CHAPTER V

DETRITAL CHROMIAN SPINEL

Chromian spinel [(Fe, Mg)(Cr, Fe,Al)$_2$O$_4$], the solid-solution mineral in a spinel group, is an accessory mineral found only about 1 or 2 % in most mafic and ultramafic igneous rocks. This mineral shows extensive solid solution between various end-member compositions, within the spinel group, as listed in Table 5.1. Due to the complexity of the spinel chemical substitutions, a prism is used for such chemical representations. Figure 5.1, after Klein and Hurlbut (1993), shows three such prisms: (a) for the compositional space between normal spinels at the base of the prism and inverse spinels, with (Fe^{2+} + Ti^{4+}) substitutions, at the top edge; (b) for the compositional space between normal spinels of the base of the prism and inverse spinels, with Fe^{3+} substitutions, along the upper edge; and (c) the general nomenclature for compositions in this prism. Chromian spinel, which its compositions locate at or near the chromite end-member, especially at the base of the prism is shown as rectangular-base prisms in Figure 5.1.

Table 5.1 Six end members of the spinel group, predominating in chromian spinel (Klein and Hurlbut, 1993).

Normal Spinel		**Inverse Spinel**	
Spinel	($MgAl_2O_4$)	Magnetite	(Fe_3O_4)
Hercynite	($FeAl_2O_4$)	Magnesioferrite	($MgFe_2O_4$)
Chromite	($FeCr_2O_4$)		
Magnesiochromite	($MgAl_2O_4$)		

From the compositional range of chromian spinel in both divalent (Mg^{2+} and Fe^{2+}) and trivalent (Al^{3+}, Cr^{3+}, and Fe^{3+}) elements, this mineral is relatively sensitive to

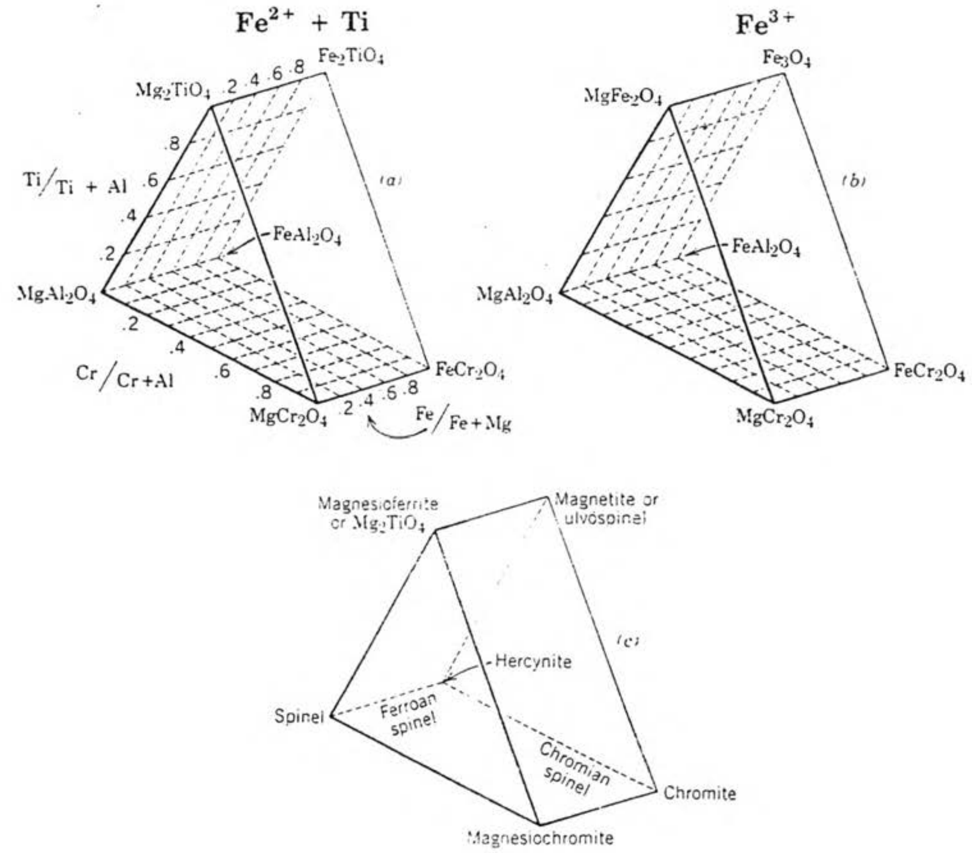

Figure 5.1 End member compositions in the spinel group as represented in a spinel prism. (a) Compositions in this space range from those of normal spinels (in the base of the prism) to those with [Fe^{2+} (or Mg^{2+}) + Ti] end members along the upper edge (these are inverse spinels). (b) Compositions in this space range from those of the normal spinels (in the base) to those with Fe^{3+}-rich end members along the upper edge (these are inverse spinels). (c) Nomenclature for members of the spinel group as based on the compositions represented in (a) and (b) (Klein and Hurlbut, 1993).

the chemical and thermal conditions accompanying its formation. Thus, its chemical compositions can be potentially used as the important indicators of host rock tectonic settings or of physico-chemical conditions under which its host rock had formed (e.g. Irvine, 1965; Dick and Bullen, 1984; Press, 1986; Pober and Faupl, 1988; Arai, 1990; Sack and Ghiorso, 1991; Huggesty, 1991; Hisada *et al.*, 1995; and Cookenboo *et al.*, 1997).

Although chromian spinel, in nature, occurs as an accessory mineral, it is chemically more durable than other mafic minerals, unaltered simply by serpentinization (Hekinian, 1985). Moreover, lack of cleavage and high degree of hardness offer the further advantages of mechanical stability (Bowie, 1967). Thus, chromian spinel still remains after the long processes of weathering, erosion, and transportation. Through these processes, together with the depositional one, this mineral can be found again in the form of detrital chromian spinel in the later clastic sedimentary rocks, especially in sandstones and siltstones.

The worldwide occurrence of detrital chromian spinels (Fig. 5.2) has been encountered by many geologists as demonstrated and summarized by Zimmerle (1984). He also mentioned that the distribution patterns of those detrital chromian spinels often show their sources on the continents, mostly in ophiolite belts, as well as in the deep-sea, in subduction zones or mid-ocean ridges.

Japan is one of several localities that detrital chromian spinel has been known from many areas in the Paleozoic and Mesozoic clastic sedimentary rocks throughout the country (e.g., Arai and Okada, 1991; Hisada and Arai, 1993; Nanayama *et al.*, 1993; Hisada *et al.*, 1994; Takeuchi, 1994; Hisada *et al.*, 1995; Yoshida *et al.*, 1995; Hisada *et al.*, 1996; and Kadoshima and Arai, 1999). Chemistry of these detrital

