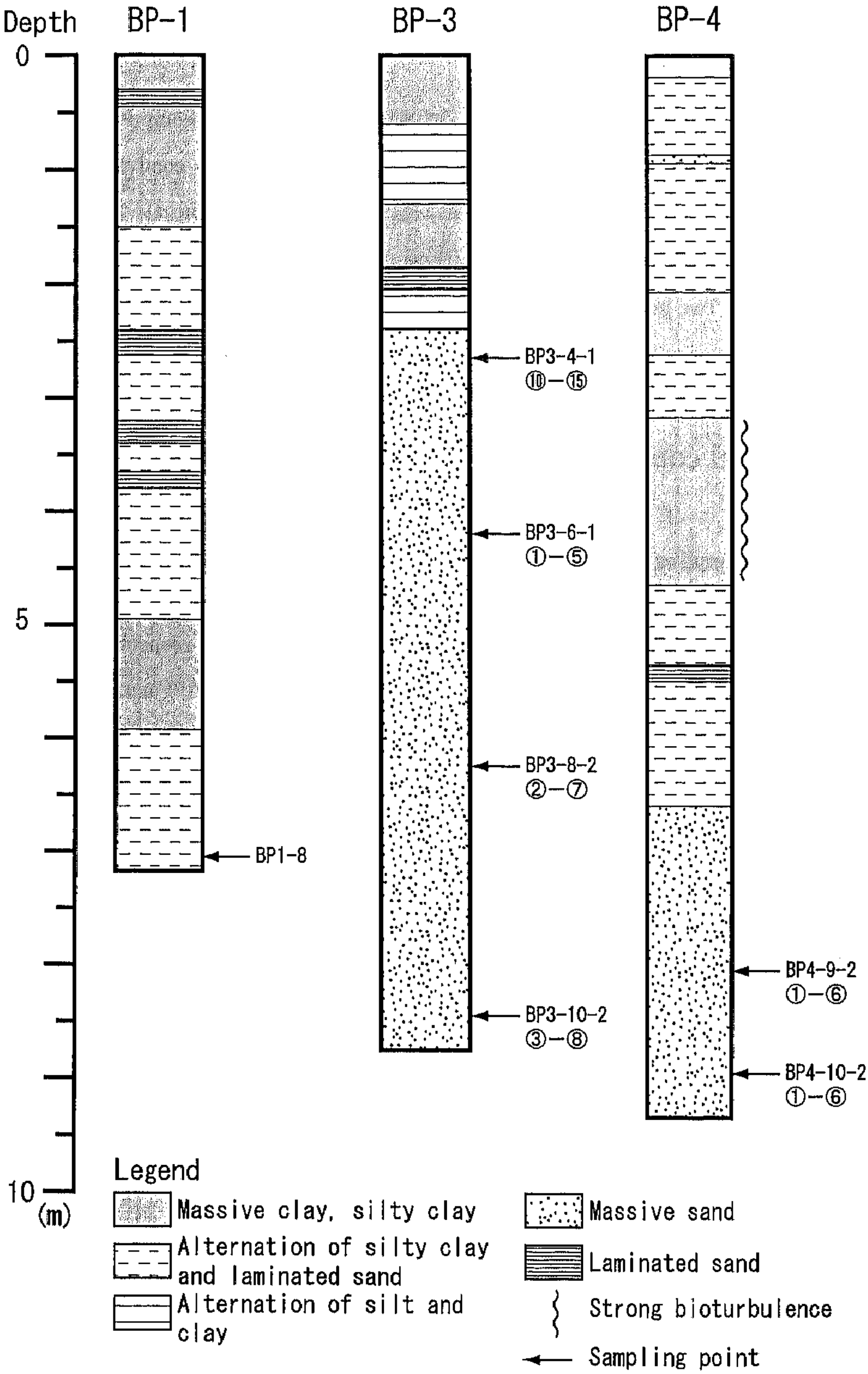


Fig. 61. Lithology of piston cores from the Bengal Fan.

channel levee near the sampling point of BP3. Its lower part is composed of massive very fine- to fine-grained sand, and its middle to upper part is composed mainly of massive clay, and alternation of massive clay and parallel laminated very fine- to fine-grained sand (Fig. 61). Strong bioturbation was observed in the clay of the middle part (Fig. 61). Two samples were collected from the massive very fine- to fine-grained sand in the lower part (Fig. 61).

4-4. Modal composition of sandstone

The sampling localities of the sandstones and sands are shown in Figs. 59 and 60, and the selected photomicrographs of sandstone are shown in Plates 9 and 10. Twenty-four sandstones and sands, comprising three samples respectivey from the Barail Formation in the Sylhet area, Bhuban and Boka Bil Formations in the Chittagong area, six samples from the Tipam Group in both the Sylhet and Chittagong areas, five samples from the Dupi Tila Formation in both the Sylhet and Chittagong areas, and two samples from the respective BP3 and BP4 of the Bengal Fan piston core samples, were measured based on both the Gazzi-Dickinson method and traditional method. The sandstone of the Kopili Formation and the sand of the BP1 piston core sample are very finer-grained, and the measure of the modal composition was not carried out. The modal composition data of these samples are listed in Tables 8 and 9, and are plotted on the diagrams in Figs. 62 and 63. The data in Table 8 were calculated on the traditional method such as Okada (1971), while Table 9 is based on the Gazzi-Dickinson method (Ingersoll et al., 1984).

The sandstones of the Barail Formation consist mainly of monocrystalline quartz with a minor amount of polycrystalline quartz, fragments of felsic volcanic and metamorphic rocks and feldspars. (Plates 9a and 9b). The modal compositions of the sandstones of the Surma and Tipam Group are similar to each other. Those sandstones are composed mainly of quartz, plagioclase, fragments of felsic volcanic

Table 8. Modal composition of sandstones and sands in the Bengal basin based on traditional method (Okada, 1971).

Formation	sample	MQz (%)	PQz	K-fel.	Pl.	Vf	Vi	Plut.	Se.	Me.	Ot	H.M.	S.M.	If & aut.	Mtx & Cem.	total	A. D. (mm)
Barail Fm. (Sylhet)	00042002	65.4	5.6	0.0	0.6	4.4	0.0	0.4	0.0	7.2	0.6	0.2	1.8	2.4	11.4	100.0	0.201
	00042006	69.0	1.0	0.4	1.6	3.0	0.0	0.2	0.0	2.4	0.0	0.6	0.0	0.0	21.8	100.0	0.153
	00042015	49.8	2.2	2.8	2.0	5.0	0.0	0.2	0.8	3.8	0.0	0.4	9.0	0.6	23.4	100.0	0.135
Bhuban Fm. (Chittagong)	CH01	31.4	5.7	6.9	8.1	6.1	0.2	1.0	0.0	4.3	0.4	1.0	3.8	0.0	31.0	100.0	0.244
	CH58	41.2	5.8	6.4	10.0	5.0	0.0	0.6	0.6	8.0	0.0	4.2	3.0	0.0	15.2	100.0	0.184
	CH59	42.8	6.8	2.8	12.8	4.2	0.0	0.0	0.0	6.4	0.0	5.2	5.0	0.0	14.0	100.0	0.155
Boka Bil Fm. (Chittagong)	CH03	28.5	1.8	7.4	16.5	9.6	0.0	1.2	0.0	5.6	0.0	2.8	1.8	0.0	24.9	100.0	0.207
	CH05	35.6	6.0	6.0	16.0	6.6	0.0	0.4	0.4	6.0	0.0	3.2	1.0	1.0	17.8	100.0	0.224
	CH56	48.0	8.4	8.6	4.4	9.2	0.0	1.0	1.2	11.2	0.2	1.6	0.4	0.0	5.8	100.0	0.184
Tipam Gr. (Sylhet)	00042103	41.9	2.4	4.8	8.7	3.6	0.2	1.2	0.4	1.6	0.2	9.1	0.8	0.2	24.9	100.0	0.228
	00042105	31.1	2.0	8.8	10.2	12.7	0.0	3.6	1.8	10.2	0.0	4.2	6.4	0.0	9.2	100.0	0.300
	00042108	45.0	2.0	8.0	12.6	9.8	0.4	1.2	0.8	5.8	0.4	4.8	1.6	0.0	7.6	100.0	0.274
Tipam Gr. (Chittagong)	CH07	33.0	3.8	5.8	16.0	8.8	0.0	0.6	0.0	3.8	0.0	5.4	2.6	0.2	20.0	100.0	0.150
	CH54	42.9	6.2	9.0	8.0	4.4	0.2	0.8	0.4	5.2	0.0	2.8	1.4	0.0	18.6	100.0	0.274
	CH55	37.0	10.0	12.8	4.0	8.8	0.0	1.0	0.0	10.2	0.0	3.6	1.2	0.0	11.4	100.0	0.349
Dupi Tila Fm. (Sylhet)	00042111	34.8	4.9	3.6	4.0	4.9	1.6	2.2	6.9	21.5	0.0	2.0	2.6	0.0	11.1	100.0	0.469
	00042201	68.0	5.4	0.2	3.2	2.6	0.0	0.0	1.6	3.8	0.0	0.8	0.4	0.0	14.0	100.0	0.232
	00042202	73.2	6.0	0.4	5.8	2.2	0.2	0.0	0.0	0.4	0.0	0.8	0.0	0.0	11.0	100.0	0.204
Dupi Tila Fm. (Chittagong)	CH51	51.0	6.0	4.4	4.2	14.2	0.2	0.0	0.0	4.6	0.0	3.6	3.8	0.0	8.0	100.0	0.223
	CH52	56.2	13.0	5.0	2.4	9.0	0.0	0.6	1.2	5.6	0.0	0.8	0.2	0.0	6.0	100.0	0.527
BP3	8-2②-⑦	41.5	5.0	10.0	10.4	0.4	0.0	1.0	3.2	10.0	0.0	16.6	0.0	1.4	0.6	100.0	0.201
	10-2③-⑧	47.0	5.2	5.2	10.8	0.2	0.0	1.6	3.6	9.4	0.0	15.6	0.0	0.6	0.8	100.0	0.180
BP4	9-2①-⑥	45.6	4.4	4.4	9.0	2.2	0.0	0.2	3.4	4.0	0.4	24.8	0.0	1.0	0.6	100.0	0.091
	10-2①-⑥	47.8	2.6	8.4	14.8	1.0	0.0	0.2	2.4	4.8	0.2	17.4	0.0	0.0	0.4	100.0	0.085

Me.: metamorphic rock fragments. The other symbols are same to those in Table 1.

Table 9. Modal composition of sandstones and sands in the Bengal basin based on Gazzi-Dickinson method (Ingersoll et al., 1984)

Formation	sample	Qm (%)	Qp	K-fel.	Pl.	Lvf	Lvi	Ls	Lm	Ot	H.M.	S.M.	If & aut.	Mtx & Cem.	total	A. D. (mm)
Barail Fm. (Sylhet)	00042002	68.4	2.6	0.0	1.0	4.4	0.0	0.0	7.2	0.6	0.2	1.8	2.4	11.4	100.0	0.201
	00042006	70.0	0.2	0.4	1.6	3.0	0.0	0.0	2.4	0.0	0.6	0.0	0.0	21.8	100.0	0.153
	00042015	52.2	0.2	2.8	2.0	4.8	0.0	0.8	3.8	0.0	0.4	9.0	0.6	23.4	100.0	0.135
Bhuban Fm. (Chittagong)	CH01	36.6	1.0	6.9	8.9	6.1	0.2	0.0	4.2	0.4	1.0	3.8	0.0	31.0	100.0	0.244
	CH58	47.6	0.0	6.6	10.6	5.0	0.0	0.6	7.2	0.0	4.2	3.0	0.0	15.2	100.0	0.184
	CH59	50.0	0.6	2.8	13.4	4.2	0.0	0.0	4.8	0.0	5.2	5.0	0.0	14.0	100.0	0.155
Boka Bil Fm. (Chittagong)	CH03	30.7	0.4	7.6	17.5	8.8	0.0	0.0	5.6	0.0	2.8	1.8	0.0	24.9	100.0	0.207
	CH05	41.4	0.4	6.2	16.2	6.4	0.0	0.4	6.0	0.0	3.2	1.0	1.0	17.8	100.0	0.224
	CH56	59.2	1.2	9.0	4.8	8.8	0.0	0.0	9.0	0.2	1.6	0.4	0.0	5.8	100.0	0.184
Tipam Gr. (Sylhet)	00042103	44.7	0.4	5.2	9.1	3.6	0.2	0.2	1.4	0.2	9.1	0.8	0.2	24.9	100.0	0.228
	00042105	36.9	0.0	9.6	11.2	12.2	0.0	1.8	8.8	0.0	4.2	6.4	0.0	9.2	100.0	0.300
	00042108	48.8	0.0	8.0	13.0	9.4	0.4	0.8	5.2	0.4	4.8	1.6	0.0	7.6	100.0	0.274
Tipam Gr. (Chittagong)	CH07	37.2	0.2	6.0	16.2	8.4	0.0	0.0	3.8	0.0	5.4	2.6	0.2	20.0	100.0	0.150
	CH54	49.7	0.4	9.2	8.2	4.4	0.2	0.0	5.0	0.0	2.8	1.4	0.0	18.6	100.0	0.274
	CH55	48.4	0.4	13.0	5.0	8.8	0.0	0.0	8.2	0.0	3.6	1.2	0.0	11.4	100.0	0.349
Dupi Tila Fm. (Sylhet)	00042111	45.1	0.4	4.5	4.7	4.9	1.6	5.5	17.6	0.0	2.0	2.6	0.0	11.1	100.0	0.469
	00042201	76.8	0.4	0.2	3.2	2.6	0.0	0.0	1.6	0.0	0.8	0.4	0.0	14.0	100.0	0.232
	00042202	79.4	0.2	0.4	5.8	2.0	0.2	0.0	0.2	0.0	0.8	0.0	0.0	11.0	100.0	0.204
Dupi Tila Fm. (Chittagong)	CH51	57.4	0.6	4.4	4.8	13.4	0.0	0.0	4.0	0.0	3.6	3.8	0.0	8.0	100.0	0.223
	CH52	72.2	0.4	5.2	2.6	8.6	0.0	0.0	4.0	0.0	0.8	0.2	0.0	6.0	100.0	0.527
BP3	8-2②-⑦	51.7	0.2	10.2	11.8	0.4	0.0	3.0	4.2	0.0	16.6	0.0	1.4	0.6	100.0	0.201
	10-2③-⑧	55.0	0.2	5.6	12.6	0.0	0.0	3.4	6.2	0.0	15.6	0.0	0.6	0.8	100.0	0.180
BP4	9-2①-⑥	49.8	0.6	4.4	9.2	2.2	0.0	3.4	3.6	0.4	24.8	0.0	1.0	0.6	100.0	0.091
	10-2①-⑥	50.6	0.2	8.4	15.2	1.0	0.0	2.4	4.2	0.2	17.4	0.0	0.0	0.4	100.0	0.085

Lm: metamorphic lithics. The other symbols are same to those in Table 2.

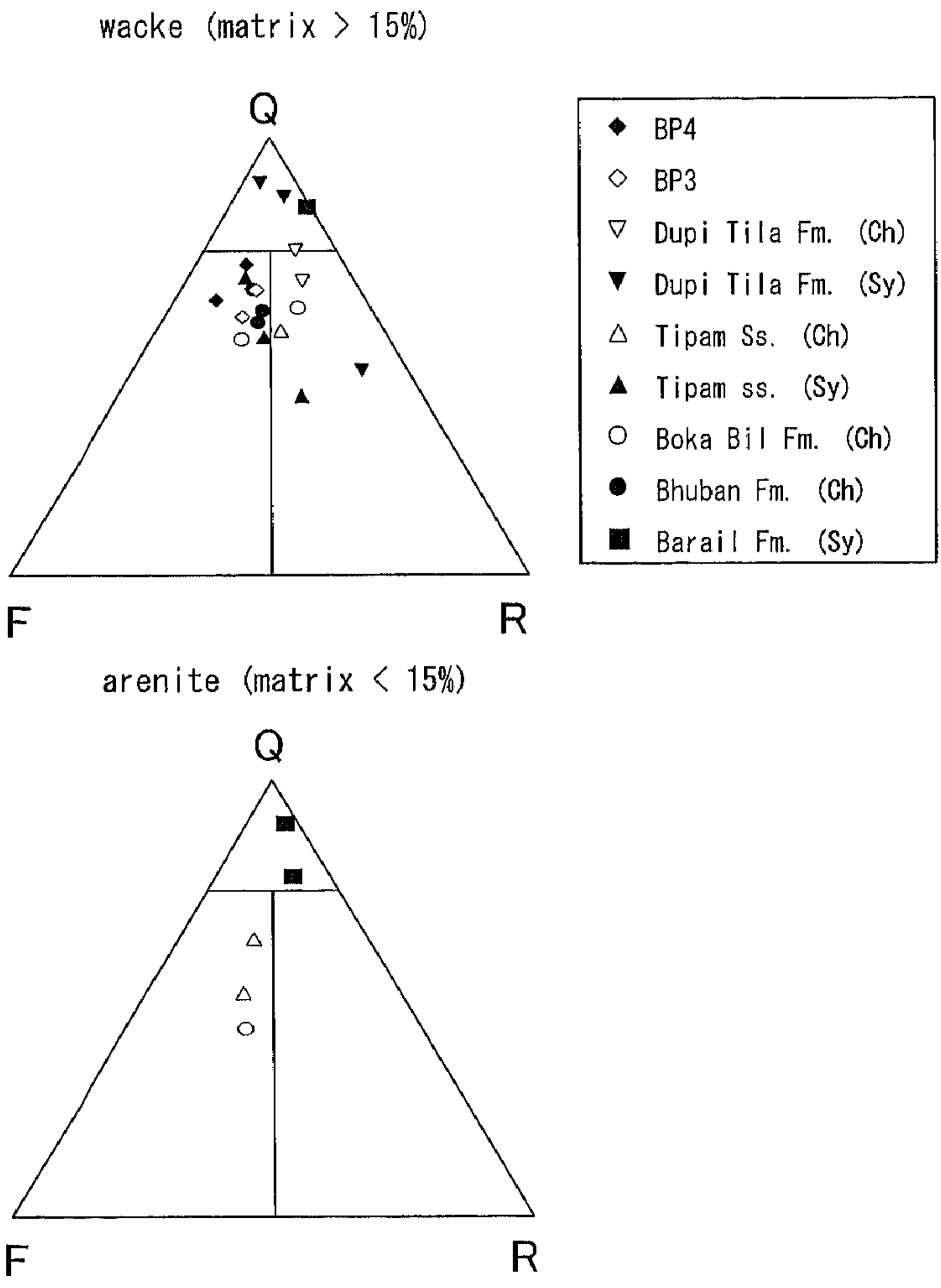


Fig. 62. Q-F-R diagrams of the sandstones and sands in the Bengal basin. Data from Table 8. The subdivisions are after Okada (1971). Q: total quartz (MQz+PQz), F: total feldspar, R: total rock fragments. Sy: Sylhet area. Ch: Chittagong area.