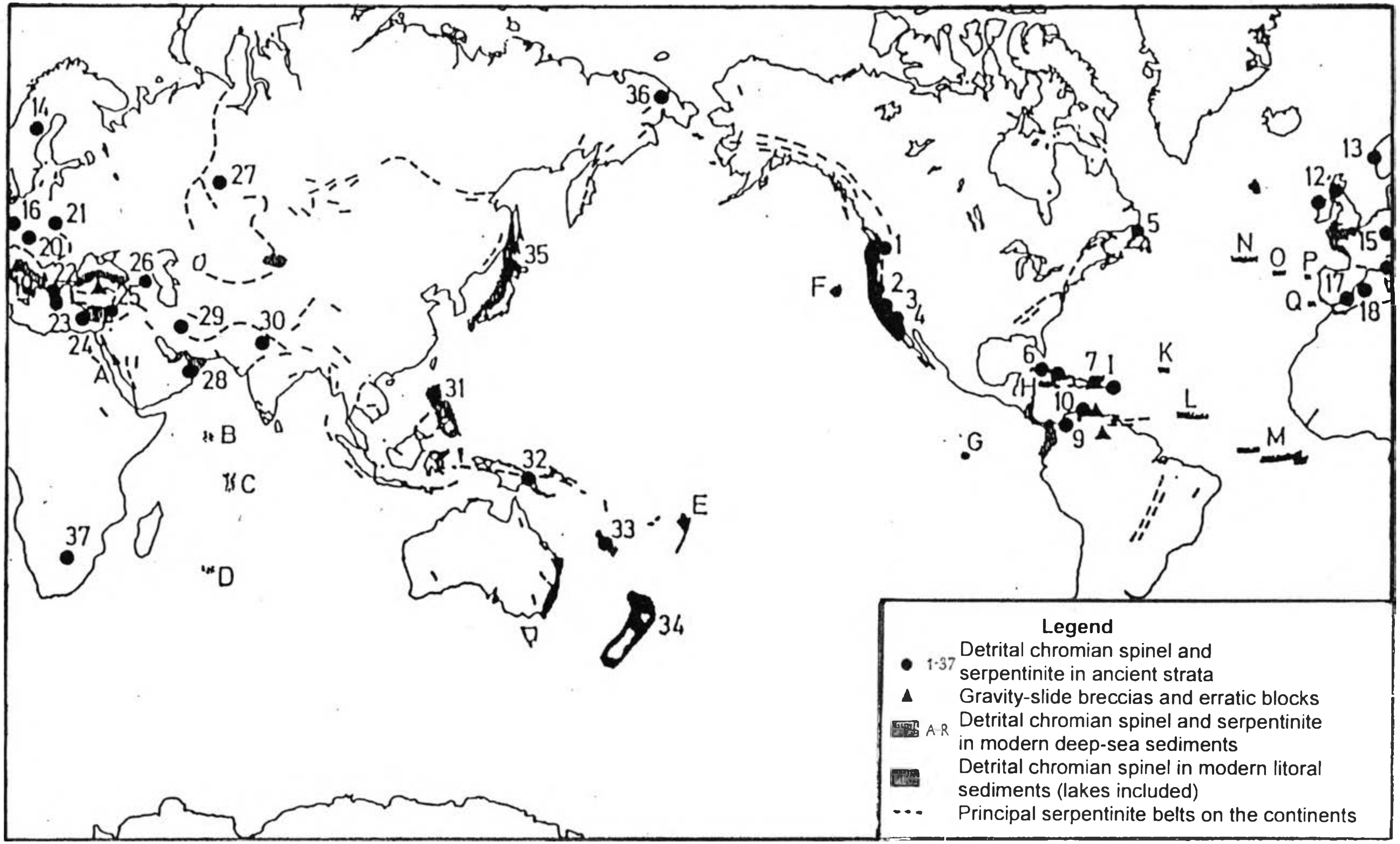

Figure 5.2 Present and ancient occurrences of detrital chromian spinels and detrital serpentinites as well as principal ophiolite belts on the continents (Zimmerle, 1984).

chromian spinels has been used, as a tool, to unravel the tectonic settings of their provenances effectively.

In Southern Kitakami area, as mentioned in the first chapter, nearly complete sequences of the Paleozoic and Mesozoic strata ranging from Silurian to earliest Cretaceous are represented. Some detrital chromian spinels had already reported in Silurian (Yoshida *et al.*, 1995), Devonian (Hisada *et al.*, 1995), and Jurassic (Takeuchi, 1994) beds within the area. However, no detrital chromian spinel has been found yet during the long periods of Carboniferous to Triassic, which span 150 million years. Thus, the author tried to search for detrital chromian spinels from the barren period.

As a result, detrital chromian spinels were detected in Devonian, Carboniferous and Triassic sandstones and siltstones. In addition, many chromian spinel crystals were detected also in the Carboniferous basalt. No detrital chromian spinel was found in Permian because of the scarcity of clastic sedimentary rocks within the sequences. Only small amount of Jurassic and Cretaceous samples were collected, thus, no detrital chromian spinel has been found in these periods also.

This new discovery of chromian spinels from Devonian, Carboniferous, and Triassic rocks gave the very important data to interpret tectonic setting of the Southern Kitakami area as it will be described in detail in Chapter VI. Physical properties and chemical compositions of the chromian spinels found in this area are described below.

5.1 Detrital chromian spinel from Devonian sandstone

Detrital chromian spinels were found in one of the six samples of Devonian sandstones collected from the Nakazato Formation in the Hikoroichi district (see Fig. 3.3 for location). This sandstone sample, lithic arkose, number 97031604, was cut and prepared in four thin-sections. Under microscope, abundant of detrital chromian spinel grains were detected in all thin-sections. The sketches in Figures 5.3 to 5.6 show distributions, shapes, and sizes of detrital chromian spinel grains within the thin-sections.

Detrital chromian spinels from lithic arkose of Nakazato Formation are characterized by the high relief, isotropic, and dominant dark reddish brown with minority of yellowish brown in color. Their sizes vary from less than 10 up to 340 microns, with the average of 60 microns. Shapes of these detrital chromian spinel grains are angular to sub rounded. Many of them show the relic of their crystal form, subhedral of octahedral crystal. Although abundant of detrital chromian spinel grains were detected, modal percents of these detrital grains are, however, not more than 2 % of the rock.

From the spinel characteristics described above, the author divided these detrital minerals, base mostly upon color and size, into two groups. One is composed of large grains and dark reddish brown color. This group is believed from their optical properties to derive from the host rock, which is formed slowly in higher temperature with lower content of Ti, and higher content of Cr. This provided the larger size and darker color of spinel grains for sandstone. Another group comprises those spinels that have yellowish brown color and small grain sizes. By contrast with the previous group, spinels of this group is believed to be transported from the provenance that their host rock occurred rapidly in lower temperature with higher content of Ti, and lower content of Cr. This originated the smaller size and paler color of chromian spinel grains for sandstone. Figure 5.7 shows characteristics of detrital chromian spinels of the first group (a-g) and the second group (h-i).

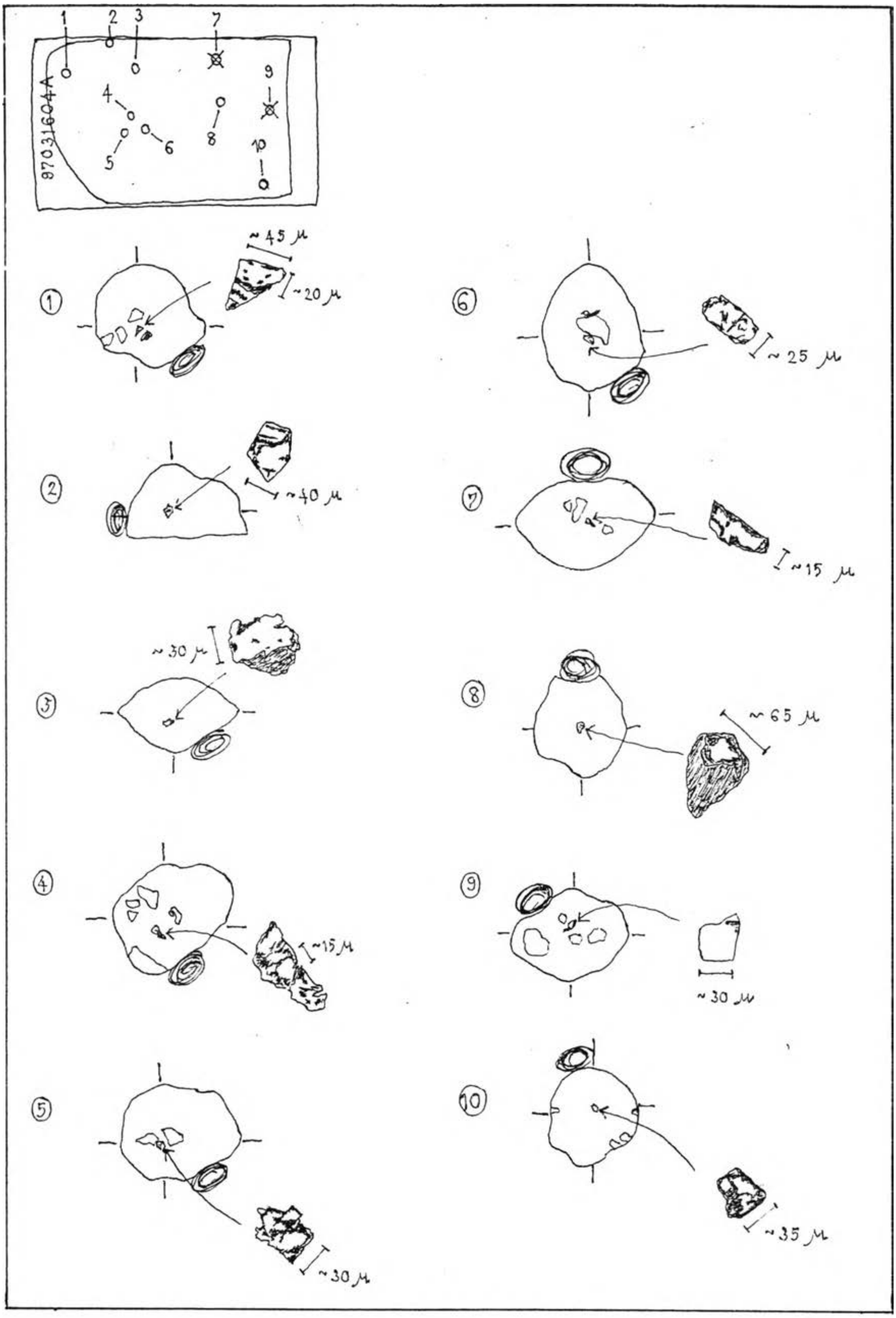

Figure 5.3 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section No. 97031604A of sandstone in Devonian Nakazato Formation.

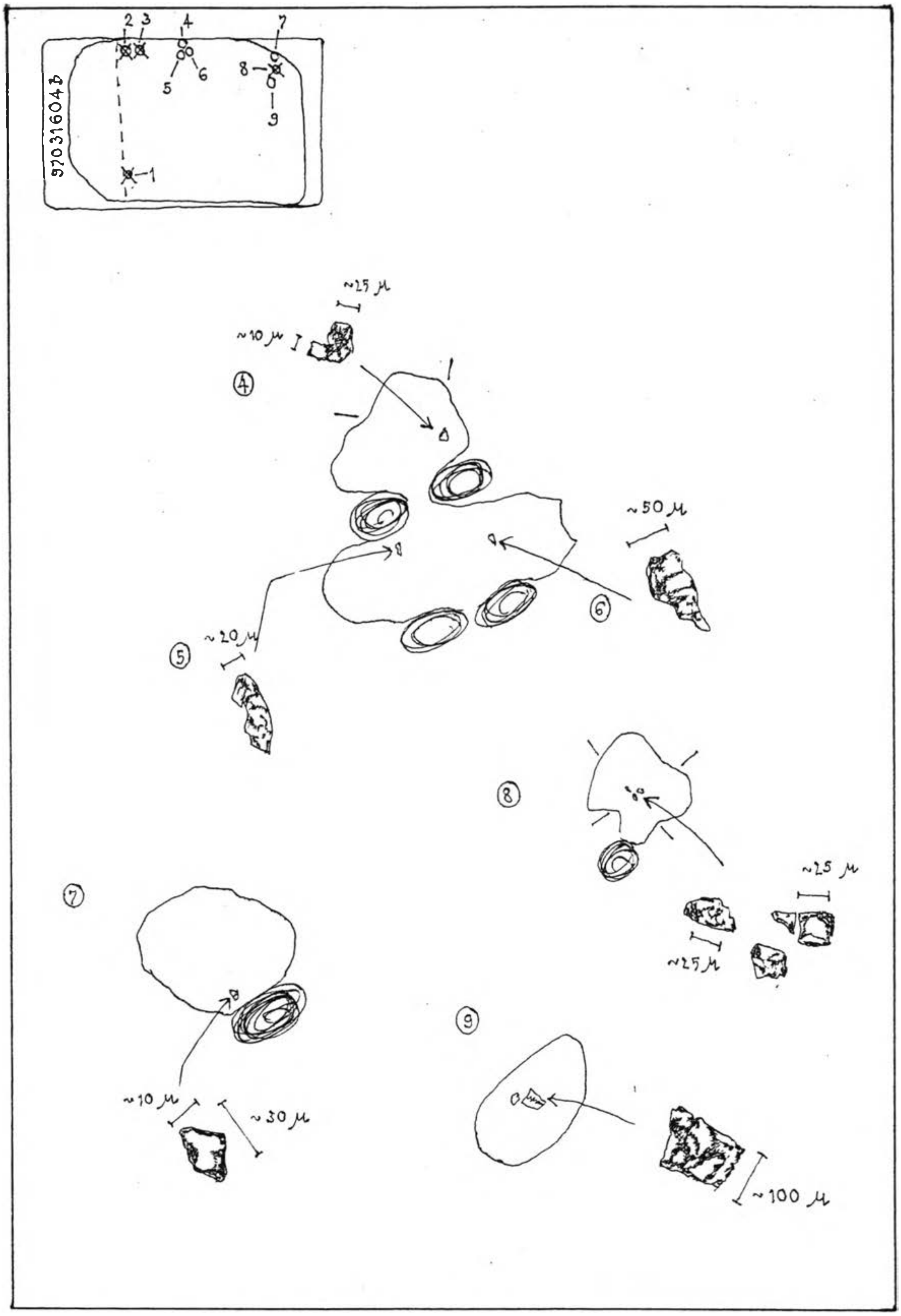

Figure 5.4 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section No. 97031604B of sandstone in Devonian Nakazato Formation.

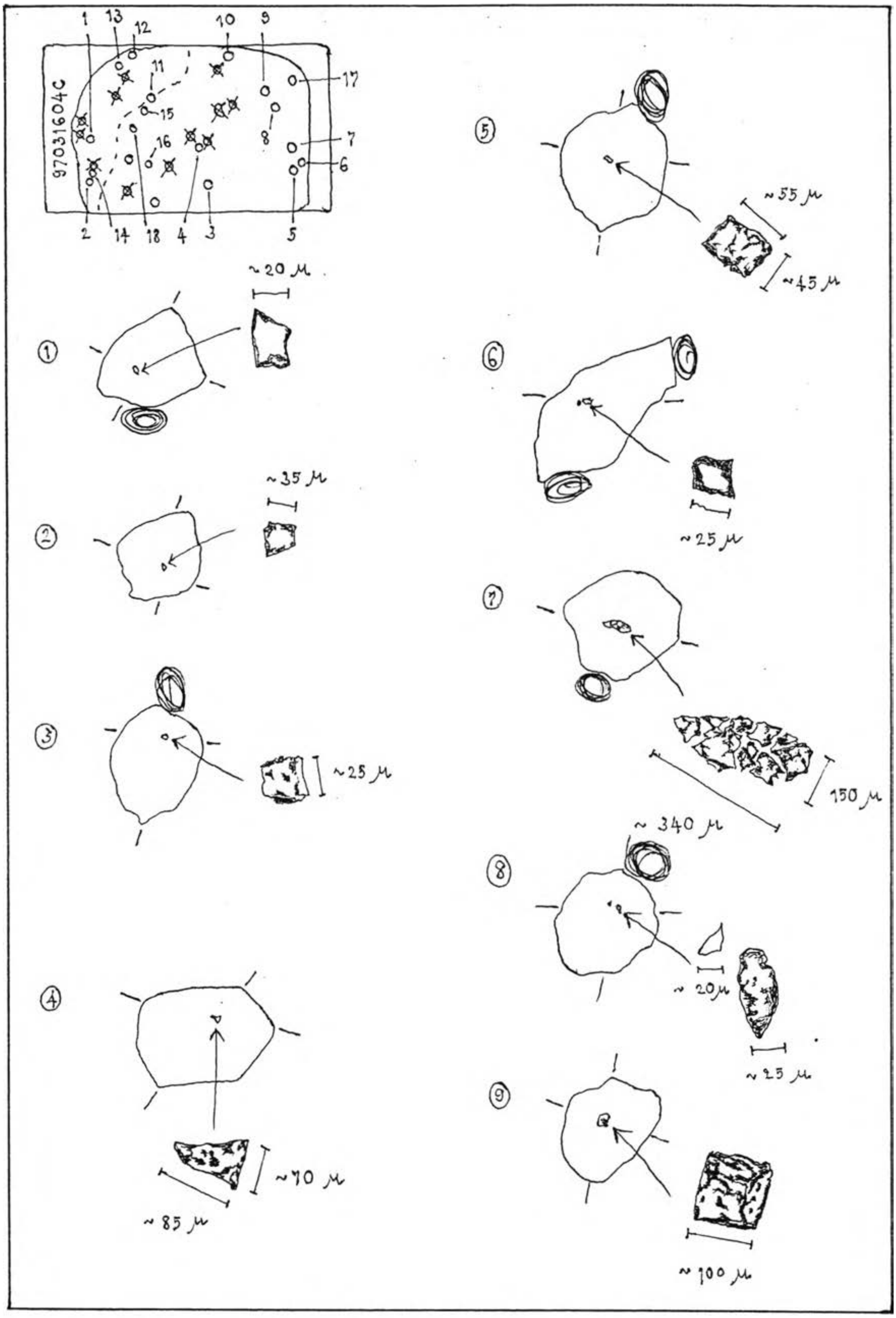

Figure 5.5 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section No. 97031604C of sandstone in Devonian Nakazato Formation.