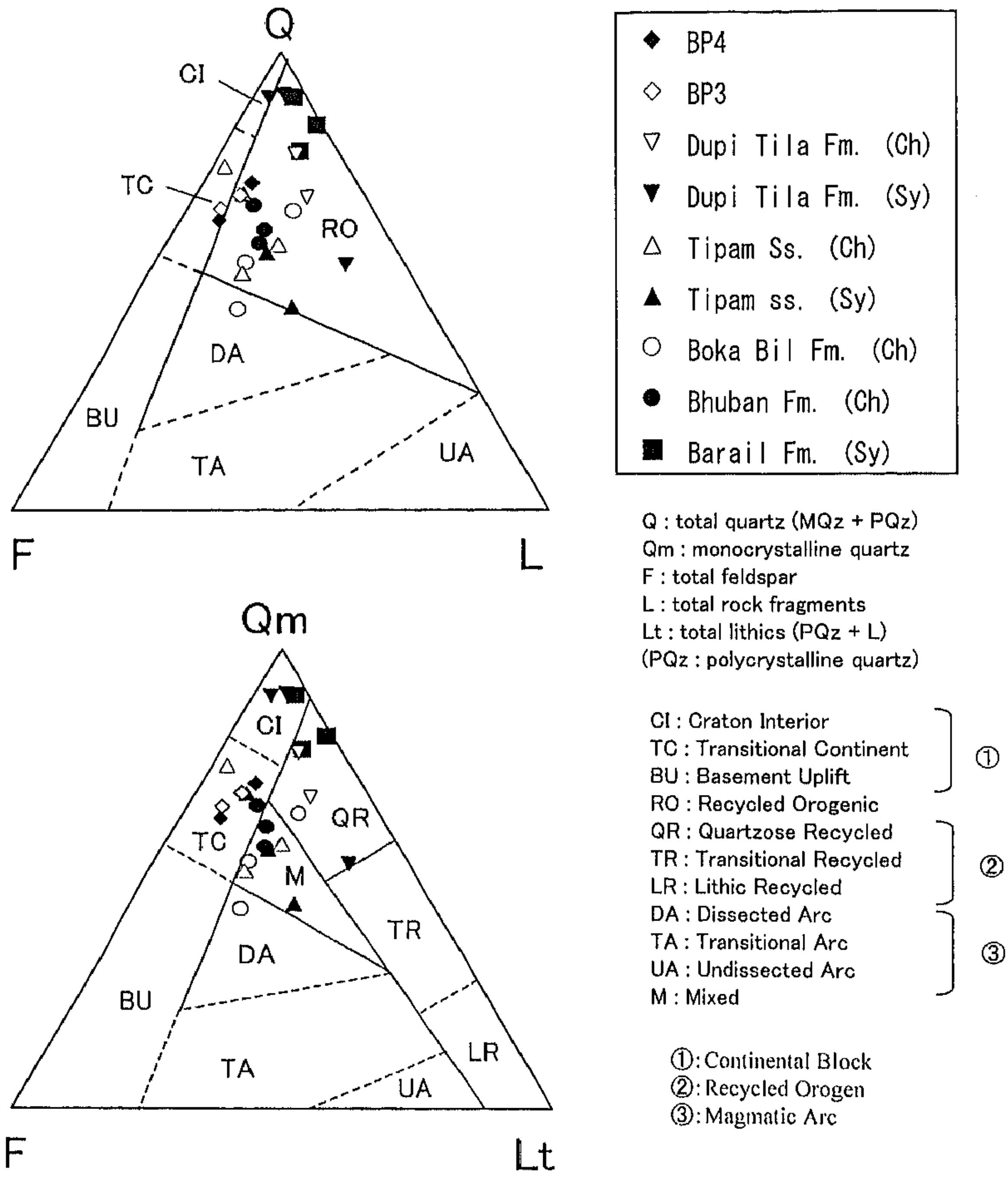


Fig. 63. Q-F-L and Qm-F-Lt diagrams of the sandstones and sands in the Bengal basin based on the Gazzi-Dickinson method. Data from Table 9. The subdivisions are after Dickinson et al. (1983). Sy: Sylhet area. Ch: Chittagong area.

metamorphic rocks, polycrystalline quartz, K-feldspar, and heavy minerals (Plates 9a to 10b). The Boka Bil Formation and the Tipam Group sandstones contain some fragments of myrmekite, and the Tipam Group sandstones also contain some fragments of quartzite. The range of the modal compositions of sandstones of the Dupi Tila Formation are relatively wider (Figs. 62 and 63). Two samples are extremely quartzose with a small amount of polycrystalline quartz, plagioclase and fragments of felsic volcanic and metamorphic rocks. The other samples are relatively lithic, and composed of quartz, fragments of felsic volcanic rock, sandstone and metamorphic rocks, plagioclase, polycrystalline quartz, K-feldspar, and heavy minerals (Plates 10c to 10f). The Dupi Tila Formation sandstones also contain some fragments of quartzite. The modal compositions of sands from BP3 and BP4 of the Bengal Fan piston core samples are similar to each other (Figs. 62 and 63). These sands are composed mainly of quartz, heavy minerals, plagioclase, fragments of metamorphic rocks, K-feldspar, and polycrystalline quartz.

4-5. Detrital chromian spinel

4-5-1. Occurrence and petrographic description

Detrital chromian spinels were obtained from the sandstones of all the groups, formations and piston core samples investigated in this study. Detrital chromian spinels were also obtained from the beach sand at Chittagong City. All the detrital chromian spinels were collected with heavy liquid separation.

All the detrital chromian spinel grains obtained from the Kopili, Barail, Bhuban and Dupi Tila Formations and the Tipam Group in the Sylhet area present yellowish brown to black (Plates 11a to 11e). The detrital chromian spinel grains obtained from the Bhuban and Boka Bil Formations and the Tipam Group in the Chittagong area also present yellowish brown to black, whereas those from the Dupi

Tila Formation in the Chittagong area and beach sand present reddish brown to black (Plates 11f and 11g). Most of the detrital chromian spinels from the piston core samples present yellowish brown to black (Plates 11h to 11j), while sands from the BP3 contain no chromian spinel which present yellowish brown.

Grain size and diameter of the detrital chromian spinels from the sand samples were measured. The spinel grains from beach sand and piston core samples are generally subangular to subrounded. Diameters of spinels from the beach sand are 0.08 to 0.20 mm. Diameters of spinels from the BP1 and BP4 are 0.03 to 0.08 mm, and those from the BP3 are 0.08 to 0.18 mm.

4-5-2. Chemical compositions

A total of 727 chemical analyses of detrital chromian spinels were obtained from the sands and sandstones of Bangladesh and Bengal Fan piston core sample in this study. Figs. 64 to 73 show the chemical compositions of spinels from each formation.

41 chemical analyses of chemical compositions of detrital chromian spinels were obtained from sandstones of the Kopili Formation. The composition varies widely without a strong concentration (Fig. 64). Cr# range is 0.26 to 0.88 and is mostly > 0.42. Mg# is 0.30 to 0.71. Fe^{3+}3# (= $Fe^{3+}/(Fe^{3+}+Cr+Al)$) range is 0.00 to 0.14, mostly below 0.08. TiO_2 wt% range is mostly 0.10 to 0.83, and five out of 41 grains have TiO_2 wt%>1.5. One grain has a high MnO and ZnO content of 2.26 and 4.18 wt%, respectively.

54 chemical analyses of detrital chromian spinel were obtained from the Barail Formation. Cr# range is mostly 0.33 to 0.85. Mg# range is 0.32 to 0.79, and concentrates in the range 0.45 to 0.7 (Fig. 65). Fe^{3+}3# range is 0.00 to 0.12, and is mostly below 0.08. TiO_2 wt% range is mostly 0.00 to 0.30, and one out of 37 grain has1.85 TiO_2 wt%. One grain has relatively higher MnO and ZnO contents of 1.03 and 0.92 wt%, respectively.

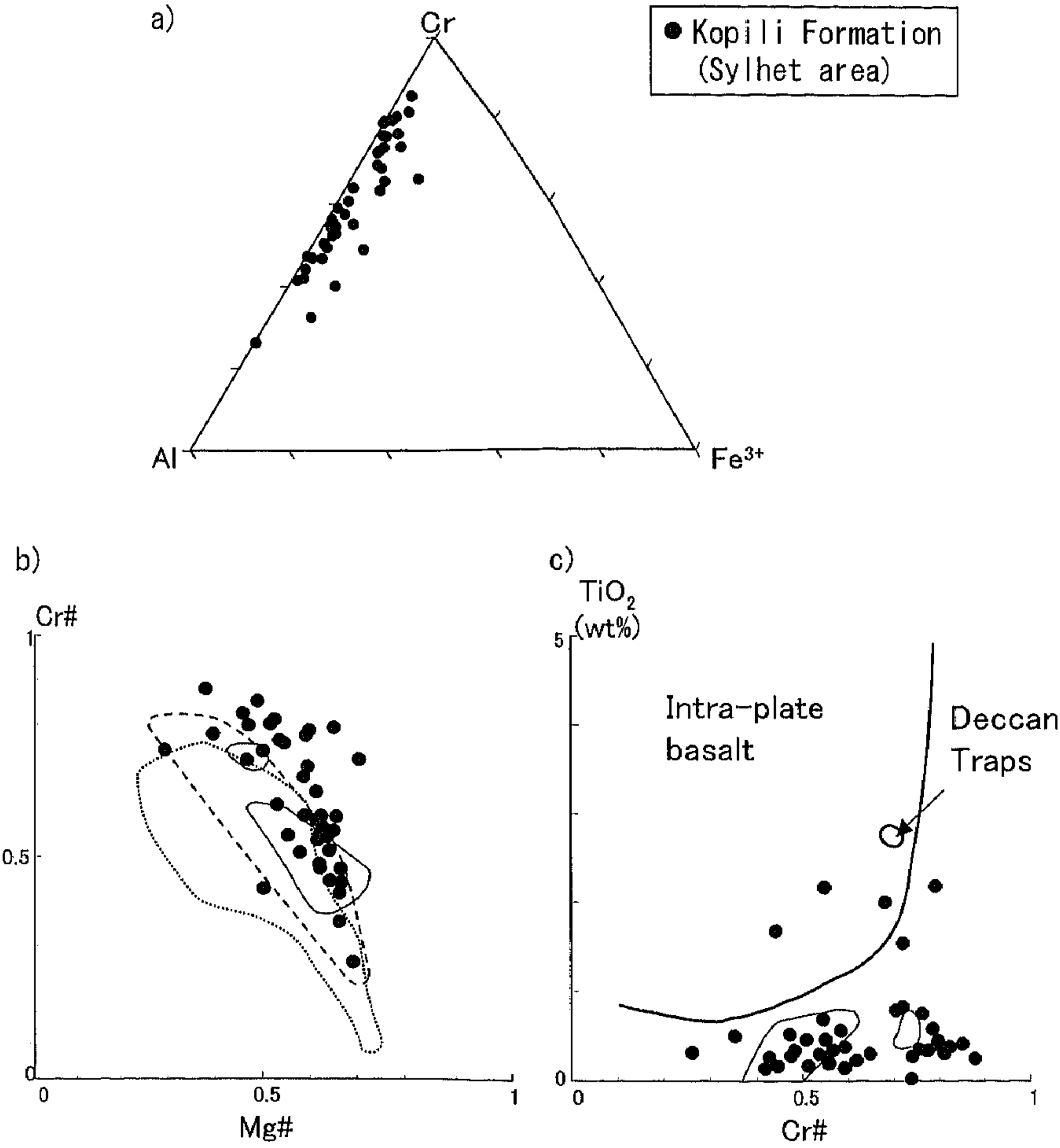


Fig. 64. Chemical compositions of detrital chromian spinels from the Kopili Formation. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

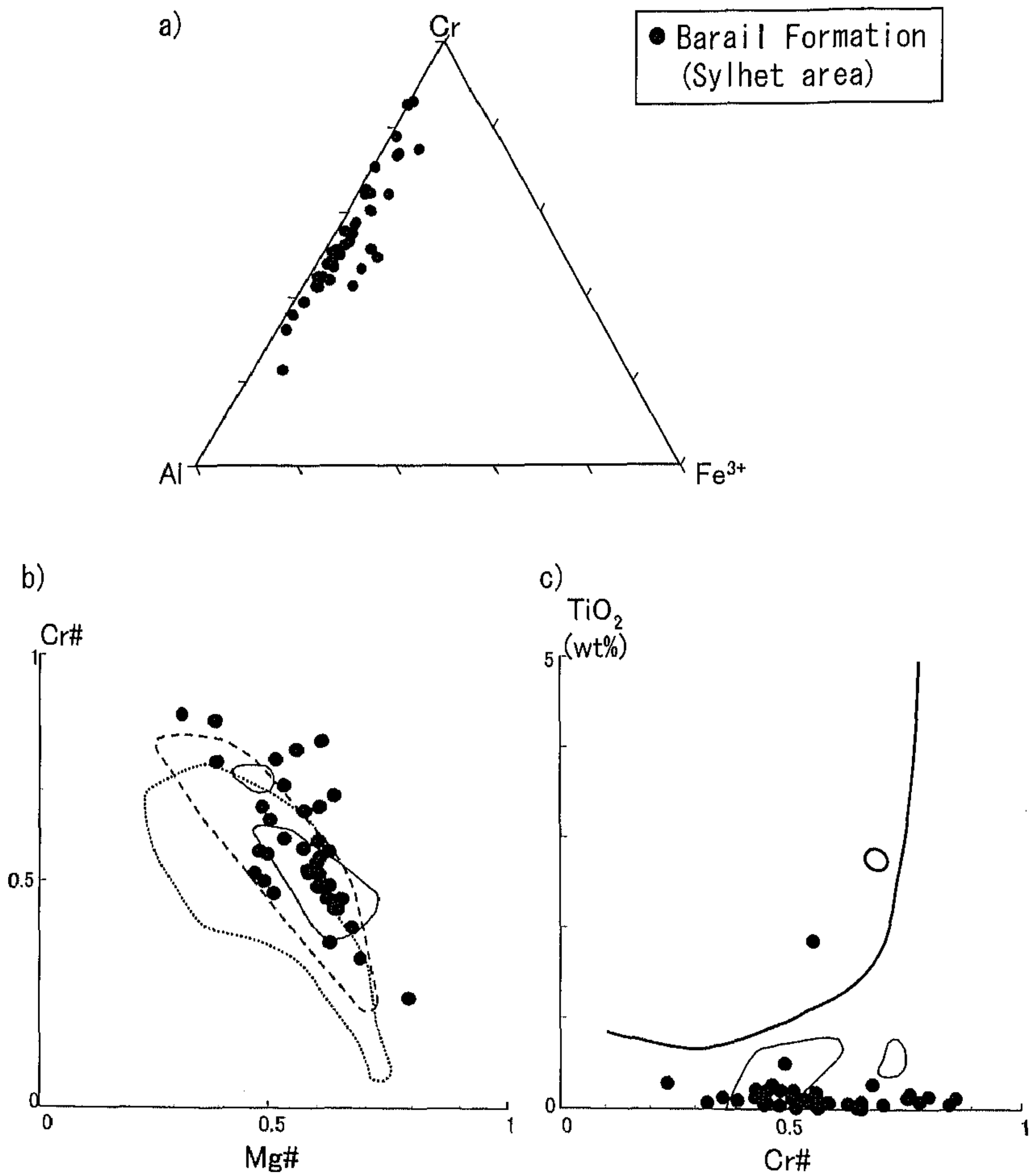


Fig. 65. Chemical compositions of detrital chromian spinels from the Barail Formation. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