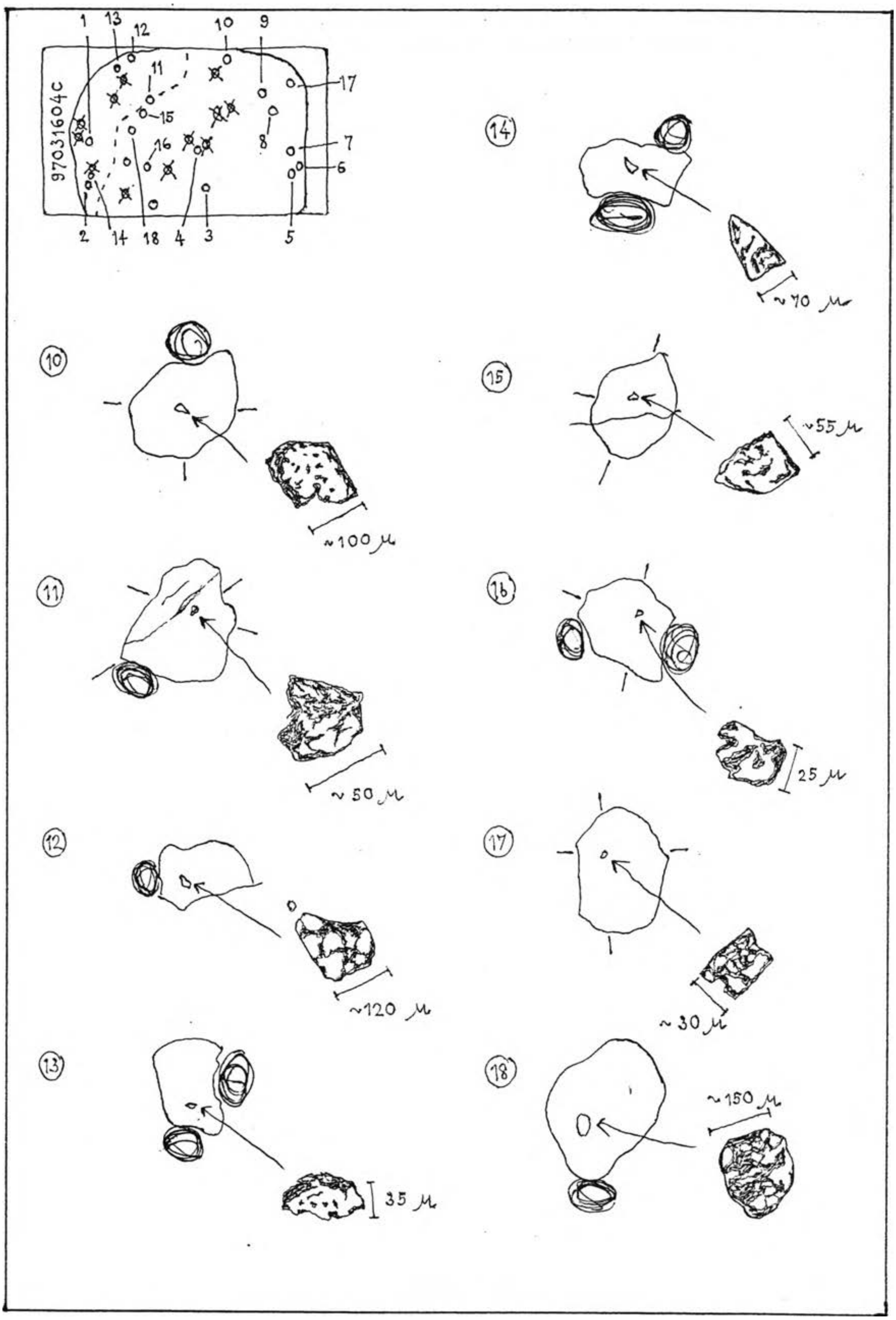

Figure 5.5 Continued.

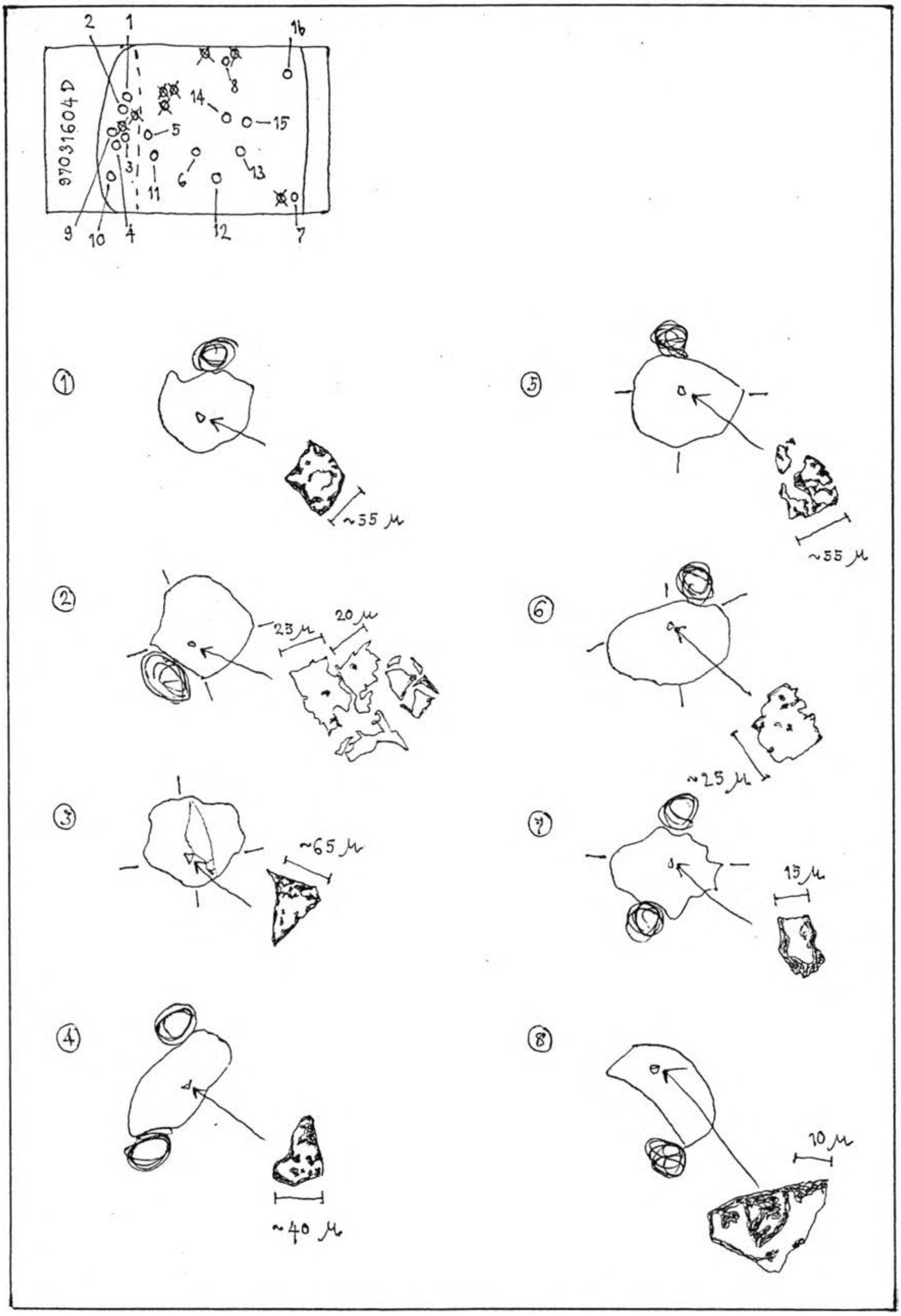

Figure 5.6 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section No. 97031604D of sandstone in Devonian Nakazato Formation.

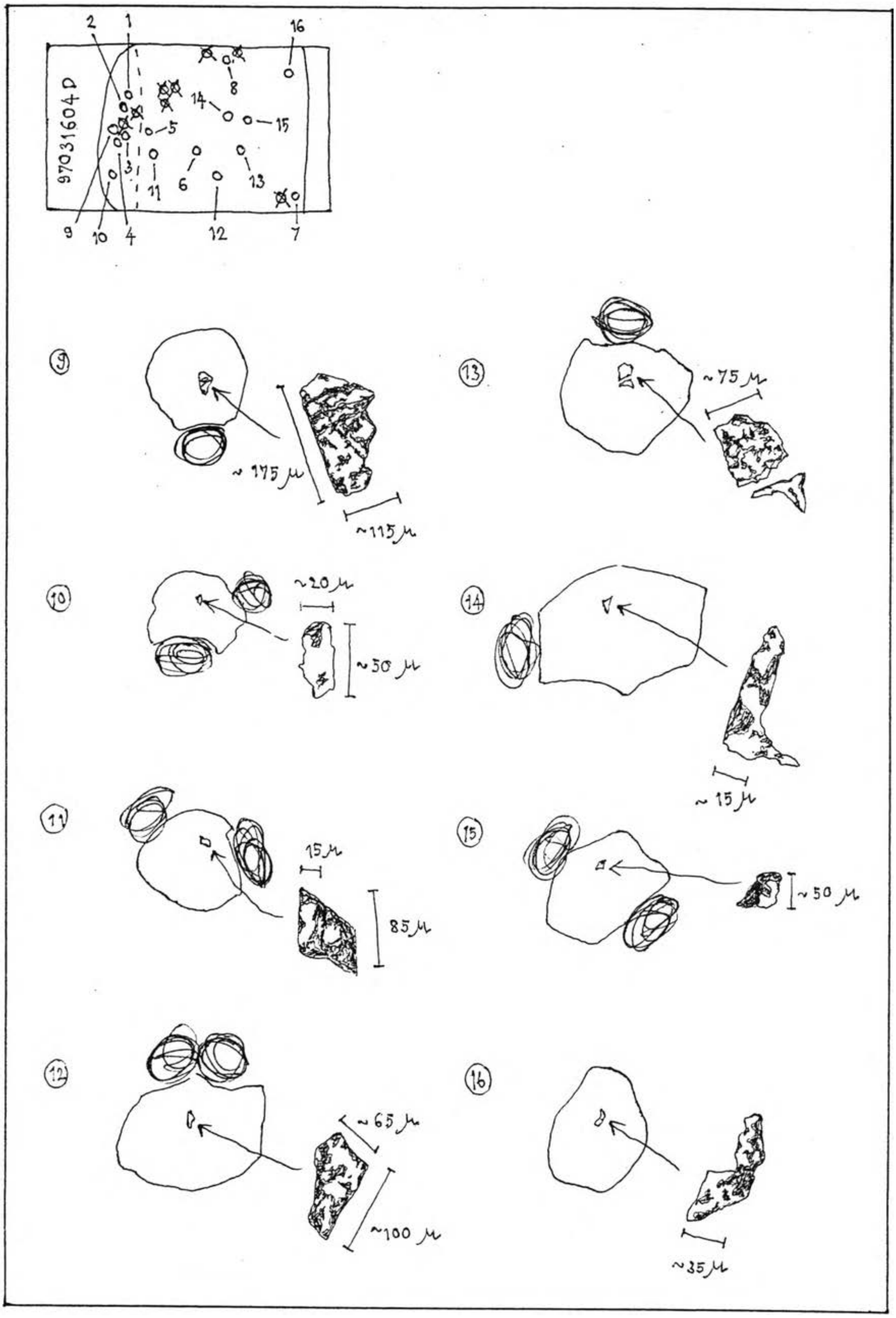

Figure 5.6 Continued.

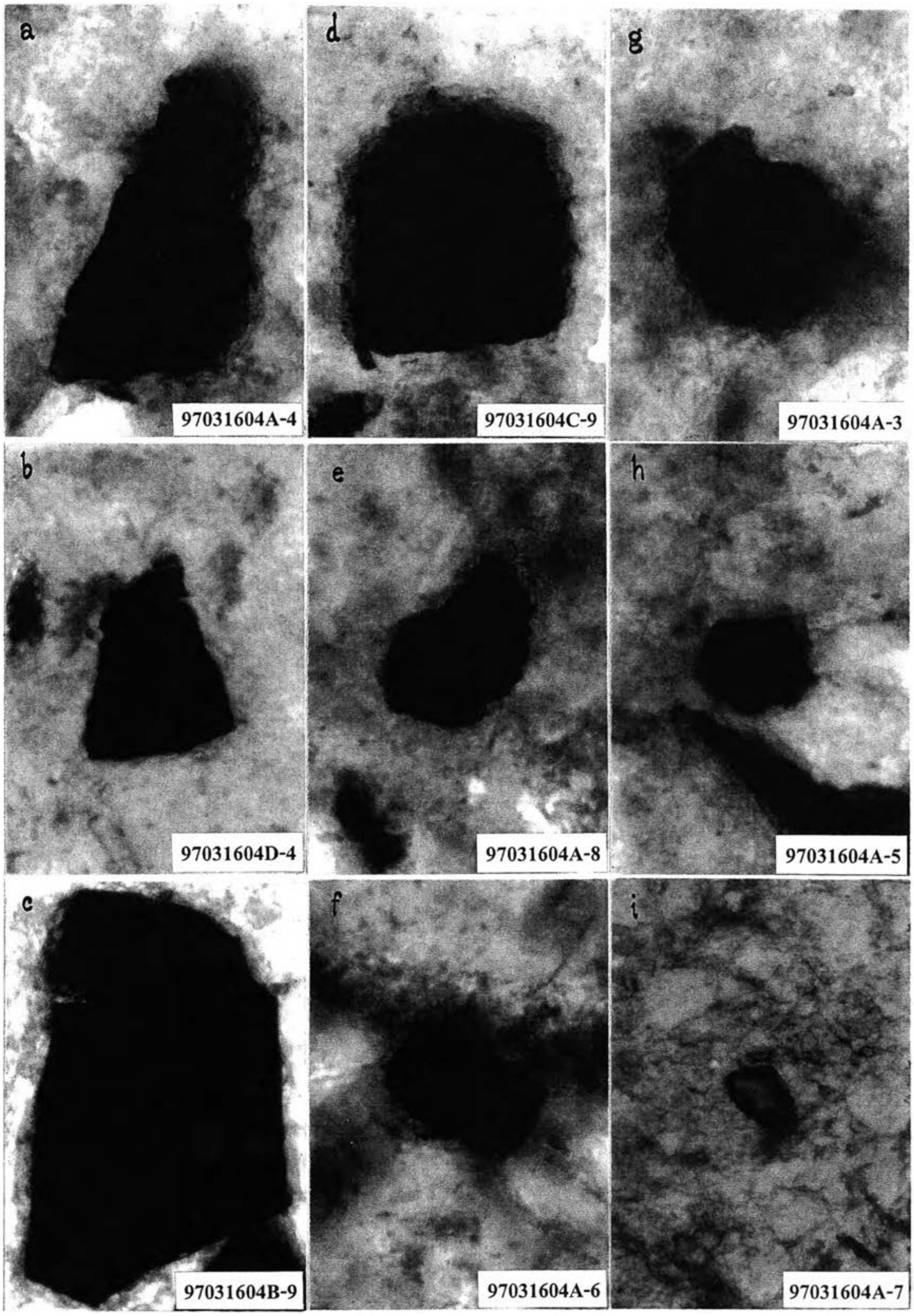

Figure 5.7 Characteristics of detrital chromian spinels from Devonian sandstone.

a-g are spinel grains of the first group, h-i are spinel grains of the second group.

100 μ

In order to know the chemical compositions of these detrital chromian spinels, thin-sections containing these mineral grains were later on polished until the smooth surfaces of the chromian spinel grains became larger than 10 microns, bigger than the tube of microprobe used. The polished thin-sections were then suitable for the spinel-chemistry analysis, using electron probe microanalysis (EPMA) technique.

The electron microprobe study using JEOL JXA-8621 was conducted at the Chemical Analysis Center, University of Tsukuba in Japan. Some detrital spinel grains that have a perfect smooth surface were selected firstly for the analysis. Major oxides resulted from the analysis of 18 samples are shown in Table 5.2.

From the chemical results of detrital chromian spinels in lithic arkose of Devonian Nakazato Formation, it can be seen that Cr_2O_3 is the major composition of the mineral, some grains contain up to 59 % (e.g., 97301604A-3 and 97031604D-9). The average of Cr_2O_3 values for these detrital spinels is 44.413 %. The large amount of Cr-content in spinels caused the darkening of their colors as seen under microscope (Fig. 5.7a-g). Al_2O_3 contents of these detrital chromian spinels are always low when compared with those of Cr_2O_3. The negative correlation between Al_2O_3 and Cr_2O_3 may indicate the substitution between Cr^{3+} and Al^{3+}. Some chromian spinel grains that Cr^{3+} was substituted by Al^{3+} contain the lowering of Cr_2O_3 content. These grains present paler color when compare with others that contain high content of Cr_2O_3.

TiO_2 content in the detrital chromian spinels are less than 0.5 %, principally less than 0.2 %, except for 3 grains, that are 97031604C-2, 97031604C-10, and 97031604C-5. This value seems also to show the slightly negative correlation with Cr_2O_3, thus, the yellowish color of spinels perhaps caused by larger amount of this TiO_2.

Table 5.2 Major oxides of detrital chromian spinels from Devonian sandstone analysing by EPMA.

Sample No.	97031604A-1	97031604C-2	97031604A-3	97031604A-4	97031604A-5	97031604A-6	97031604A-7	97031604A-8	97031604C-9
SiO2	0.192	0.068	0.072	0.107	0.024	0.062	2.197	0.301	0.047
Al2O3	8.525	24.478	7.92	26.381	33.57	34.16	2.212	12.608	15.704
TiO2	0.045	0.782	0.248	0.052	0.055	0.115	0.21	0.036	0.039
Cr2O3	57.149	36.911	59	39.653	35.568	35.603	35.267	56.812	54.493
FeO	19.853	26.936	21.899	14.525	16.045	16.178	22.674	18.449	18.183
NiO	0.007	0.093	0.028	0.062	0.067	0.141	0.052	0.039	0.019
MnO	0.425	0.343	0.338	0.214	0.182	0.256	0.341	0.615	0.445
MgO	8.619	8.744	10.483	13.272	15.473	15.466	0.906	10.532	11.335
CaO	0.043	0	0.012	0.011	0.018	0.034	0.019	0.028	0.029
Na2O	0.006	0	0	0.246	0.046	0.545	0.088	0	0
K2O	0.038	0.012	0.015	0.067	0.05	0.072	0.039	0.041	0.012
Total	94.902	98.366	100.015	94.59	101.099	102.633	64.004	99.46	100.304

Table 5.2 Continued.

Sample No.	97031604C-10	97031604C-11	97031604D-12	97031604D-13	97031604D-3	97031604C-4	97031604C-5	97031604D-9	97031604C-12
SiO2	0	0.055	0.088	0.048	0	0.01	0.04	0.025	0.112
Al2O3	23.744	33.732	31.519	12.29	25.701	28.51	17.867	9.017	16.945
TiO2	0.843	0.429	0.035	0.164	0.041	0.434	0.613	0.128	0
Cr2O3	36.255	31.455	36.52	53.809	39.073	32.58	49.09	59.034	51.145
FeO	25.708	17.57	20.077	23.334	20.422	23.344	20.628	14.341	18.27
NiO	0.165	0.098	0.161	0.019	0.065	0.139	0.079	0.078	0.067
MnO	0.325	0.249	0.251	0.364	0.236	0.232	0.248	0.169	0.249
MgO	11.075	14.877	13.441	9.256	11.441	11.456	11.664	13.576	12.846
CaO	0.013	0.01	0.019	0	0.008	0.002	0.038	0	0
Na2O	0	0.014	0	0.006	0	0.045	0.005	0.07	0.089
K2O	0.02	0.037	0	0.003	0.003	0.025	0.03	0	0.04
Total	98.148	98.526	102.112	99.292	96.99	96.775	100.304	96.437	99.764

Based upon the work of Arai and Okada (1991), the darker reddish brown chromian spinel grains which contain large amount of Cr_2O_3, but low content of Al_2O_3 and TiO_2 may be derived from the host rocks occurring at higher temperature-ultramafic rocks. The paler yellowish brown chromian spinel grains which contain small amount of Cr_2O_3, but high content of Al_2O_3 and TiO_2 may be derived from the host rocks occurring at lower temperature-basalts. Therefore, most of detrital chromian spinels from Devonian sandstone showing dark reddish brown color should be derived from ultramafic rocks whereas small amount of this detrital mineral showing yellowish brown color should be transported from basalt.