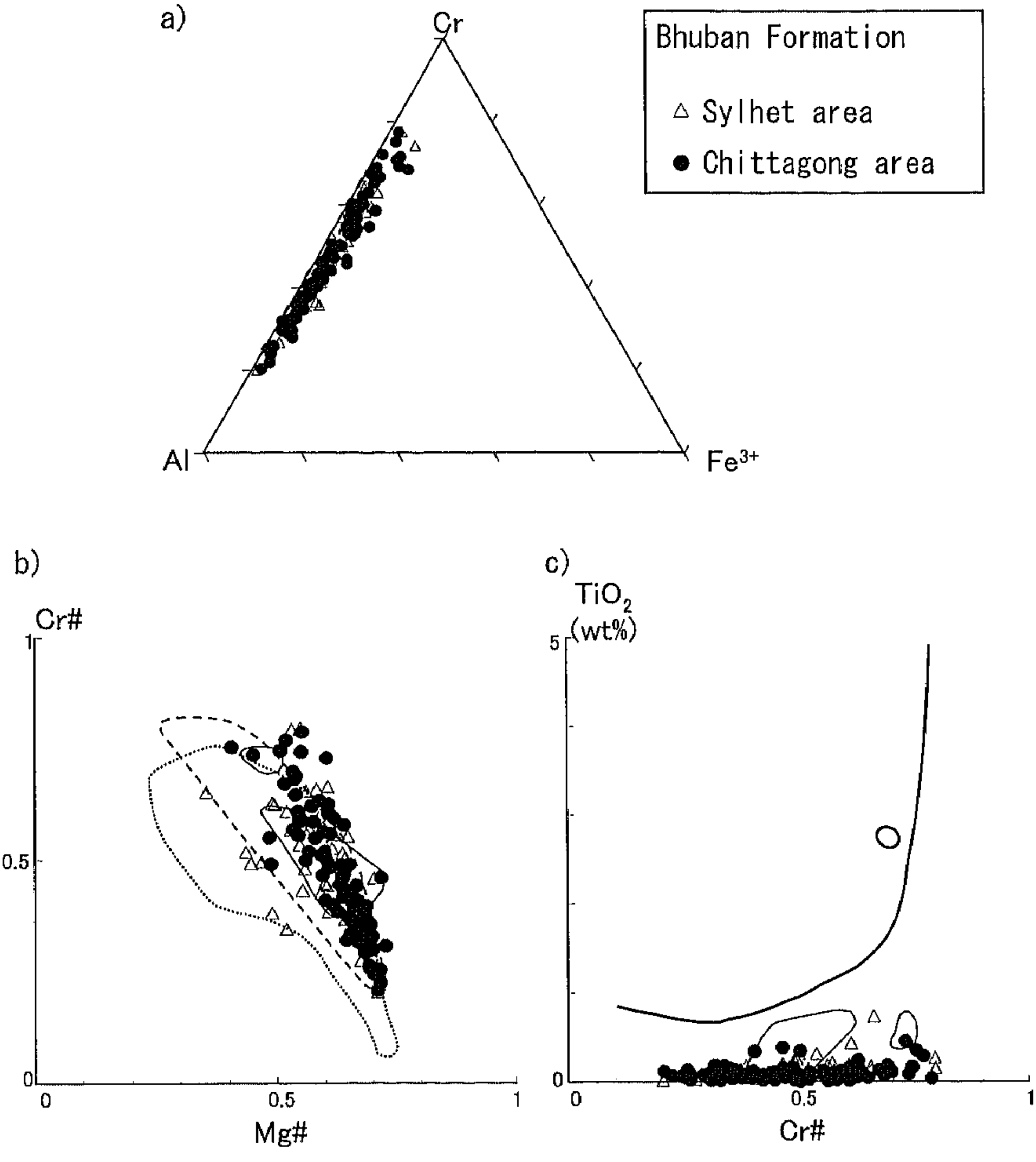


Fig. 66. Chemical compositions of detrital chromian spinels from the Bhuban Formation. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

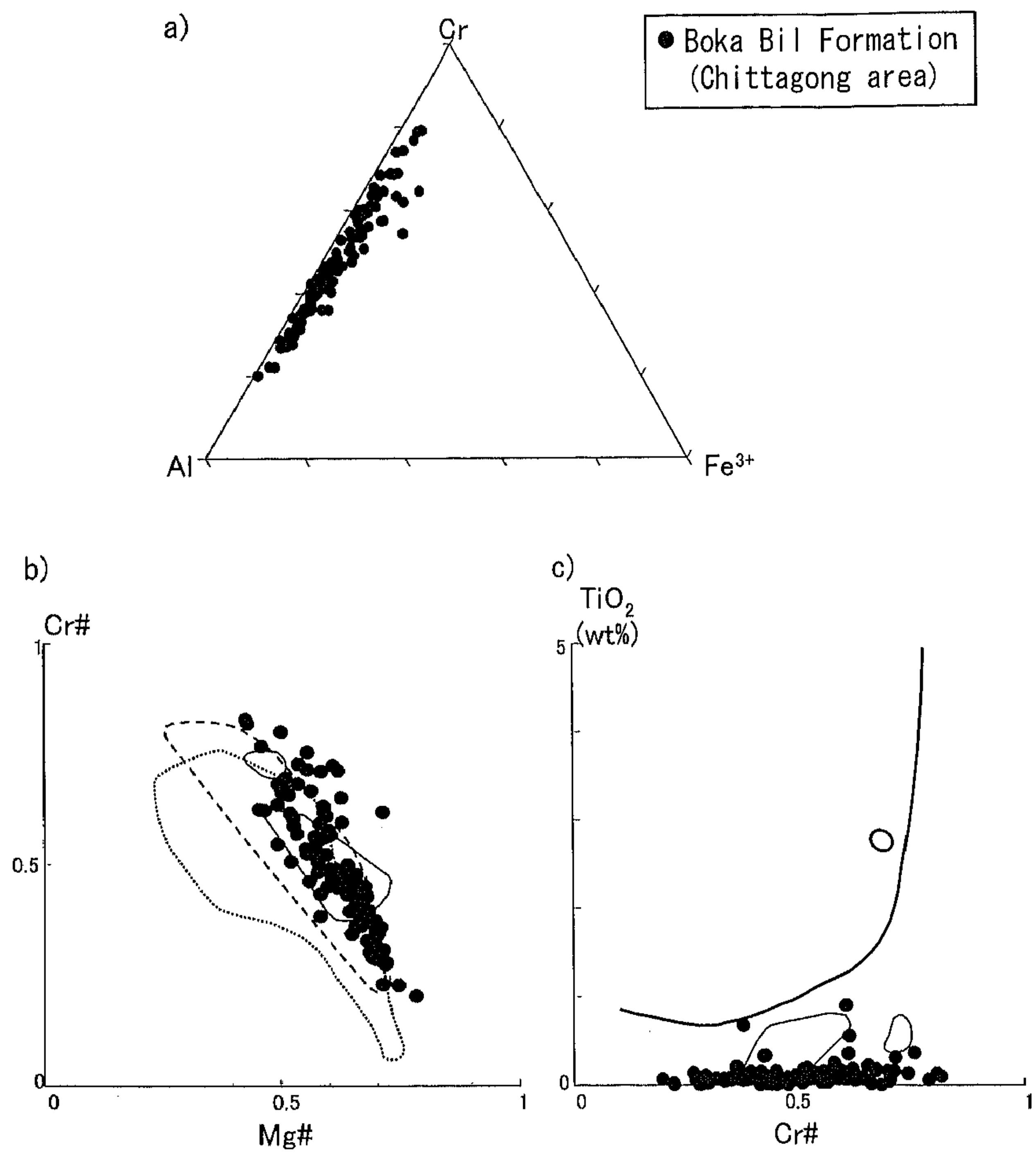


Fig. 67. Chemical compositions of detrital chromian spinels from the Boka Bil Formation. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

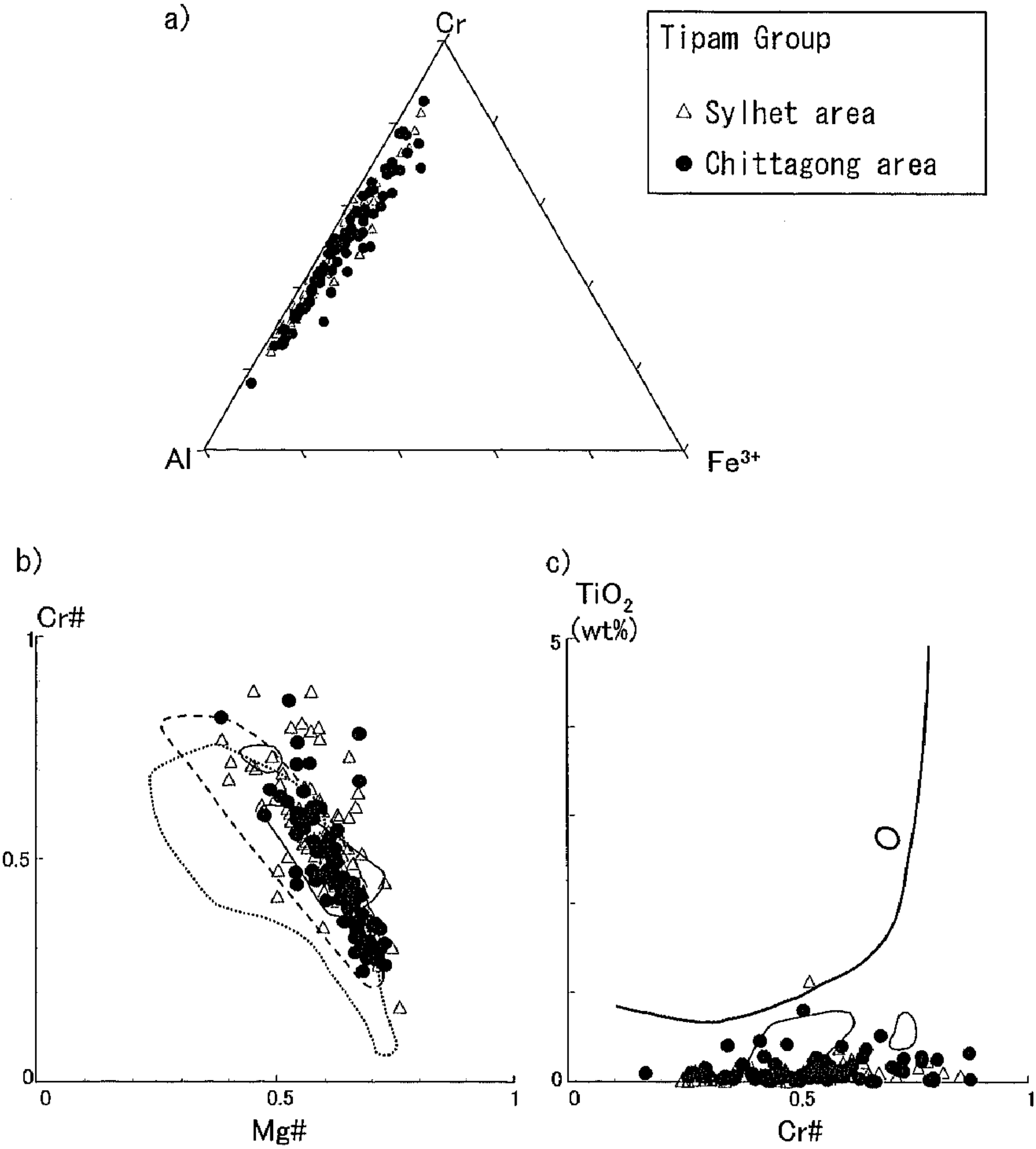


Fig. 68. Chemical compositions of detrital chromian spinels from the Tipam Group. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

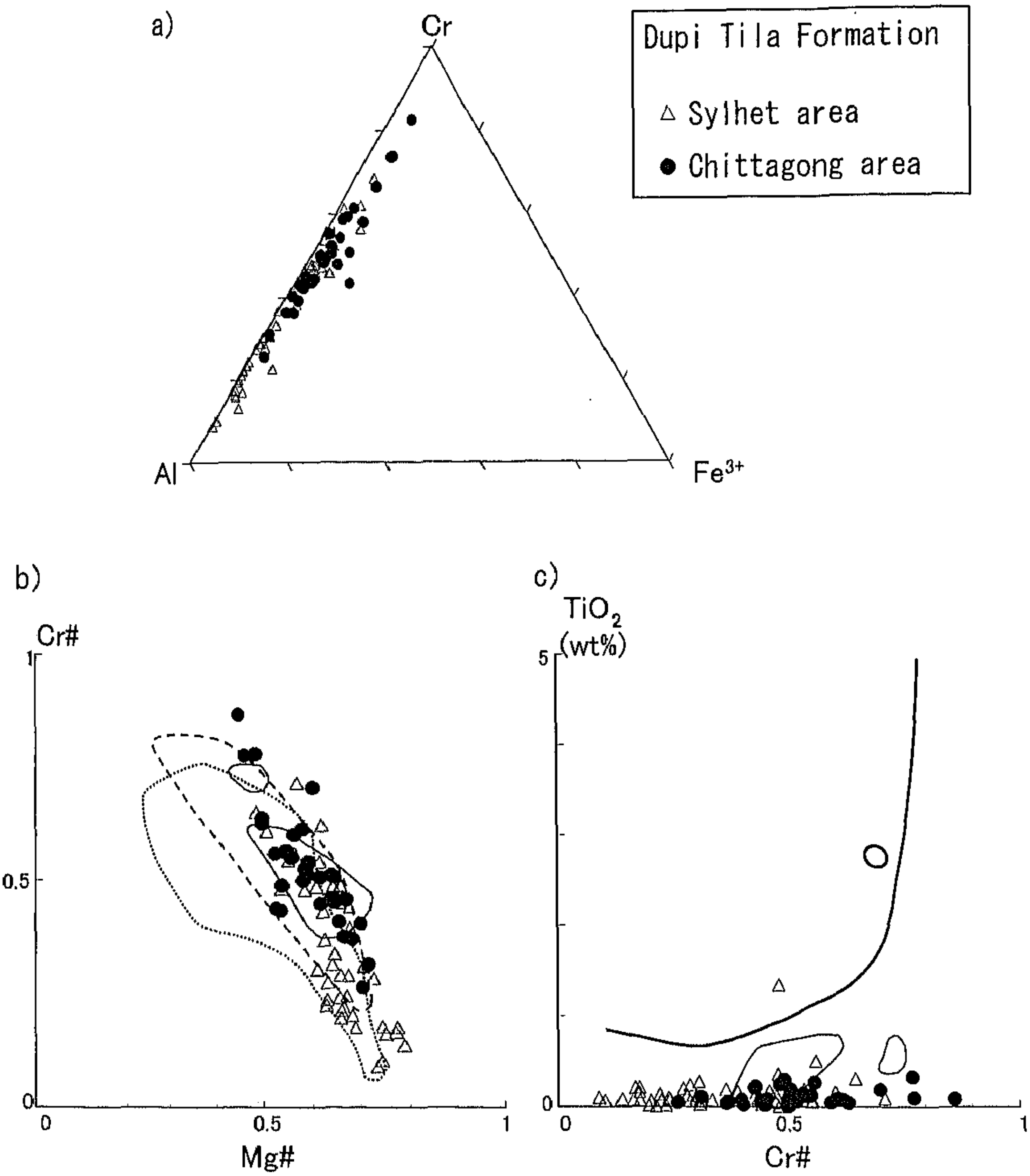


Fig. 69. Chemical compositions of detrital chromian spinels from the Dupi Tila Formation. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

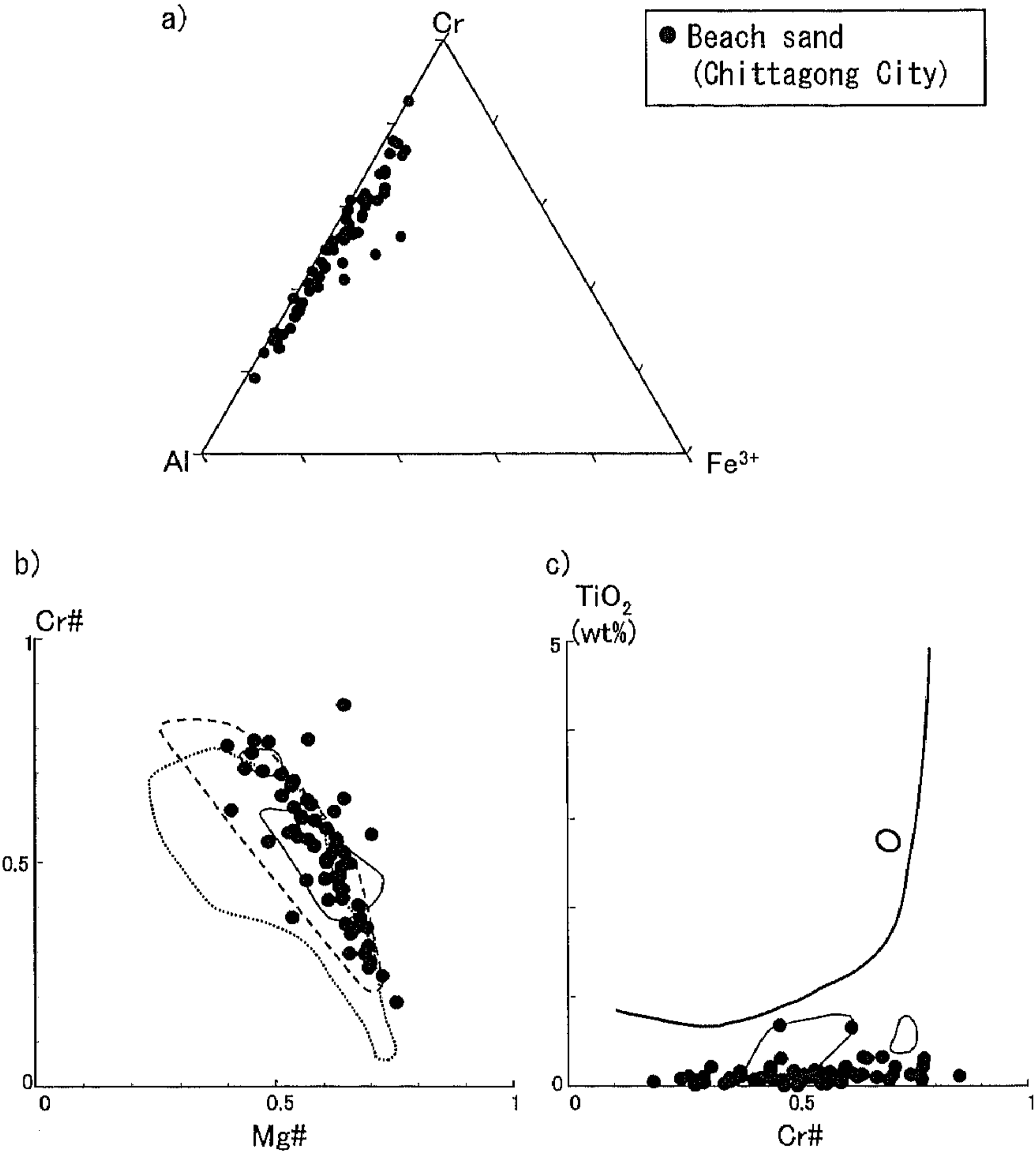


Fig. 70. Chemical compositions of detrital chromian spinels from beach sand in the Chittagong City. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