5.2 Detrital chromian spinels from Carboniferous sandstones and siltstones

Three samples of siltstones, 93120206, 93120207, and 93120208, from Carboniferous Hikoroichi Formation were found to contain detrital chromian spinels. These samples were collected from the Onimaru quarry in the Hikoroichi district (see Fig. 3.3). Under microscope, 19 grains of spinel were detected from 3 thin-sections of sample number 93120206, only one grain from a thin-section of sample number 93120207, and six grains from 2 thin-sections of sample number 93120208. Distributions, shapes, and sizes of these detrital chromian minerals within the thin-sections are shown in Figures 5.8 to 5.10.

Detrital chromian spinels from siltstones of Hikoroichi Formation are characterized by high relief, isotropic, and dark reddish brown in color. Sizes of these grains vary from less than 10 up to 60 microns, with the average of 25 microns. Their shapes are angular, most of them show the relic of the octahedral crystal form. Modal percents of detrital chromian spinels in siltstones are less than 1 %.

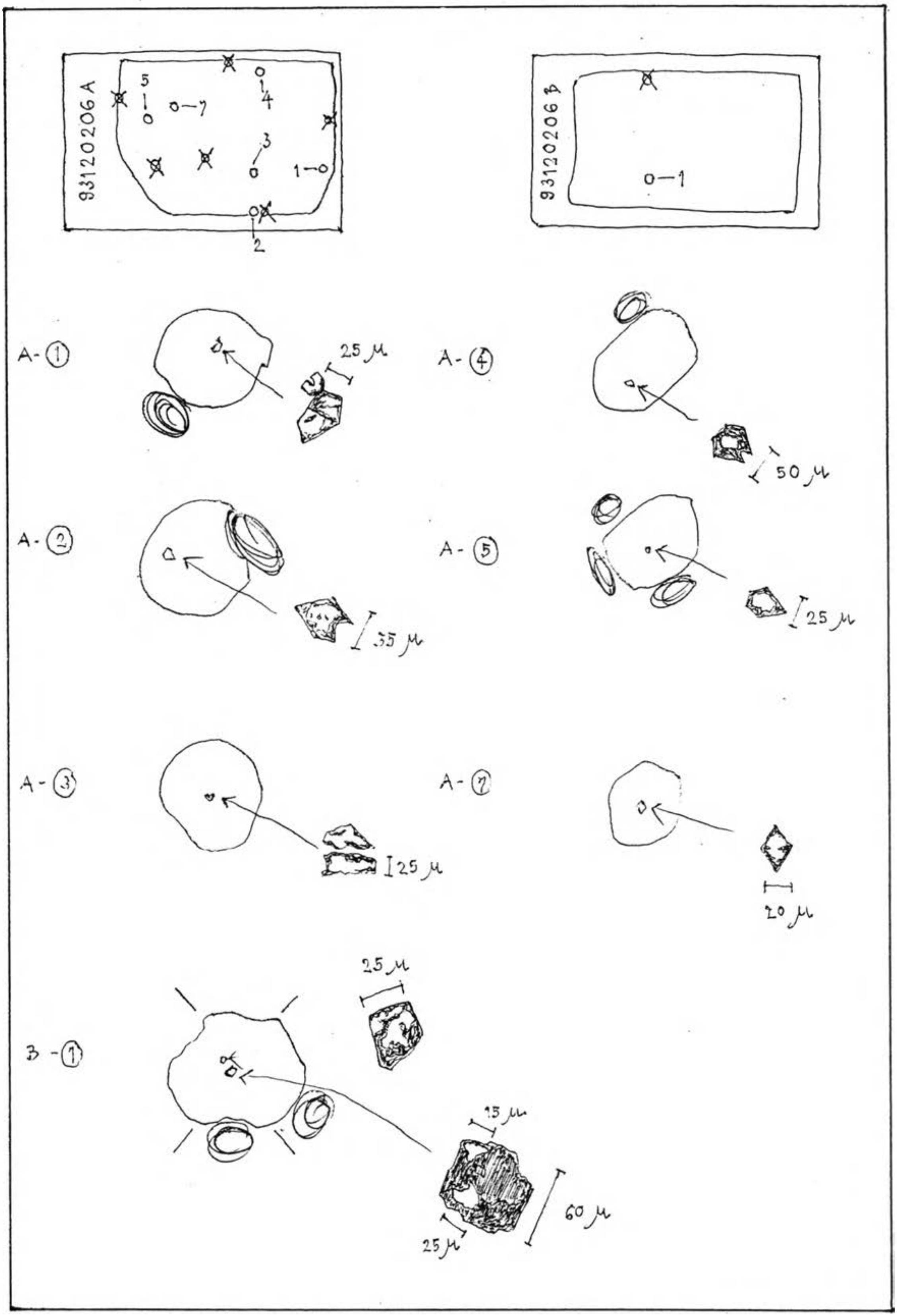

Figure 5.8 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section numbers 93120206A and 93120206B of siltstone in Carboniferous Hikoroichi Formation.

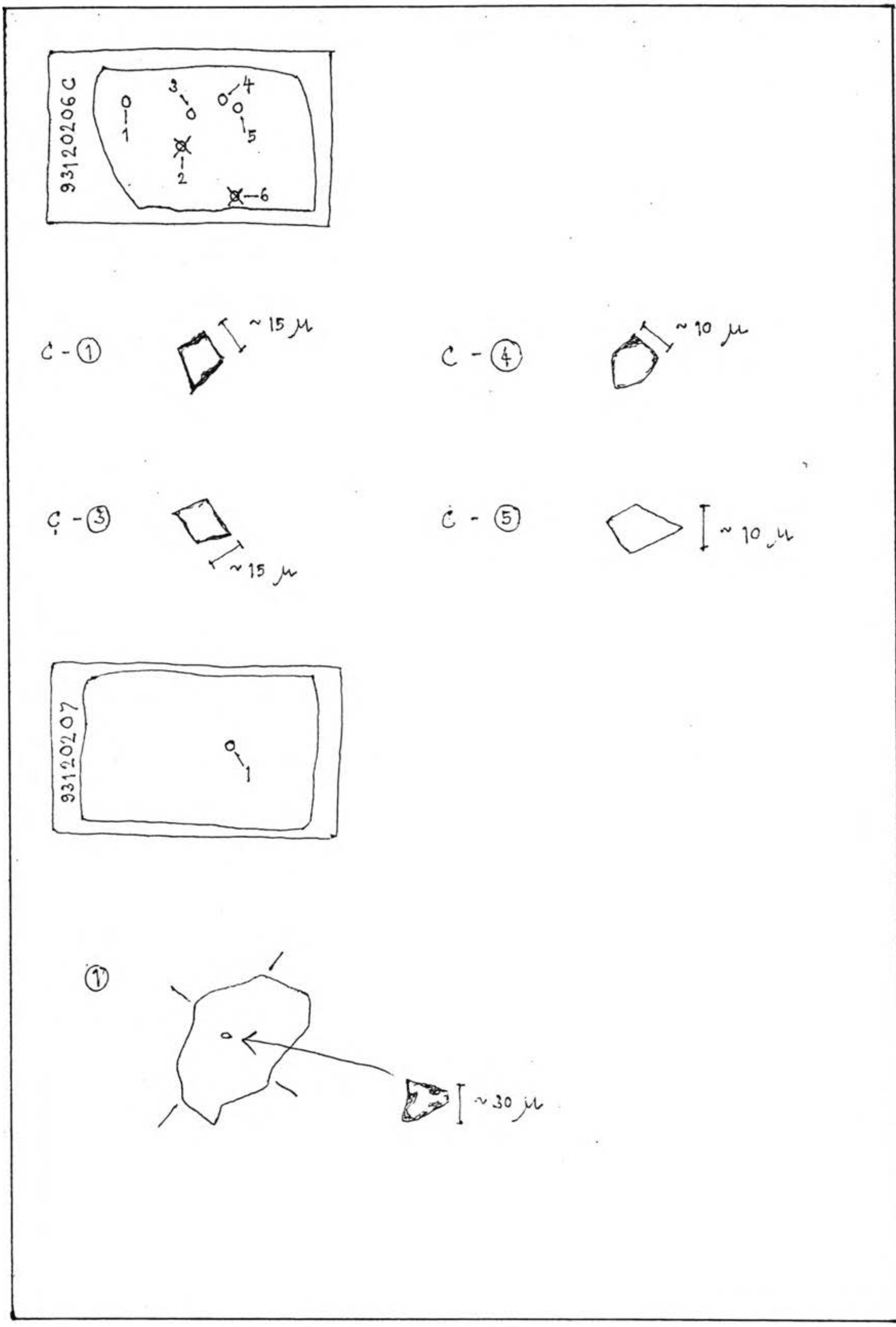

Figure 5.9 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section numbers 93120206C and 97120207 of siltstones in Carboniferous Hikoroichi Formation.

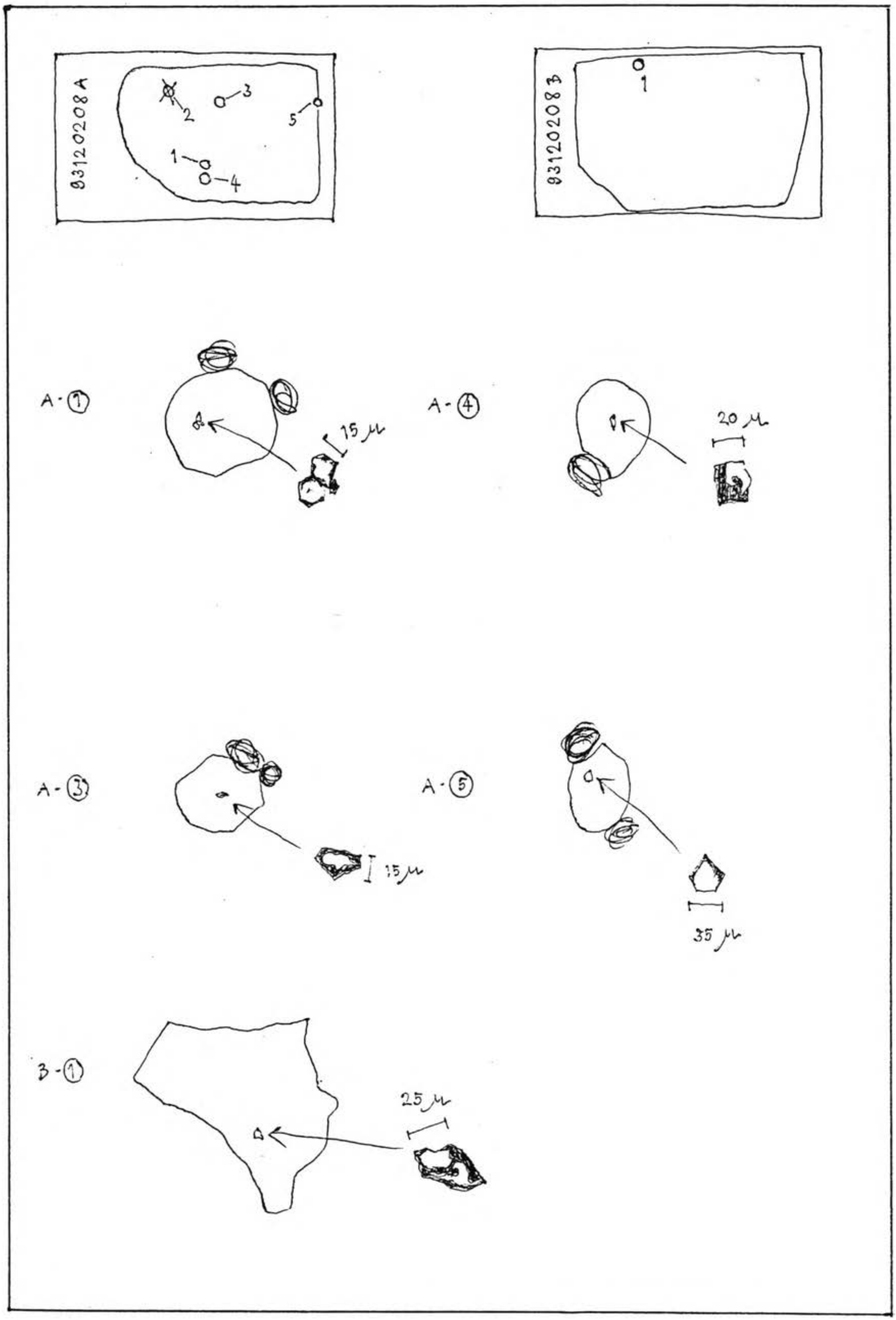

Figure 5.10 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section numbers 93120208A and 93120208B of siltstone in Carboniferous Hikoroichi Formation.

For Carboniferous sandstones, although there are many sandstone samples collected from this period, only four samples, that are 97031605-3, 97112302, 97112316, and 97112217, were found to contain detrital chromian spinels. The first three samples are from Hikoroichi Formation, sample numbers 97031605-3 (litharenite) and 97112302 (feldspathic litharenite) were collected in the Hikoroichi district (see Fig. 3.3) while sample number 97112316 (lithic arkose) was collected from the Sabukura district (see Fig. 3.9). The last one, litharenite, is from Odaira Formation in the Yokota district (see Fig. 3.10). Under microscope, 14 grains of detrital chromian spinels were detected on 4 thin-sections of these four samples, 8 grains from 97031605-3, 4 grains from 97112316, 1 grain from 97112312, and 1 grain from 97112217. Figures 5.11 to 5.13 show the sketches of distributions, shapes, and sizes of the detrital chromian spinel grains within the thin-sections.

Detrital chromian spinels from the Carboniferous sandstones are characterized by high relief, isotropic, and the colors are principally dark reddish brown with a few yellowish brown grains. Sizes of these detrital minerals vary from less than 10 up to 90 microns, but dominatly with the 25 microns. Their shapes are angular, most of them show the relic of the octahedral crystal form. Modal percents of detrital chromian spinels in sandstones are much less than 1 %.

From the characteristics of detrital chromian spinels in carboniferous clastic rocks, similar to those from the Devonian sandstone, the author divided these detrital spinels into two groups, base on their colors and sizes. The first group comprises those spinels that have dark reddish brown and large grains. This is the major group believed to derive from the host rock occurred slowly at higher temperature with lower content of Ti, higher content of Cr, which provided the larger size and darker color grains for sandstone. The second group is composed of those spinels that have yellowish brown and small grains. This is the minor group, only a few such grains of chromian spinel

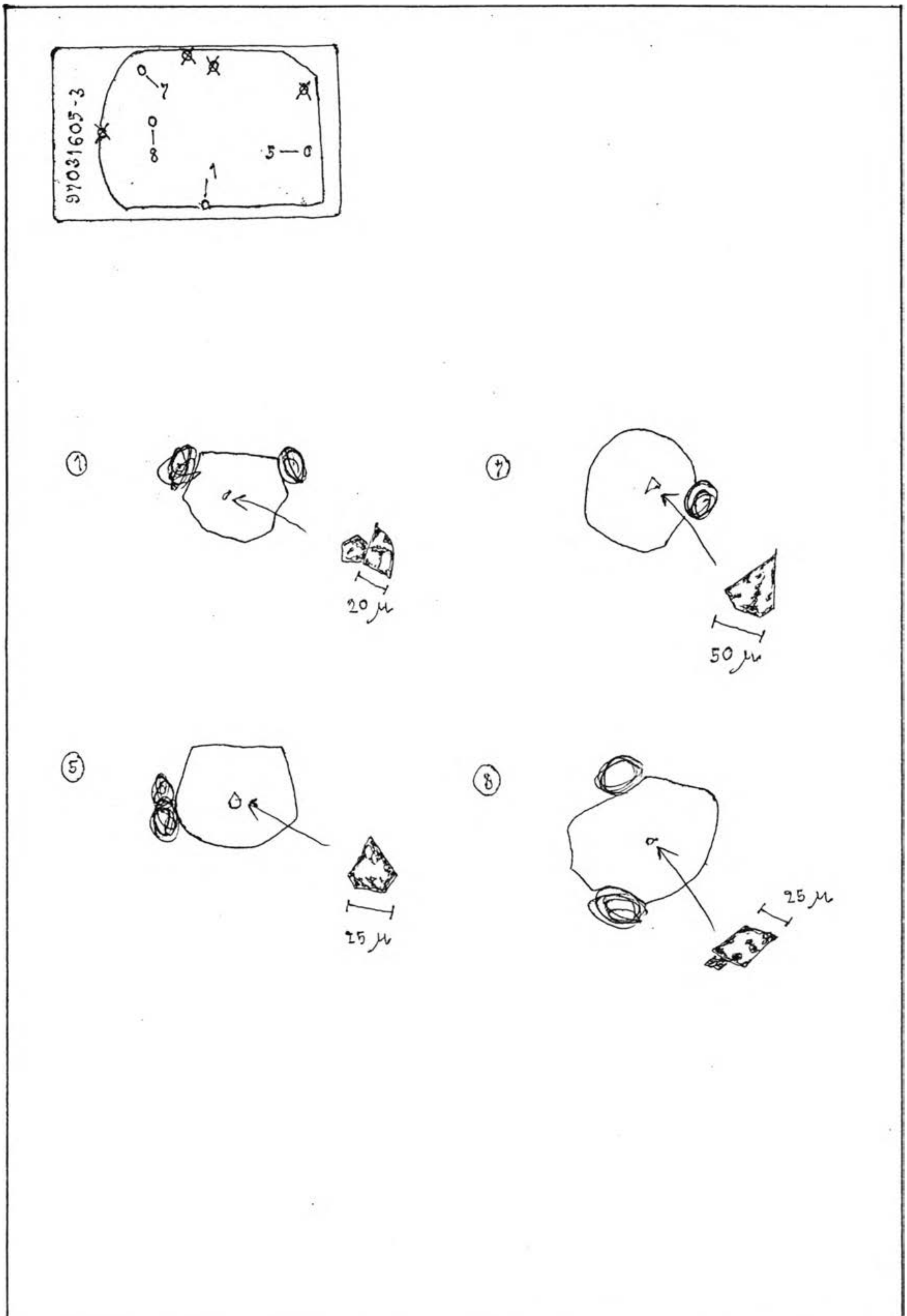

Figure 5.11 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section No. 97031605-3 of sandstone in Carboniferous Hikoroichi Formation.