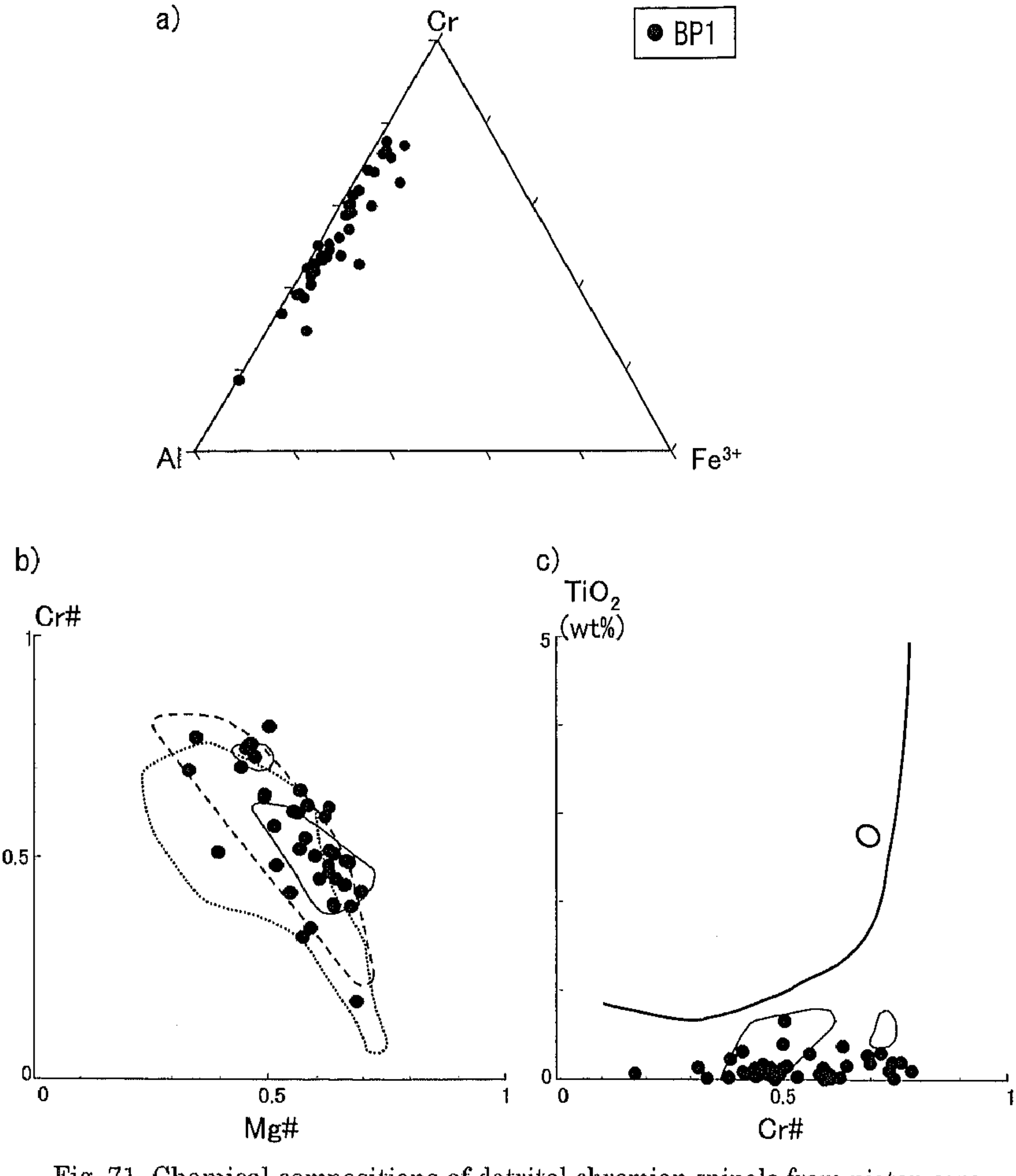


Fig. 71. Chemical compositions of detrital chromian spinels from piston core sample of BP1. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

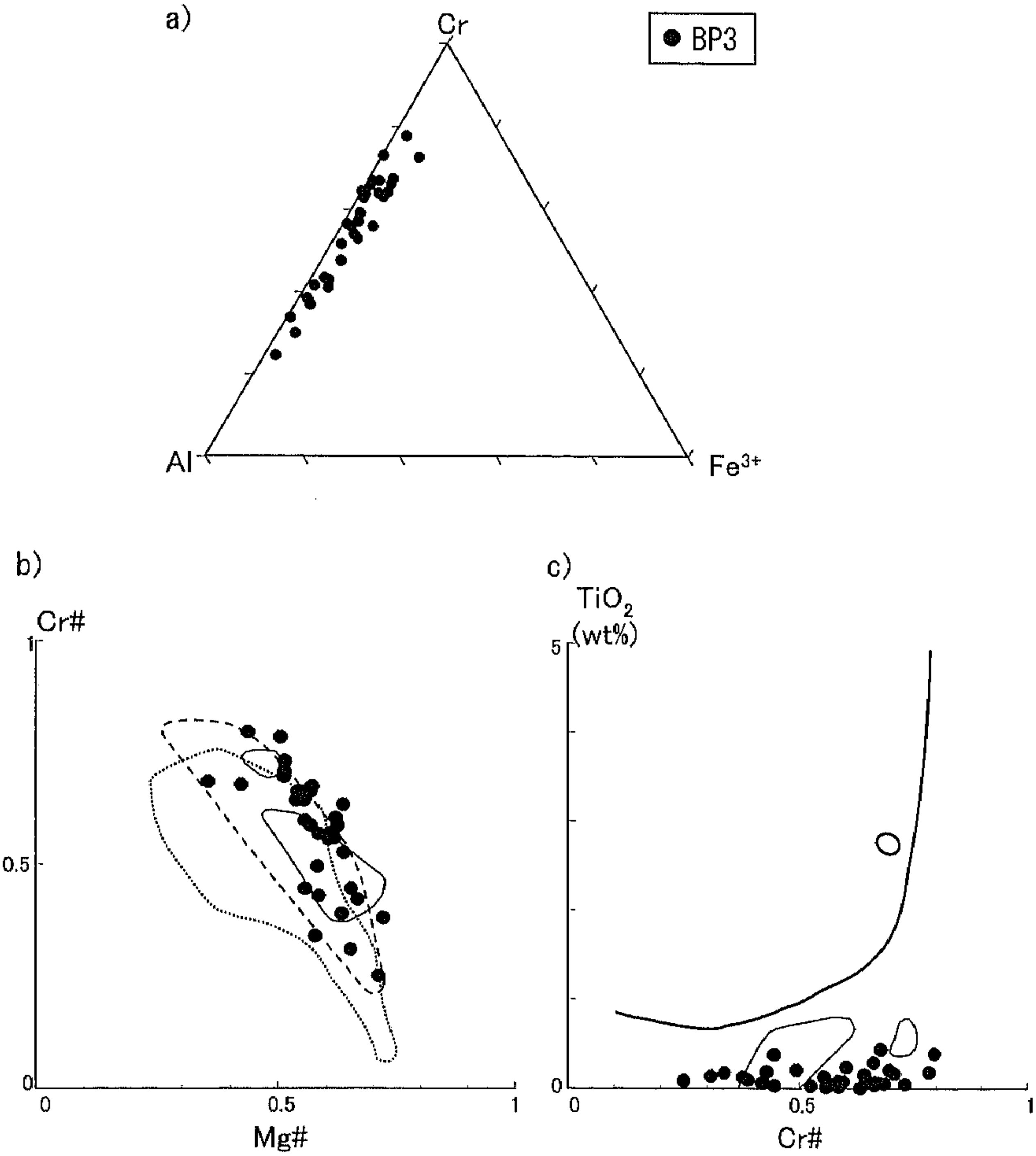


Fig. 72. Chemical compositions of detrital chromian spinels from piston core sample of BP3. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

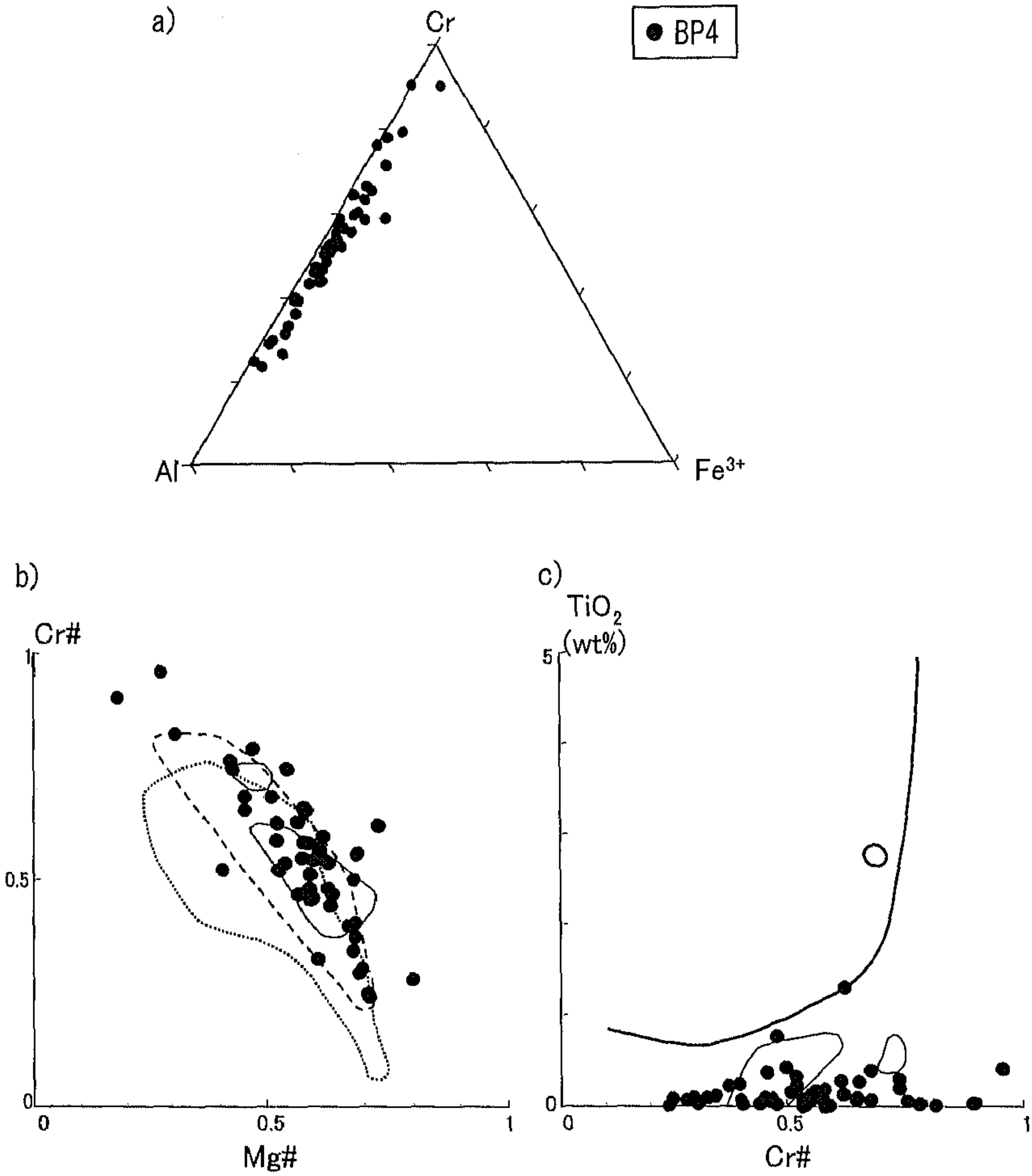


Fig. 73. Chemical compositions of detrital chromian spinels from piston core sample of BP4. a) Cr-Al-Fe^{3+} diagram, b) Mg# vs. Cr# diagram, c) Cr# vs. TiO_2 diagram. The range of serpentinite from the Yarlung-Zangbo ophiolite is surrounded by a dotted line (Wang et al., 2000) and thin lines (Huot et al., 2002). The range of intra-plate basalt (Arai, 1992) and basalt in the Deccan Traps (Krishnamurthy and Cox, 1977) is surrounded by thick lines. The range of detrital chromian spinels from the Chulung La Formation is surrounded by a broken line (Garzanti et al., 1987).

132 chemical analyses of detrital chromian spinels, comprising 48 grains from the Sylhet area and 84 grains from the Chittagong area, were obtained from the Bhuban Formation. The plots of the chromian spinels from these areas show a similar distribution (Fig. 66). Cr# range is 0.20 to 0.80, while Mg# is mostly 0.40 to 0.70. Fe^{3+}3# range is 0.00 to 0.06. TiO_2 wt% range is mostly 0.00 to 0.50, though one grain has TiO_2 wt% > 0.5.

110 chemical analyses of detrital chromian spinels were obtained from the Boka Bil Formation in the Chittagong area (Fig. 67). Cr# range is 0.20 to 0.83, and Mg# is 0.43 to 0.78. Fe^{3+}3# range is 0.00 to 0.13, mostly below 0.10. TiO_2 wt% range is mostly 0.00 to 0.36, and three out of 110 grains have TiO_2 wt% > 0.5.

123 chemical analyses of detrital chromian spinels, comprising 56 grains from the Sylhet area and 67 grains from the Chittagong area, were obtained from the Tipam Group. The plots of the chromian spinels from both areas show a similar distribution (Fig. 68). Cr# range is 0.20 to 0.85, while Mg# is mostly 0.45 to 0.73. Fe^{3+}3# range is 0.00 to 0.10. TiO_2 wt% range is mostly 0.00 to 0.42, and four out of 123 grains have TiO_2 wt% > 0.5.

84 chemical analyses of detrital chromian spinels, comprising 32 grains from the Sylhet area and 52 grains from the Chittagong area, were obtained from the Dupi Tila Formation. The chemical tendencies of the chromian spinels from both areas are different each other (Fig. 69). Cr# range of the Sylhet area is 0.25 to 0.80, while Cr# range of the Chittagong area is 0.09 to 0.62. Mg # range of the Sylhet area is mostly 0.45 to 0.72, while Mg # range of the Chittagong area is 0.49 to 0.79. Fe^{3+}3# ranges of both areas are mostly 0.00 to 0.08. TiO_2 wt% range of both areas are mostly 0.00 to 0.35, though one grain from the Chittagong area has TiO_2 wt% > 1.0. One spinel grain which consists mainly of Al_2O_3, ZnO and FeO, that is, zincian spinel, was found from the Dupi Tila Formation in the Chittagong area. This spinel presents green color.

62 chemical analyses of detrital chromian spinels were obtained from the beach sand sample from Chittagong City (Fig. 70). Cr# range is mostly 0.25 to 0.78, and Mg# range is 0.40 to 0.75. Fe^{3+}3# range is 0.00 to 0.15, mostly below 0.08. TiO_2

wt% range is mostly 0.00 to 0.32, and two out of 110 grains have TiO_2 wt% > 0.5.

121 chemical analyses of detrital chromian spinels, comprising 31 grains from the BP1, 33 grains from the BP3 and 49 grains from the BP4, were obtained from the Bengal Fan piston core samples. The plots of the chromian spinels from these areas show s similar distribution (Figs. 71 to 73). Cr# range is mostly 0.24 to 0.82, while Mg# is mostly 0.27 to 0.73. Fe^{3+}3# range is 0.00 to 0.11. TiO_2 wt% range is mostly 0.00 to 0.43, and three out of 123 grains have TiO_2 wt% > 0.5. Two grains have higher ZnO contents of 1.06 and 12.88 wt%, respectively.

4-6. Detrital garnet

4-6-1. Occurrence and petrographic description

Many sand and sandstone samples from Bangladesh and Bengal Fan yield numerous detrital garnets. The Kopili and Barail Formations yield detrital garnets using the heavy liquid separation. Few detrital garnets, however, were extracted from the sandstones of the Bhuban Formation in the Sylhet area and the Dupi Tila Formation in the Chittagong area.

The detrital garnets obtained from the Kopili and Barail Formations are colorless, while those from the Bhuban, Boka Bil, Dupi Tila Formations, and the Tipam Group are colorless to light pink or light brown (Plates 12a to 12f). The detrital garnets obtained from the beach sand at Chittagong City are colorless to light pink (Plate 12g), and those from the Bengal Fan piston core samples are colorless to light pink or light brown (Plates 12h to j).

All the detrital garnets obtained from the Bangladesh and Bengal Fan are sub-angular to sub-rounded. Their diameters vary with the grain size of the sands and sandstones, and the ranges of the grain size of the detrital garnets from the Bhuban Formation, the Boka Bil Formation, the Tipam Group, the Dupi Tila

Formation, Beach sand at Chittagong City, BP1, BP3 and BP4 correspond to 0.1 to 0.23, 0.08 to 0.13, 0.08 to 0.15, 0.1 to 0.23, 0.1 to 0.3, 0.03 to 0.15, 0.05 to 0.5 and 0.04 to 0.1 mm, respectively. The sandstones from the Bhuban to Dupi Tila Formations contain numerous detrital garnets containing many inclusions such as quartz. One of the detrital garnets obtained from the Boka Bil Formation has inclusions arranged in a curved line (Plate 12d).

4-6-2. Chemical compositions

A total of 741 chemical analyses of detrital garnets were obtained from the sands and sandstones of Bangladesh and Bengal Fan piston core sample in this study. Figs. 74 to 83 show the chemical compositions of garnets from each formation.

32 grains of detrital garnet was obtained from the Kopili Formation sandstone. Most of these grains correspond to pyrope-rich almandine (Pyr = 8 to 43 mol. %), while spessartine-rich almandine (Sps = 24 mol. %), Ca-rich almandine (Ugr = 23 mol. %), almandine-rich spessartine (Sps = 52 mol. %), and almandine-rich pyrope (Pyr = 53 mol. %) are also contained (Fig. 74).

22 grains of detrital garnets were obtained from the sandstones of the Barail Formation. Most of them correspond to pyrope-rich almandine (Pyr = 9 to 37 mol. %), while three and two grains correspond to Ca-rich almandine (Ugr = 11 to 24 mol. %) and spessartine-rich almandine (Sps = 26 and 29 mol. %), respectively (Fig. 75).

94 grains of detrital garnets were obtained from the sandstones of the Bhuban Formation. 43 grains correspond to pyrope-rich almandine (Pyr = 6 to 39 mol. %), 33 grains to Ca-rich almandine (Ugr = 13 to 35 mol. %), and 13 grains to spessartine-rich almandine (Sps = 5 to 32 mol. %). Four and one grains are grossular (Grs = 81 to 97 mol. %) and almandine-rich spessartine (Sps = 34 mol. %), respectively (Fig. 76). Zoning was observed under the microscope in two detrital garnets from the Bhuban Formation, and chemical zoning was also observed in one of two grains. MnO content was higher, and CaO content was lower at core than that of rim.

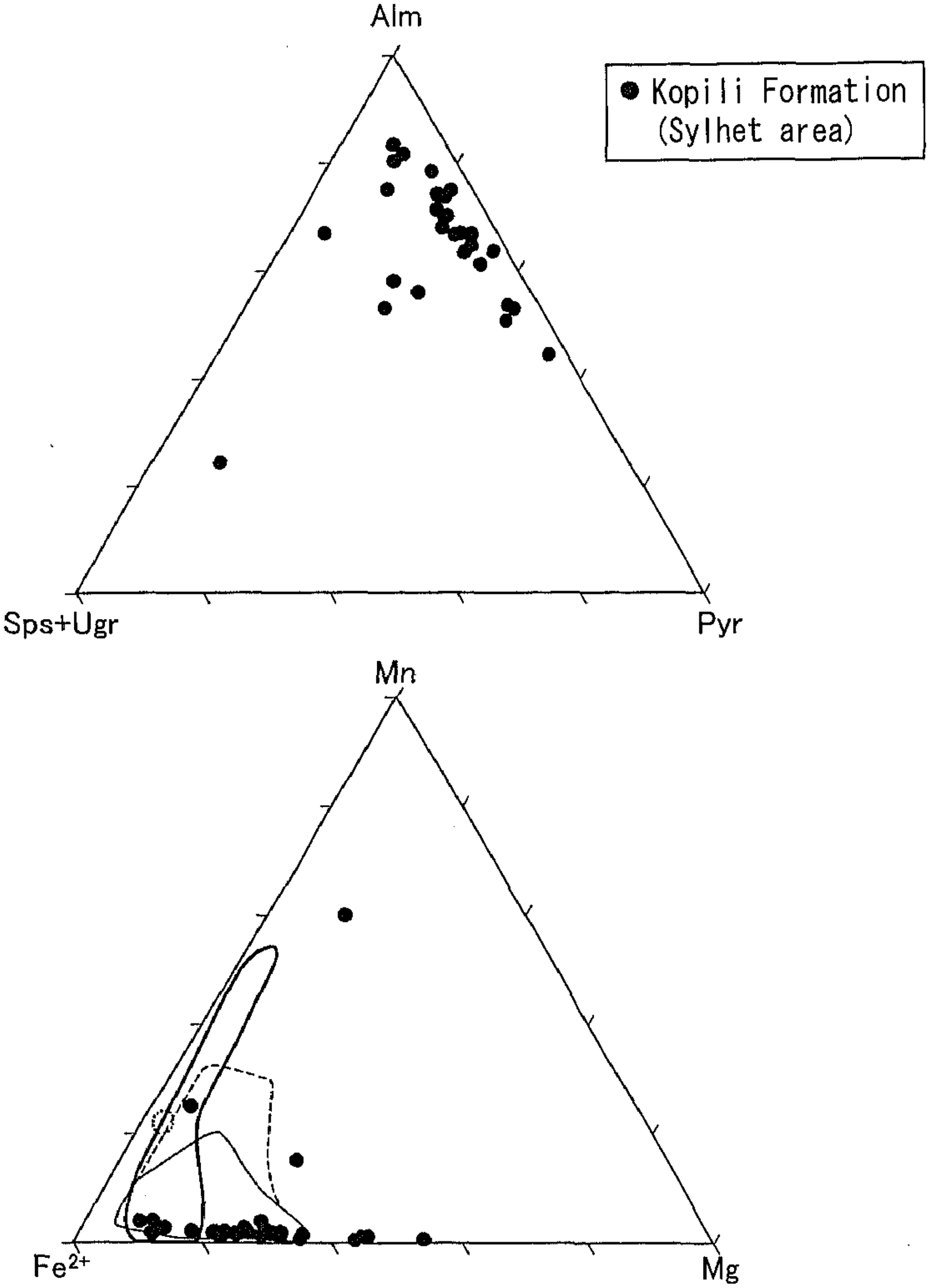


Fig. 74. Chemical compositions of detrital garnets from the Kopili Formation.
a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Scarle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

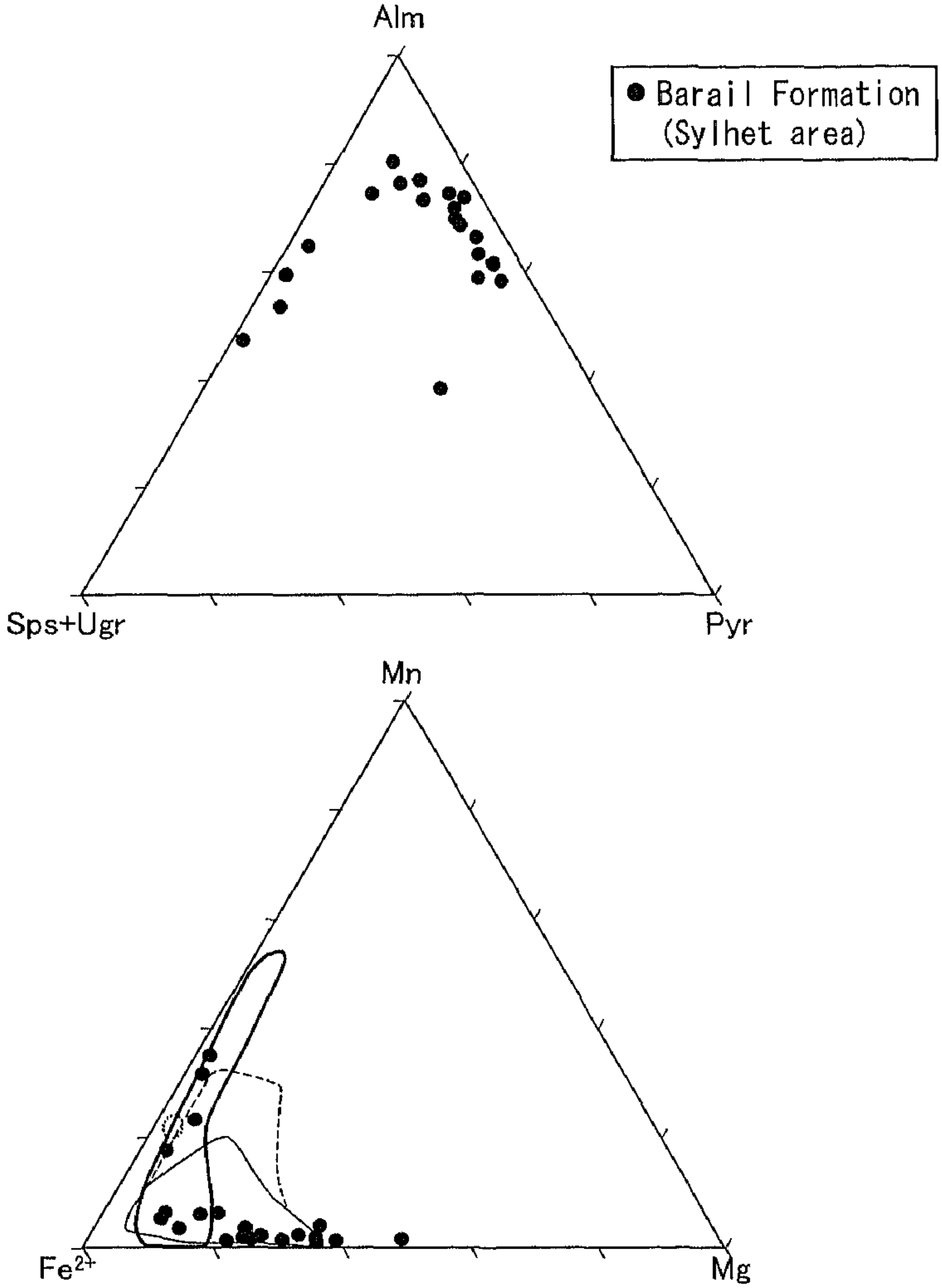


Fig. 75. Chemical compositions of detrital garnets from the Barail Formation.
a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

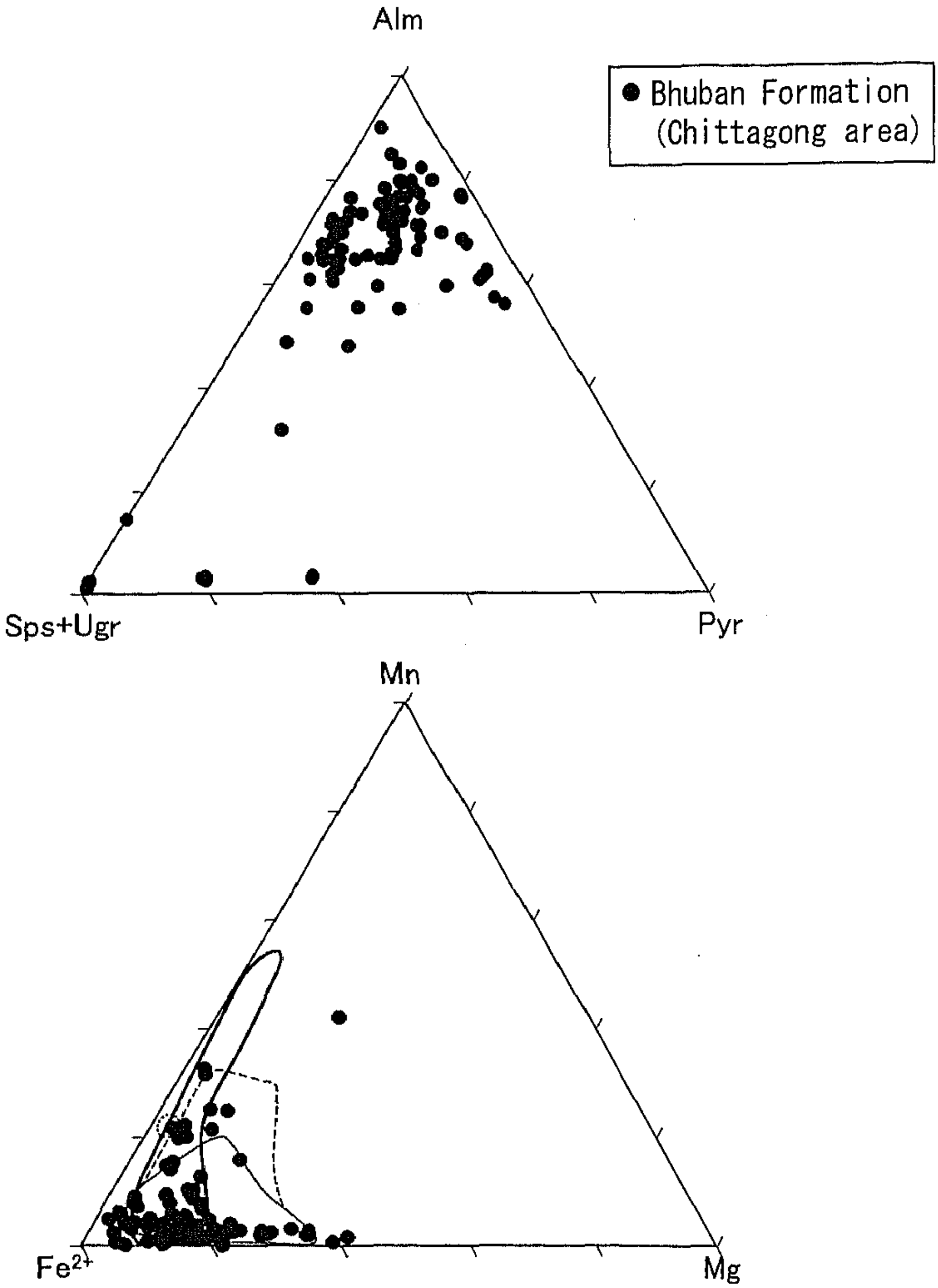


Fig. 76. Chemical compositions of detrital garnets from the Bhuban Formation. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

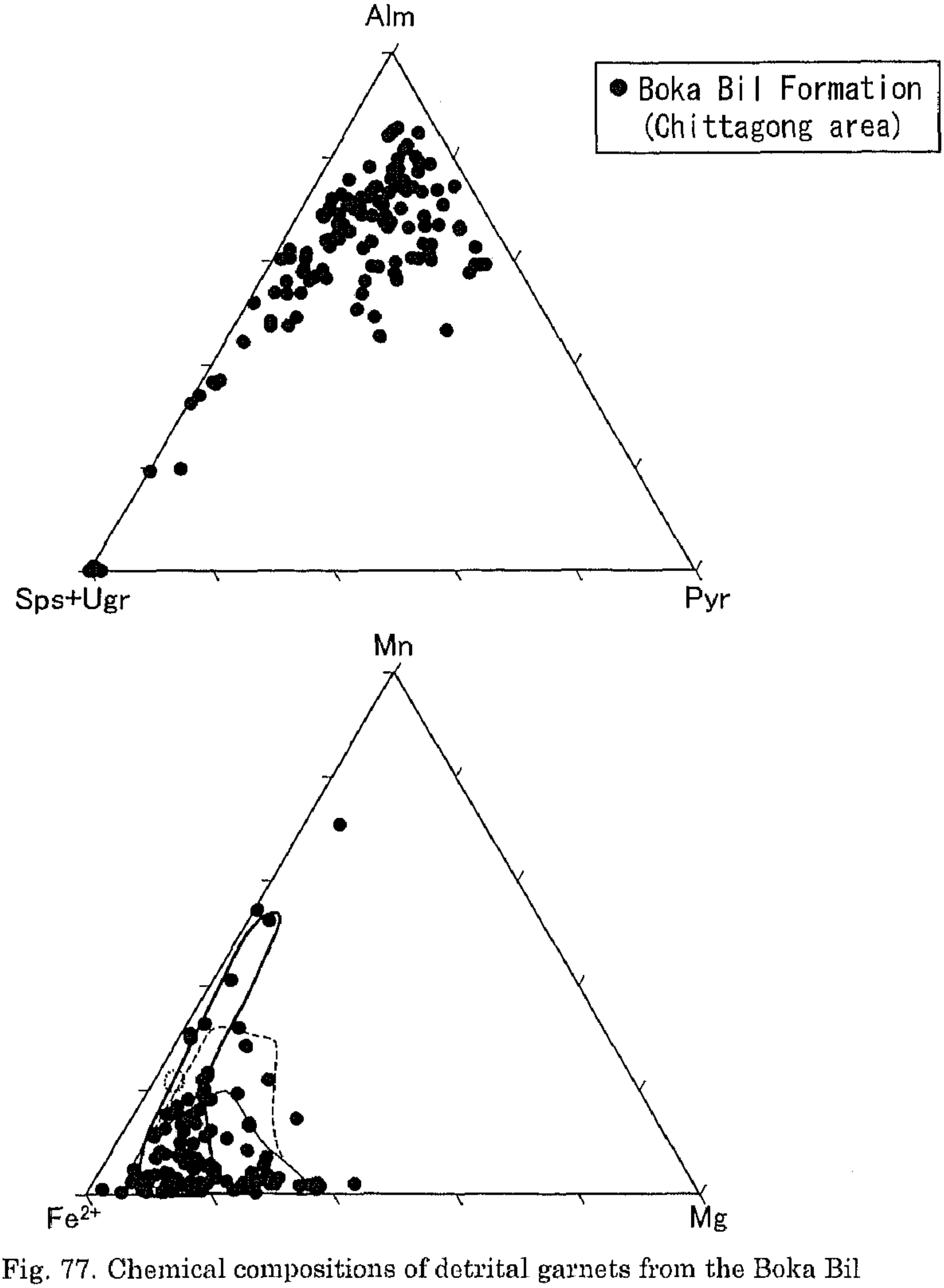


Fig. 77. Chemical compositions of detrital garnets from the Boka Bil Formation. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

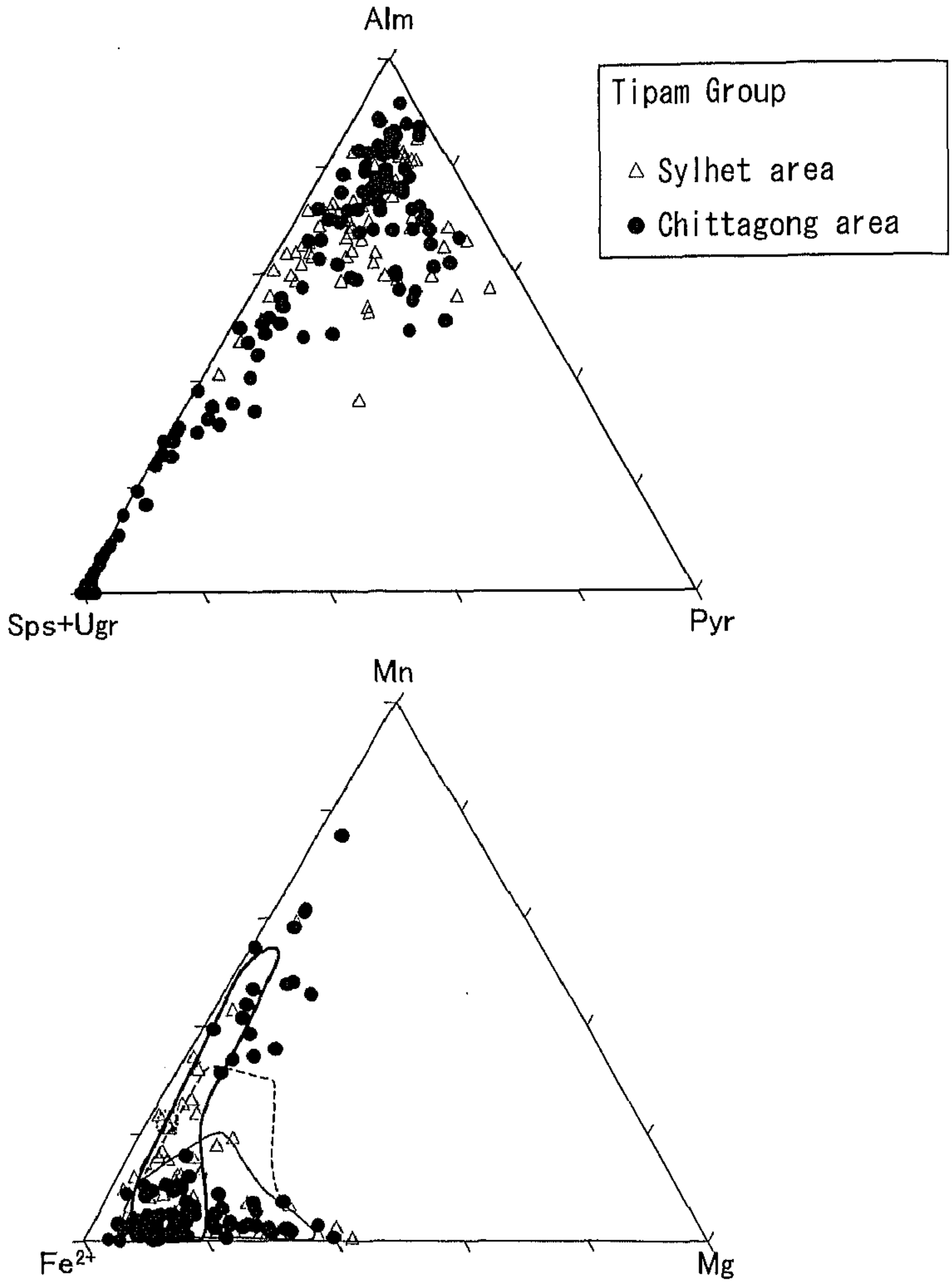
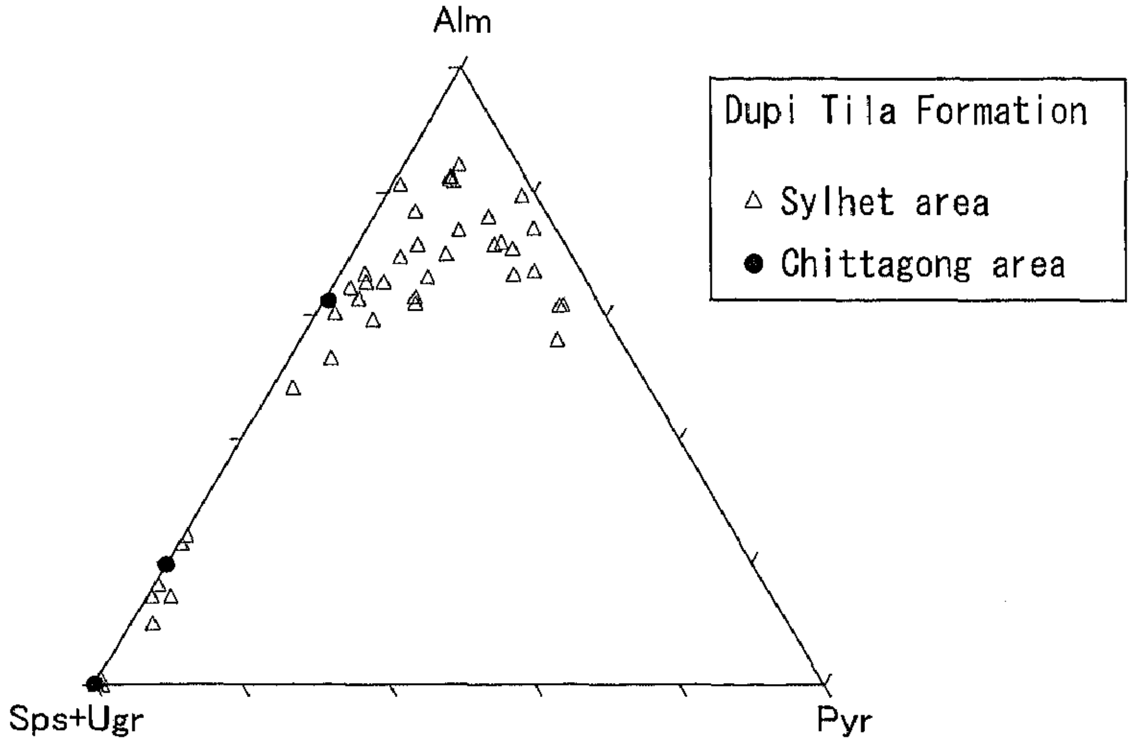


Fig. 78. Chemical compositions of detrital garnets from the Tipam Group. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.



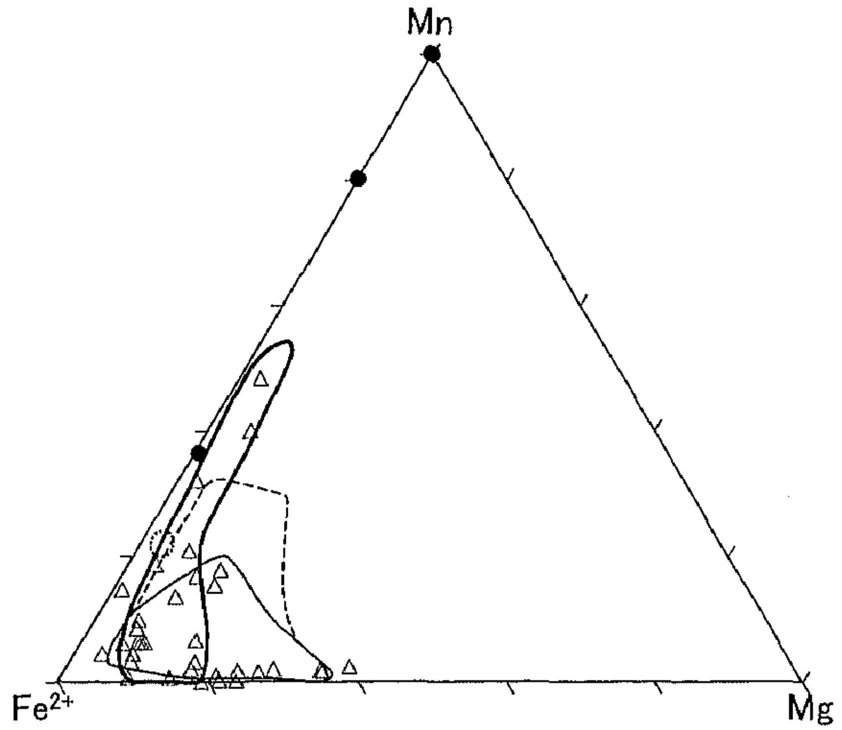


Fig. 79. Chemical compositions of detrital garnets from the Dupi Tila Formation. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

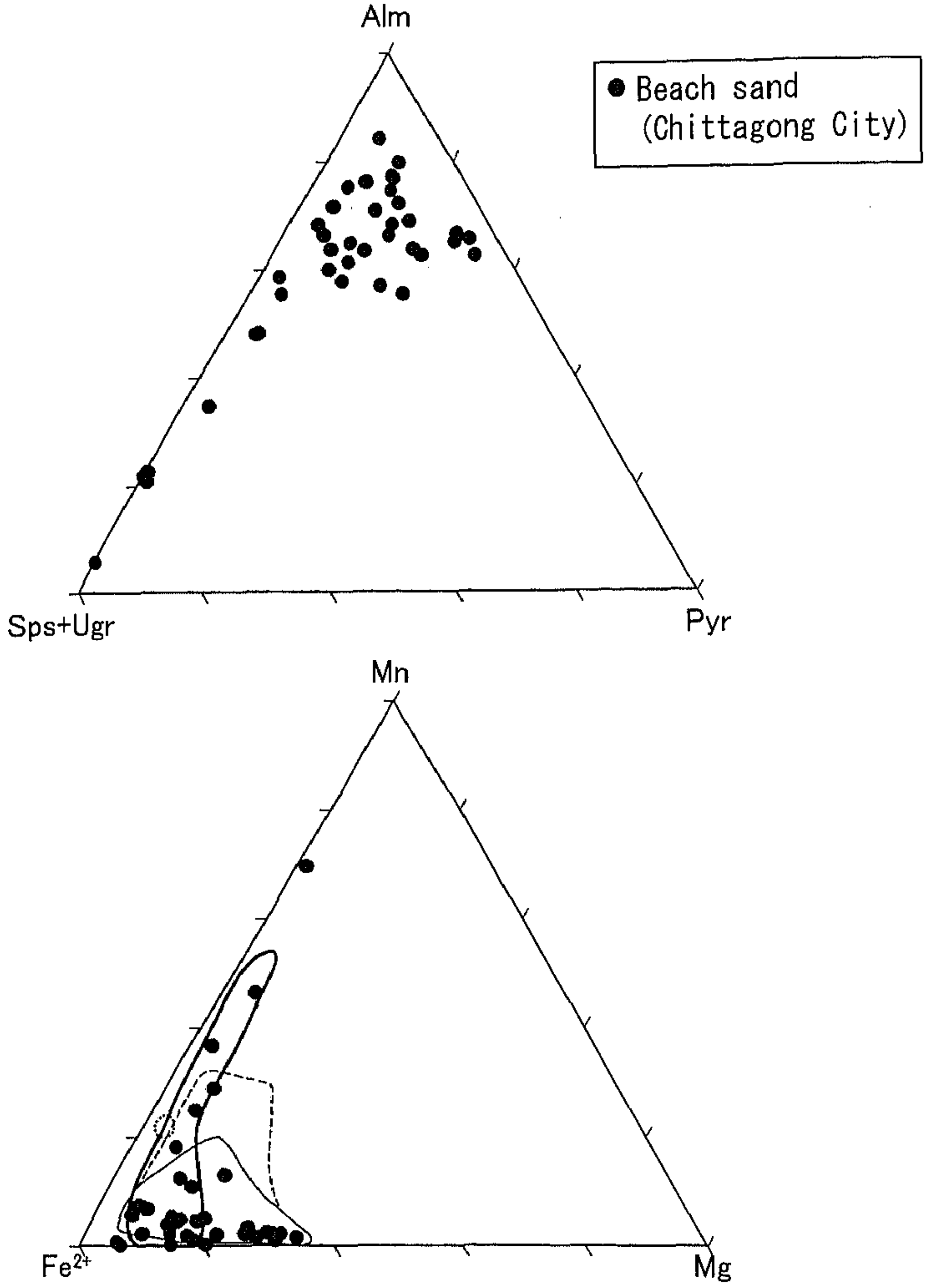


Fig. 80. Chemical compositions of detrital garnets from beach sand in the Chittagong City. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

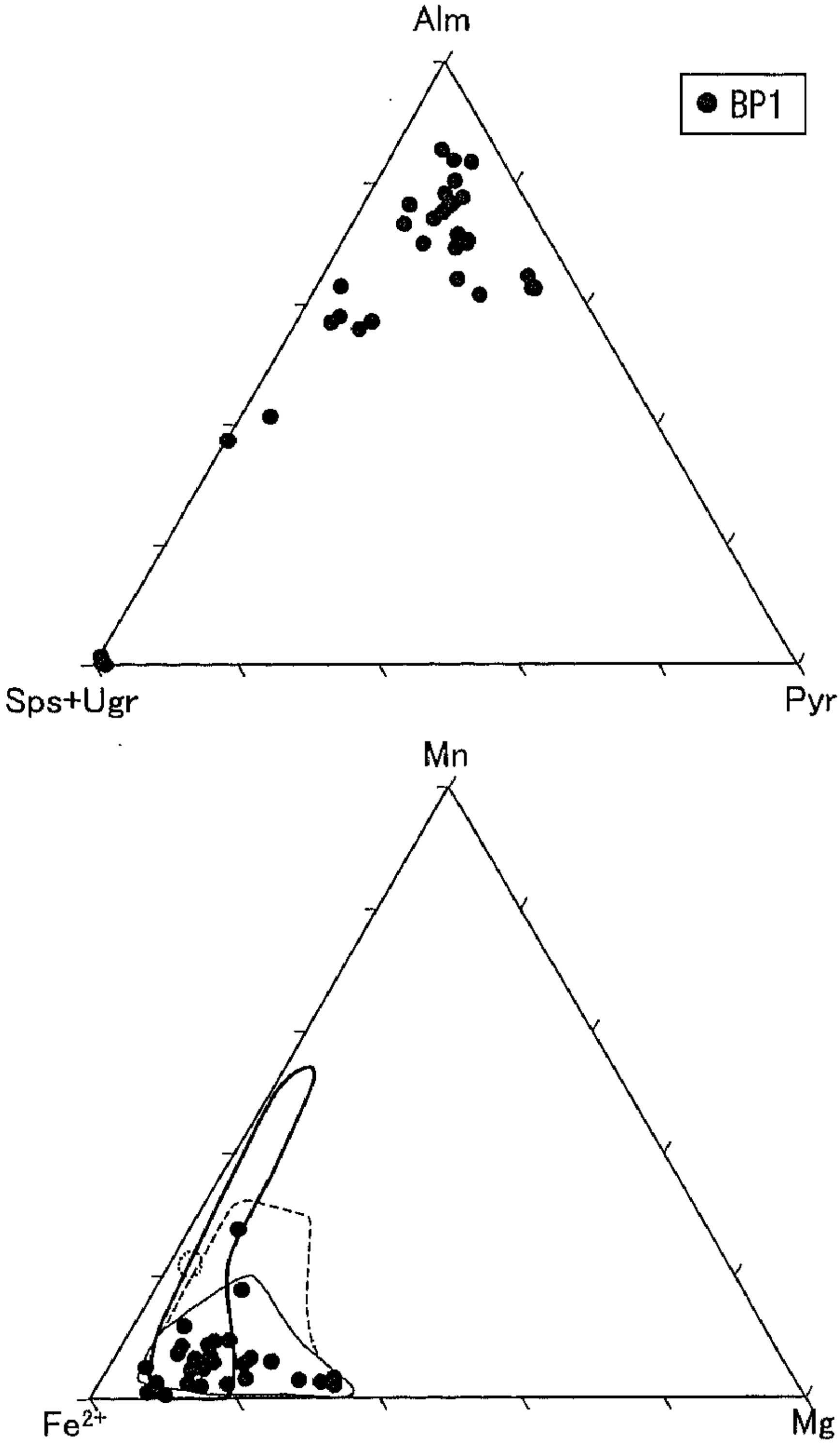


Fig. 81. Chemical compositions of detrital garnets from piston core sample of BP1. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

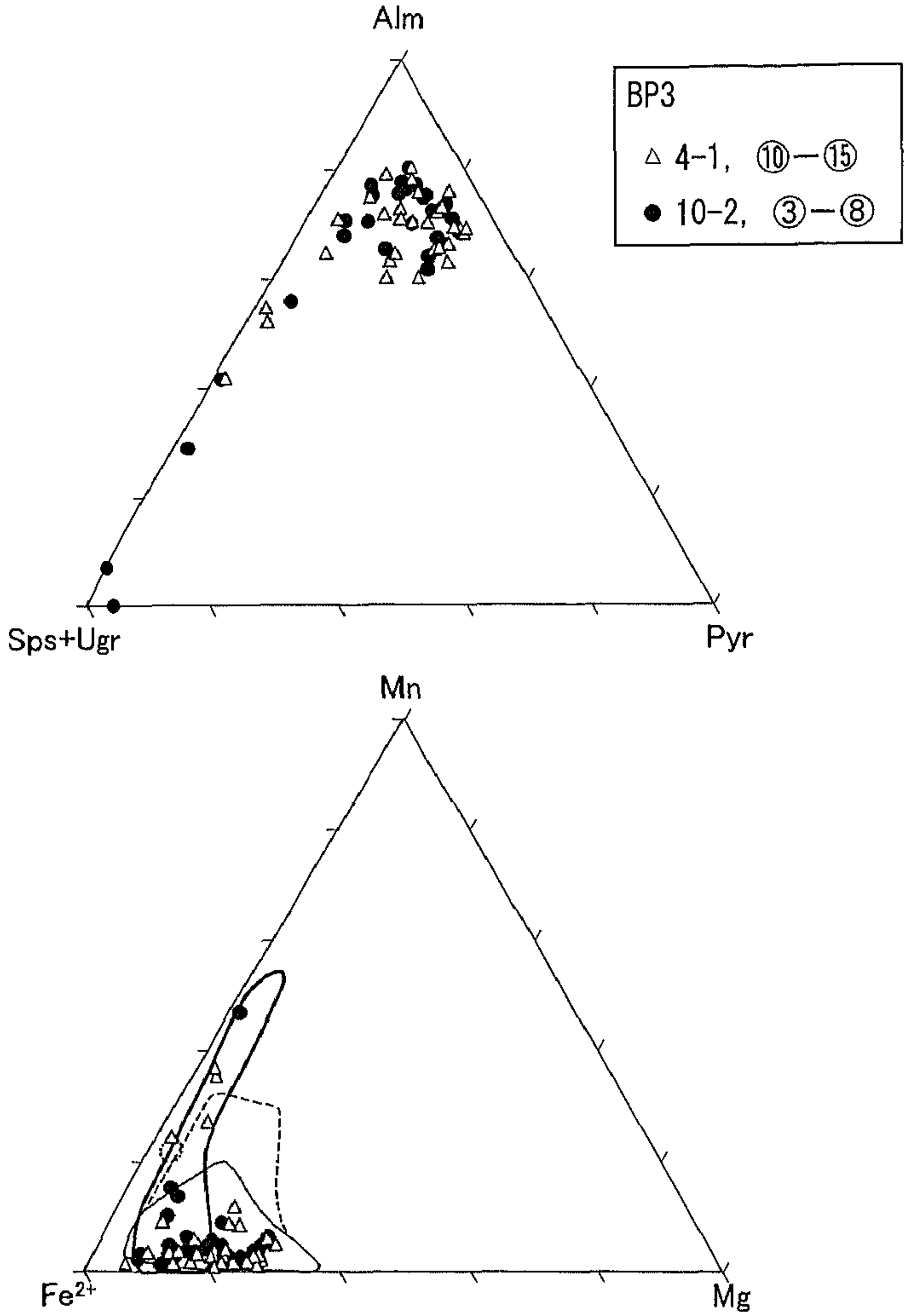
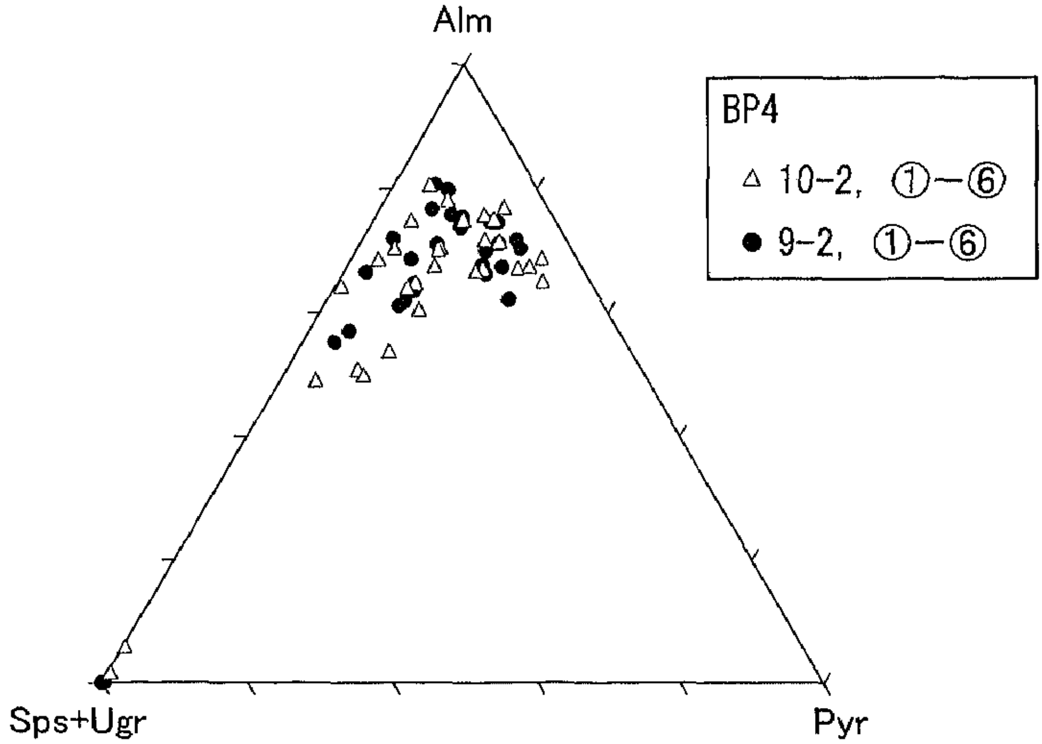


Fig. 82. Chemical compositions of detrital garnets from piston core sample of BP3. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.



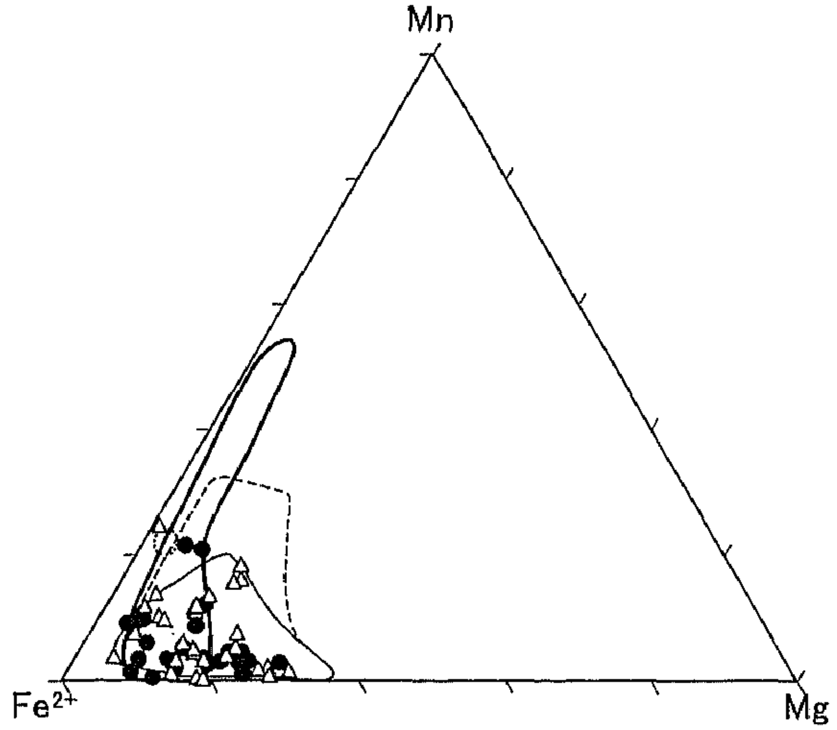


Fig. 83. Chemical compositions of detrital garnets from piston core sample of BP4. a) Alm-Sps+Ugr-Pyr diagram, b) Mn-Fe^{2+}-Mg diagram. The range of the garnets in the Tethys and Higher Himalayas is surrounded by a thin line and broken line. The range of garnets in the Tethys and Higher Himalayas is surrounded by a thick line(after Maruo and Kizaki, 1983). The range of garnets in the Tertiary granitic rocks in the Himalayas is surrounded by a dotted line (Searle et al., 1992). Alm: almandine, Sps: spessartine, Ugr: Ugrandite, Pyr: pyrope.

124 grains of detrital garnets were obtained from the sandstones of the Boka Bil Formation. 51 grains correspond to pyrope-rich almandine (Pyr = 7 to 36 mol. %), 42 grains to Ca-rich almandine (Ugr = 11 to 47 mol. %), 18 grains to spessartine-rich almandine (Sps = 8 to 30 mol. %), 10 grains to grossular (Grs = 53 to 98 mol. %) and three grains to almandine-rich spessartine (Sps = 39 to 60 mol. %) (Fig. 77).

230 chemical analyses of detrital garnets, comprising 77 grains from the Sylhet area and 153 grains from the Chittagong area, were obtained from the Tipam Group. There is a chemical difference of detrital garnets among those from each sample obtained from both the Sylhet and Chittagong areas (Fig. 78). The difference is especially remarkable among the samples from the Chittagong area. Most of the detrital garnets obtained from the samples CH13 and CH55 are grossular, though those from the samples CH07 and CH54 are Mg- and Ca-rich almandine. The detrital garnets from the sample CH53 have intermediate characteristics. As a whole, most detrital garnets from the Tipam Group correspond to pyrope-rich almandine (Pyr = 4 to 38 mol. %), grossular (Grs = 36 to 100 mol. %), Ca-rich almandine (Ugr = 4 to 46 mol. %) and spessartine-rich almandine (Sps = 8 to 45 mol. %), with a minor amount of almandine-rich spessartine (Sps = 36 to 60 mol. %) and andradite (And = 49 to 71 mol. %).

50 chemical analyses of detrital garnets, comprising 47 grains from the Sylhet area and 3 grains from the Chittagong area, were obtained from the Dupi Tila Formation. There is a chemical difference of detrital garnets among those from each sample obtained from the Sylhet areas. The sample 00042110 contains no grossular, though almost a half of the detrital garnets obtained from the sample 00042111 are grossular. As a whole, detrital garnets from the Dupi Tila Formation correspond mostly to pyrope-rich almandine (Pyr = 7 to 35 mol. %), grossular (Grs = 62 to 97 mol. %), Ca-rich almandine (Ugr = 8 to 34 mol. %), and spessartine-rich almandine (Sps = 12 to 47 mol. %), with a minor amount of spessartine (Sps = 69 to 97 mol. %) and andradite (And = 89 mol. %) (Fig. 79).

38 grains of detrital garnets were obtained from the beach sand at Chittagong

City. 16 grains correspond to pyrope-rich almandine (Pyr = 12 to 32 mol. %), 15 grains to Ca-rich almandine (Ugr = 9 to 30 mol. %), four grains to grossular (Grs = 36 to 82 mol. %), two grains to spessartine-rich almandine (Sps = 36 and 46 mol. %), and one grain to almandine-rich spessartine (Sps = 50 mol. %) (Fig. 80).

151 detrital garnets, comprising 31 grains from the BP1 and 60 grains from respective BP3 and BP4, were obtained from the Bengal Fan piston core samples. The ranges of chemistries of those garnets are similar to each other (Figs. 81 to 83). As a whole, 87 grains correspond to pyrope-rich almandine (Pyr = 9 to 30 mol. %), 40 grains to Ca-rich almandine (Ugr = 7 to 40 mol. %), 13 grains to spessartine-rich almandine (Sps = 9 and 38 mol. %), and 11 grains to grossular (Grs = 49 to 100 mol. %).

4-7. Discussion

4-7-1. Modal compositions of sandstone

According to the diagram of Dickinson et al. (1983), the sandstones of the Barail Formation are extremely quartzose, and are plotted in the field of Craton Interior and Quartzose Recycled (Fig. 63). The sandstones of the Bhuban Formation are more feldspathic than those of the Barail Formation, and they are plotted in the field of Transitional Continent to Mixed. The modal compositions of sandstones of the Boka Bil Formation are similar to those of the Bhuban Formation, and they are plotted in the field of Quartzose Recycled, Mixed and Dissected Arc (Fig. 63). The plots of the Tipam Group sandstones are relatively scattered, and they are plotted in the fields of Transitional Continent to Mixed (Fig. 63). The plots of the Dupi Tila Formation sandstones are also scattered. Two samples are extremely quartzose, and are plotted in the fields of Craton Interior. The remainder of the Dupi Tila Formation sandstones are relatively lithic and are plotted in the field of Quartzose Recycled (Fig. 63). Modal compositions of the sands from the BP3 and BP4 of the Bengal Fan piston cores are similar to each other and are plotted in the field of Transitional Continent (Fig. 63). They have similar distributions of the plots on the diagrams to those of the Tipam Group sandstones. It seems to be concluded that the modal compositions of sandstone in Bangladesh changed between the Oligocene and the Early Miocene times, and that the tectonic setting of the provenance of the sandstone changed from the Craton Interior and Quartzose Recycled to Transitional Continent and Mixed.

All the sandstones contain a small amount of feldspars and fragments of metamorphic, felsic volcanic rocks, and granite (Table 8). It is inferred that most of metamorphic rock fragments originated mainly from metamorphic rocks in the Higher and Lesser Himalayas, though there are no suitable source rocks of the felsic volcanic rock fragments in them. The felsic volcanic rock fragments seem to originate from the Transhimalaya or Lhasa Block which is distributed to the north of the Transhimalaya. The Transhimalaya and Lhasa Block contain a large amount of volcanic rocks (e.g. Dürr 1996). Granitic rocks are distributed in the Tethys and Higher Himalayas (e.g. Arita et al., 1997). Some fragments of granite found in the sandstone in Bangladesh might have been supplied from the granitic rocks in the Tethys and Higher Himalayas.

4-7-2. Detrital chromian spinel

Detrital chromian spinels are obtained from all the sandstones and sands in the Bengal basin investigated in this study using the heavy liquid separation. There are some differences in their trends of chemical compositions of detrital chromian spinels from each formation.

Cr# range of nearly all grains is 0.20 to 0.85, though the Dupi Tila Formation in the Chittagong area yields spinels whose Cr# is around 0.1 (Fig. 69). All the spinel suites have a negative trend in the Mg# vs. Cr# diagram, and the negative trend slope of spinel suites of those sandstones and sands are similar to each other (Figs. 64 to 73).

Cr# vs. TiO_2 wt% diagrams show that there are also some differences in each spinel suite. Most of the detrital chromian spinels are TiO_2 wt% <0.25, while the range of TiO_2 wt% of the spinels from the Kopili Formation is mostly 0.1 to 0.8 (Figs. 64 to 73). The spinel suite of the Kopili Formation also contains some spinels whose TiO2 wt% > 1%, though those of the other formations or piston core samples contain few such spinels. The detrital chromian spinels from the sandstone of the Kopili Formation can be divided into three groups on the Cr# vs. TiO_2 wt% diagrams (Fig. 64). First group is composed of spinels with relatively low C# (0.25 to 0.65) and low Ti content (TiO_2 wt% <1.0). Second group is composed of spinels with high Cr# (0.7 to 0.9) and low Ti content (TiO_2 wt% < 1.0). Third group is composed of spinels with high Ti content (TiO_2 wt% > 1.5).

There is somewhat differences in the plotted area of Fe^{3+} in the Cr-Al-Fe^{3+} diagram of each formation and piston core sample. Most of the detrital chromian spinels are Fe^{3+}3# <0.1, while the spinel suites of the Kopili Formation contain some spinels having Fe^{3+}3# more than 0.1 (Figs. 64 to 73).

There are four possible source rocks for the detrital chromian spinels obtained from Bangladesh and Bengal Fan. The first is the Yarlung–Zangbo ophiolite which is distributed in the Transhimalaya and extended from northeastern to northwestern part of India (Fig. 2, Wang et al., 2000). The second is the Naga Hills ophiolite which is distributed in the northeastern India and Myanmar (Fig. 2, Acharyya et al., 1989). The southern extent of the Naga Hills ophiolite in Andaman-Nicobar Island Arc is called Andaman ophiolite (Fig. 2, Acharyya et al., 1989). The third is flood basalts in Indian Peninsula such as Deccan Traps (e.g. Krishnamurthy and Cox, 1977). The fourth is ultramafic rocks in the Shillong Plateau which is distributed in northeast India (e.g. Kumar et al., 1996).

The chemical analyses of chromian spinels from the Yarlung–Zangbo ophiolite in the Transhimalayas are given by Wang et al. (2000), Huot et al. (2002) and Miller et al. (2003). Most of the detrital chromian spinels are plotted in the field of the Yarlung–Zangbo ophiolite in the Mg#-Cr# diagram shown by Wang et al. (2000) and

Huot et al. (2002) (Figs. 64 to 73), though some spinel grains in each spinel suite have higher Cr# than spinels in the Yarlung–Zangbo ophiolite. According to Huot et al. (2002), the ranges of Mg# and Cr# of spinels in dunite in the Yarlung–Zangbo ophiolite are 0.4 to 0.5, and 0.7 to 0.8, respectively. Some detrital chromian spinels with high Cr# from the Bengal basin are plotted in this field (Figs. 64 to 73). The plots of the low Ti group spinels with high Cr# from the Kopili Formation on the Cr# vs. TiO_2 wt% diagrams show a similar distribution to those of the spinels in dunite of the Yarlung Zangbo ophiolite (Fig. 64, Huot et al., 2002). The plots of the low Ti group spinels with relatively low Cr# from the Kopili Formation also show a similar distribution on the Cr# vs. TiO_2 wt% diagram to those of the spinels in harzburgite of the Yarlung Zangbo ophiolite shown by Huot et al. (2002) (Fig. 64).

No chemical data of chromian spinels have been reported from the Naga Hills ophiolite so far. Recently, some chemical data of chromian spinels from the Andaman ophiolite which is the southern extension of the Naga Hills ophiolite have been reported by Niida et al. (2003). According to them, the range of Cr# of spinels in the Andaman ophiolite is about 0.1 to 0.3. There is a possibility that the detrital chromian spinels from the Dupi Tila Formation in the Chittagong area were supplied from the Naga Hills ophiolite, because only the sandstones from the Dupi Tila Formation in the Chittagong area contain detrital chromian spinels with low Cr# (about 0.1) (Fig. 69).

The chemical analyses of chromian spinels in the basalts of Deccan Traps are reported by Krishnamurthy and Cox (1977), and Arai (1992a) compiled the chemistry of chromian spinels in intra-plate basalts. According to them, the chromian spinels in the intra-plate basalts including basalts in Deccan Traps have characteristically a higher Ti content. Some sandstone and sand samples, especially those from the Kopili Formation, contain high Ti chromian spinels (Fig. 64). The detrital chromian spinels with a higher Ti content seem to be supplied from the intra-plate basalts such as those in the Deccan Traps.

No chemical data of chromian spinel also has been reported from the ultramafic rocks in the Shillong Plateau so far. According to Kumar et al. (1996), the ultramafic rocks in the Shillong Plateau are composed of pyroxenite and peridotite, and they include no chromian spinel but magnetites. It is inferred that those magnetites have been generated by an alteration of chromian spinels. Therefore, there is still a possibility that fresh parts of the ultramafic rocks in the Shillong Plateau contain chromian spinels.

At present, the Yarlung–Zangbo ophiolite supplies detritus to the Bengal Fan at present via Yarlung–Zangbo and Brahmaputra Rivers. Taking into account that the tendency of chemistries of detrital chromian spinels have not changed from the Oligocene to the present, it is inferred that most of the detrital chromian spinels from Bengal Basin have been supplied from the equivalent of the Yarlung–Zangbo ophiolite at least from the Oligocene.

There is a possibility that the detrital chromian spinels from the Kopili Formation and Dupi Tila Formation in the Chittagong area have different source rocks from those of the other formation sandstones. The detrital chromian spinels from the Kopili Formation are characterized by relatively high TiO_2 content (Fig. 64). As mentioned above, the higher Ti group spinels from the Kopili Formation seem to have been derived from the intra-plate basalt such as flood basalt in the Deccan Traps. The low Ti group spinels from the Kopili Formation have slightly higher Ti content than most of the detrital chromian spinels from the other formations, though the negative trend slope in the Mg# vs. Cr# diagram are similar to those of the spinels in the Yarlung–Zangbo ophiolite and other Bangladesh sandstones (Fig. 64). Taking into account that Fe^{3+}3# of the low Ti group spinels are mostly less than 0.05 and 60 % of the low Ti group spinels are less than 0.025 (Fig. 64), it seems to be difficult to regard these chromian spinels as a volcanic rock in origin (Arai, 1992a). In the Yarlung–Zangbo ophiolite, there are some serpentinites whose spinels have relatively high TiO_2 content at the Cr# range of 0.4 to 0.6 (harzburgite) and 0.7 to 0.8 (dunite) (Huot et al., 2002). The low Ti group spinels from the Kopili Formation are plotted in similar fields of Cr# vs. TiO_2 wt% diagram (Fig. 64). According to Dick and Bullen

(1984) and Ohara (2003), abyssal or backarc basin peridotites bearing plagioclase contain such chromian spinels with high TiO_2 content at the Cr# range of 0.4 to 0.6. Forearc peridotites also contain chromian spinels high Cr# (e.g. Ishii et al., 1992), however, it is difficult to interpret that the low Ti group spinels are forearc peridotite in origin owing to the slightly high Ti content. There is another possibility that the chromian spinels with low Ti content and high Cr# were derived from the chromitite. The chromian spinels with low Ti content and high Cr# have also high Mg# (Fig. 64). It is known that chromian spinels in chromitite are characterized by high Cr# and Mg# (Hisada and Arai, 1995). As a whole, it is probable that the detrital chromian spinels from the Kopili Formation were derived from plagioclase bearing harzburgite and cumulate in the Yarlung–Zangbo ophiolite and intra-plate basalts such as those in Deccan Traps.

As mentioned above, the detrital chromian spinels from the Dupi Tila Formation have been probably supplied from the Naga Hills ophiolite in India and Myanmar, because the range of the Cr# of those spinels are different from the other sandstones in Bangladesh including the Dupi Tila Formation in the Sylhet area (Fig. 69).

The occurrence and chemistry of detrital chromian spinels from the Chulung La Formation of Tethys Himalaya in Northwest India have been reported by Garzanti et al. (1987). The Chulung La Formation is considered to have been deposited in the Early Eocene when Indian Peninsula collided to the Eurasia Plate, and its detritus was supplied from the Transhimalaya which includes the Yarlung–Zangbo ophiolite (Garzanti et al. 1987). The range of the chemistry of detrital chromian spinels from the Chulung La Formation is similar to those of the detrital chromian spinels obtained in this study in the Mg# vs Cr# diagrams (Figs. 64 to 73). The fact that the chemistry of detrital chromian spinels derived from the Yarlung–Zangbo ophiolite has not changed from the Early Eocene (Chulung La Formation) to the present (Bengal Basin) suggests that the petrographic characteristics of the ophiolite exposed in the Transhimalaya has been nearly constant for a long while.

4-7-3. Detrital garnet

The detrital garnets from the sandstones and sands from Bangladesh and Bengal Fan were analyzed. Those chemical data were plotted on the ternary diagrams of almandine—spessartine + ugrandite—pyrope and Mn—Fe—Mg (Figs. 74 to 83). There are differences in the chemical composition of the detrital garnets from each formation. As shown in these diagrams, the plots of the garnets from the Kopili and Barail Formations show similar distributions. Those garnets are composed mainly of pyrope-rich almandine (Figs. 74 and 75). The detrital garnets obtained from the other formations, piston core samples, and beach sand are composed mainly of spessartine-rich almandine, pyrope-rich almandine, and ugrandite (Figs. 76 to 83), and spessartine-rich almandine is often predominant in those garnets.

According to Maruo and Kizaki (1983), the garnets in metamorphic rocks in the Higher and Tethys Himalayas are relatively pyrope-rich almandine and those in the Lesser Himalaya are spessartine-rich (Fig. 74). They also mentioned that the garnets in the Lesser Himalaya have a chemically marked zoning, that is, these garnets are spessartine-rich in their core and almandine-rich in their margin. On the other hand, the garnets in the Higher and Tethys Himalayas have a small chemical zoning, that is, pyrope-rich in their core and almandine-rich in their margin. Tertiary Granitic rocks and the metamorphic in the Main Central Thrust (MCT) also contain garnets which are composed of slightly spessartine-rich almandine and almandine, respectively (Fig. 74: Arita, 1983; Searle et al., 1992). In comparison with the garnets in the Himalayas, the detrital garnets of pyrope-rich almandine seem to originate from the metamorphic rocks in the Higher and Tethys Himalayas, while the detrital garnets of spessartine-rich almandine originate probably from the metamorphic rocks in the Lesser Himalaya. In the Mn—Fe—Mg diagrams, numerous detrital garnets from the Boka Bil Formation, Tipam Group, Dupi Tila Formation, beach sand at Chittagong City and BP3 of piston core sample are plotted in the field of the garnets in the Lesser Himalaya (Figs. 77 to 83). It is probable that the exposure of the Lesser

Himalaya started while the Boka Bil Formation had been deposited. Actually, the metamorphic age of the Lesser Himalaya is the same or older than that of the Boka Bil Formation (13.6 to 44.0 Ma: Arita et al., 1997). However, almost all the detrital garnets from the Bhuban Formation are plotted in the field of the garnets in the Higher and Tethys Himalayas (Fig. 76), though the spessartine-rich almandine is predominant in those garnets like detrital garnets from the Boka Bil Formation. As mentioned above, the slightly spessartine-rich almandine is contained in the granitic rocks in the Himalayas (Searle et al., 1992). In the Himalayas, there are Tertiary granitic rocks whose age are 21.7 to 35.8 Ma (Hodges et al., 1996). It is presumed that the difference between chemistries of detrital garnets from the Barail and Bhuban Formations means that the beginning of exposure of Tertiary granitic rocks in the Himalayas was nearly contemporaneous with the deposition of the Bhuban Formation. In summary, the detrital garnets of the Kopili and Barail Formations were derived from the Higher and Tethys Himalayas, and those from the Bhuban Formation were derived from the Higher and Tethys Himalayas and Tertiary granitic rocks. After the sedimentation of the Bhuban Formation, the Higher, Tethys, and Lesser Himalayas have supplied detrital garnets to the Bengal Fan.

4-7-4. Uplift history of the Himalayas

The model of uplift history of the Himalayas was newly constructed based on the modal composition of sandstones and chemistries of the detrital heavy minerals obtained this study (Fig. 84).

Eocene to Oligocene

In the Early Eocene, when the initial collision between Eurasian Continent and Indian Subcontinent occurred, the Chulung La Formation which contains detrital chromian spinels with similar chemistries to those of the spinels in the Yarlung-

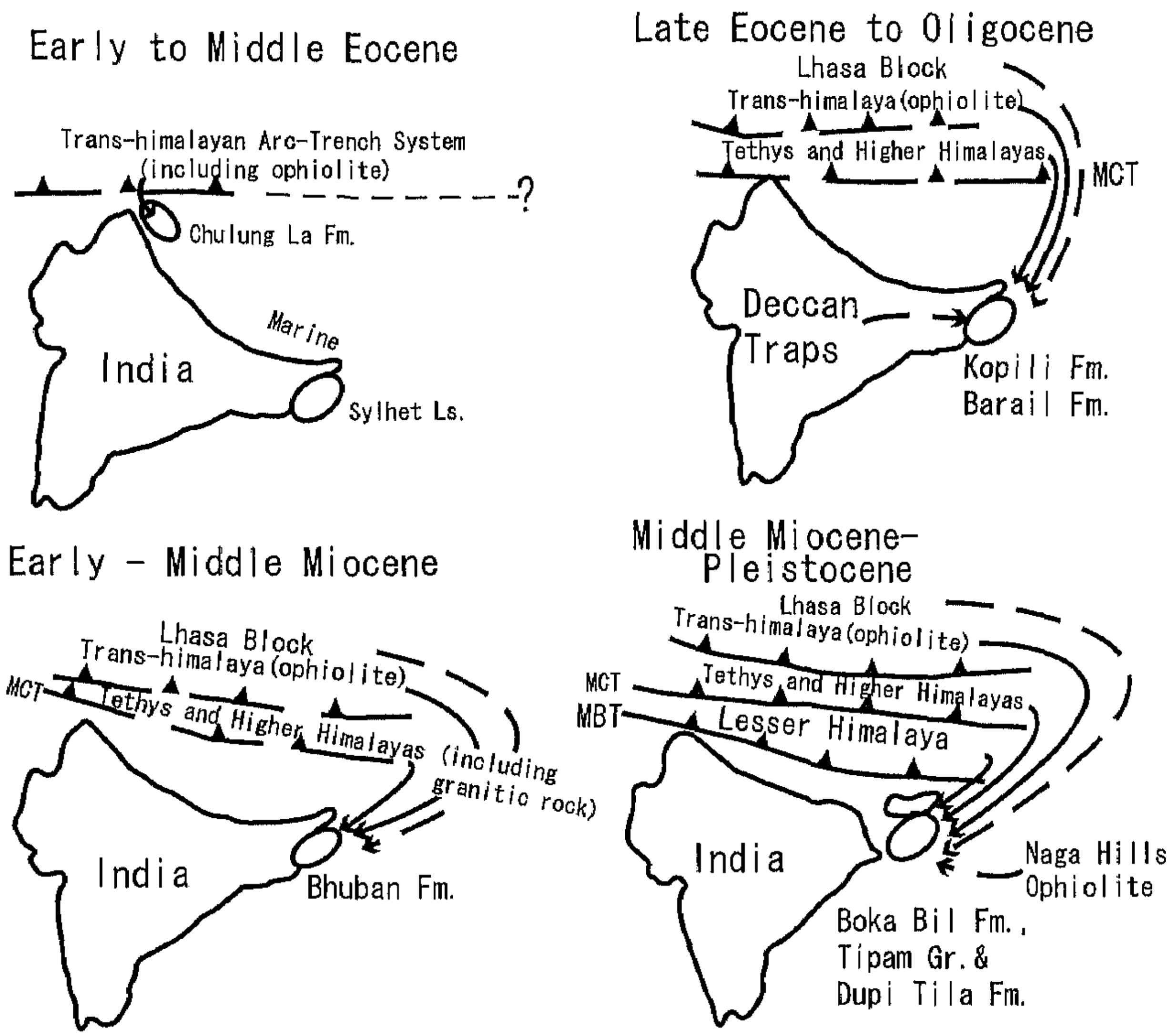


Fig. 84. Model of the provenance changes of sediments in the Bengal basin.
Modified from Uddin & Lundberg (1998) and Garzanti et al.(1987).

Zangbo ophiolite was deposited in northwest India.

In the Middle Eocene, the Sylhet Limestone which is composed of Nmmulites bearing limestone, was deposited in the Bengal Basin. No detritus was supplied from the Himalayas.

In the Late Eocene, the Kopili Formation was deposited in the Bengal Basin. The supply of detritus from the Transhimalaya and the Higher and Tethys Himalayas to the Bengal Basin had started in this period, because the Kopili Formation sandstone contains detrital chromian spinels and garnets whose chemistries are similar to those of the chromian spinels and garnets in the Yarlung-Zangbo ophiolite and Higher and Tethys Himalayas, respectively. Intra-plate basalts which might be in the Indian Peninsula, also supplied detritus to Bangladesh as indicated by the occurrence of detrital chromian spinels with high Ti content.

In the Oligocene, the Barail Formation was deposited in Bangladesh. The detritus from the Transhimalaya and the Higher and Tethys Himalayas had supplied to Bangladesh continuously. However, the supply of detritus from the intra-plate basalts had nearly disappeared, and the nature of the serpentinites in the Yarlung-Zangbo ophiolite had slightly changed.

Early to Middle Miocene

In the Early to Middle Miocene, the Bhuban and Boka Bil Formations were deposited in Bangladesh. The detritus from the Transhimalaya and the Higher and Tethys Himalayas had supplied to Bangladesh continuously. In addition, the supply of detritus from the Tertiary granitic rocks in the Himalayas had started while the Bhuban Formation had been deposited. This is because the Bhuban Formation sandstone contains not only the detrital garnets whose chemistries are similar to those of garnets in the Tethys and Higher Himalayas but also detrital garnets whose chemistries are similar to those of garnets in the Tertiary granitic rocks in the Himalayas. This suggests that the Tertiary granitic rocks in the Himalayas became to be exposed while the Bhuban Formation had been deposited. The timing of beginning of the exposure of the Tertiary granitic rocks suggested by the detrila garnets is concordant with their age data of the granitic rocks (Hodges, et al., 1996). Furthermore, the supply of detritus from the Lesser Himalaya had started while the Boka Bil Formation had been deposited. This is because the Boka Bil Formation sandstone also contains detrital garnets whose chemistries are similar to those of garnets in the Lesser Himalaya. The timing of beginning of the exposure of the Lesser Himalayas suggested by the detrila garnets is concordant with the age data of the metamorphic rocks in the Lesser Himalayas (Arita, et al., 1997) and with the age of the initial activity of Main Boundary Thrust (MBT) in Pakistan (Meigs, et al., 1995). MBT is the floor thrust of the Lesser Himalaya.

Late Miocene to present

From the Late Miocene to the present, the detritus from the Transhimalaya and the Higher, Tethys and Lesser Himalayas have been supplied to Bangladesh and Bengal Fan. However, there is a possibility that the Naga Hills ophiolite had supplied detritus to the Chittagong area in southeast Bangladesh while the Dupi Tila Formation had been deposited. This is because of the following three points; 1) The chemistry of detrital chromian spinels from the Dupi Tila Formation in the Sylhet area in northeast Bangladesh is similar to those of detrital chromian spinels from the other formations and Bengal Fan piston core samples, and the chemistry of detrital chromian spinels from the Dupi Tila Formation in the Chittagong area is different from those of detrital chromian spinels from the others. 2) The Chittagong area is nearer to the Naga Hills ophiolite than the Sylhet area. 3) The Dupi Tila Formation sandstones in the Chittagong area contains detrital chromian spinels with low Cr# characteristically. Also serpentinites in the Andaman ophiolite, which is interpreted to be equivalent of the Naga Hills ophiolite, contains such low Cr# chromian spinels (Niida et al., 2003). However, it seems difficult to conclude that the detrital chromian spinels from the Dupi Tila Formation in the Chittagong area were derived from the Naga Hills ophiolite, since the Yarlung-Zangbo ophiolite also contains low Cr# spinels (Wang et al., 2000).