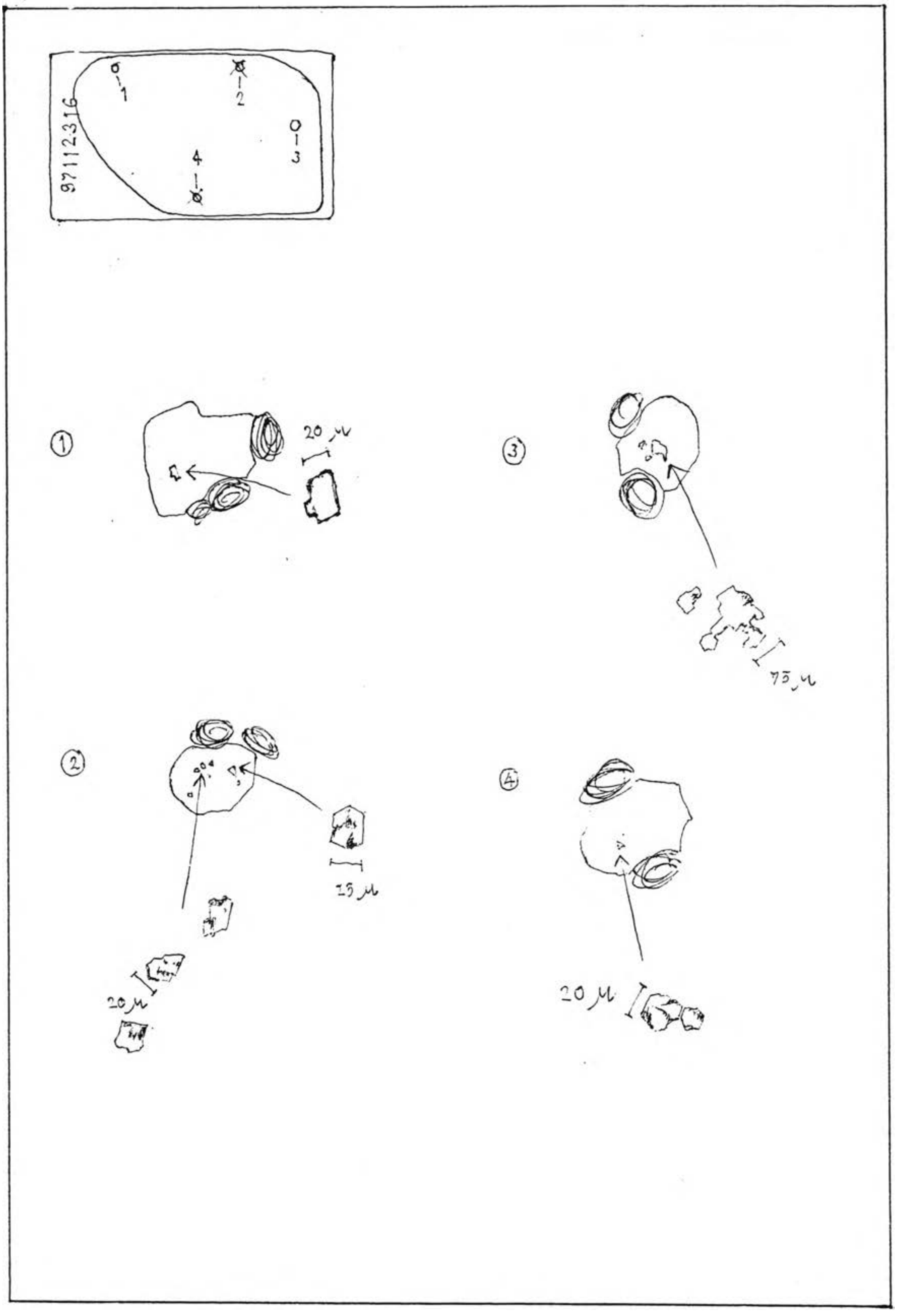

Figure 5.12 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section No. 97112316 of sandstone in Carboniferous Hikoroichi Formation.

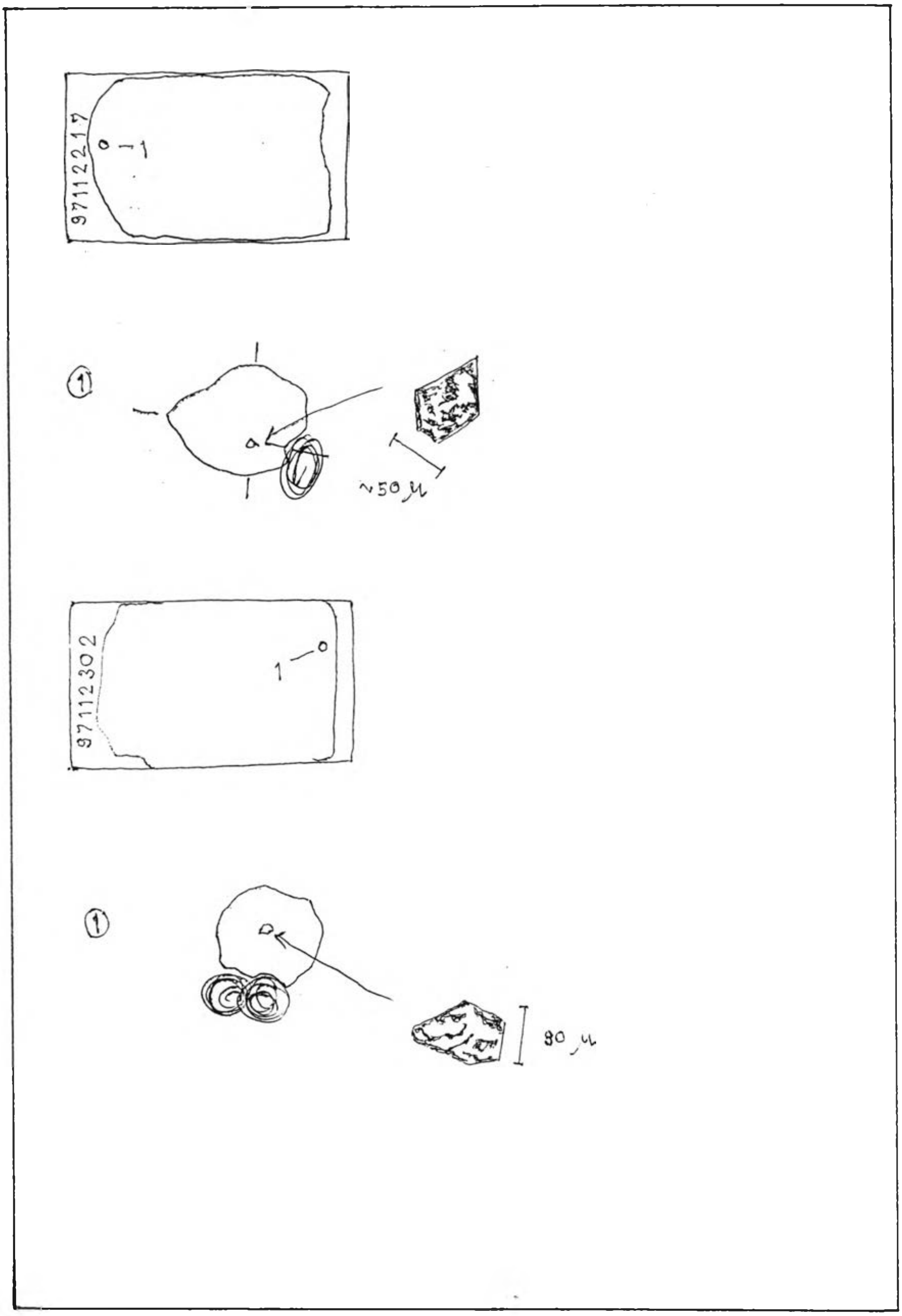

Figure 5.13 Sketches for distributions, sizes, and shapes of chromian spinel grains within the thin-section numbers 97112217 and 97112302 of sandstones in Carboniferous Odaira and Hikoroichi Formations, respectively.

were found. On the contrary to the first group, spinels of this group is believed to be transported from the provenance that their host rock occurred rapidly at lower temperature with higher content of Ti, lower content of Cr, which provided the smaller size and paler color grains for sandstone. Figure 5.14, shows the characteristics of detrital chromian spinel grains from the Carboniferous siltstones and sandstones, first group (a-g) and the second group (h-i).

Chemistry of 15 selected detrital chromian spinels from Carboniferous sandstones and siltstones analysed by EPMA are shown in Table 5.3. Most of the chromian spinel grains contain high percentage of Cr_2O_3, from 32.478 to 60.042 %, with the average of 48.366 %. This made chromian spinels show their dark colors of reddish brown. Al_2O_3 of these spinels are quite low due to the strong Cr^{3+}-substitution. TiO_2 of these detrital chromian spinels are less than 0.4 %, except for only one grain of spinel from siltstone number 93120206B-1 that this value is up to 0.6 %. Most of the spinels' TiO_2 are generally in the range of 0.17 to 0.38 %.

From the compositions of detrital chromian spinels (Table 5.3), together with their optical properties described above, it can be said base on Arai and Okada (1991) that most of the detrital chromian spinels found from Carboniferous clastic sedimentary rocks should be derived from the host rocks occurred at high temperature and could be ultramafic igneous rocks. A few yellowish brown grains of chromian spinels that contain high amount of TiO_2 may be derived from basalts occurring at lower temperature.

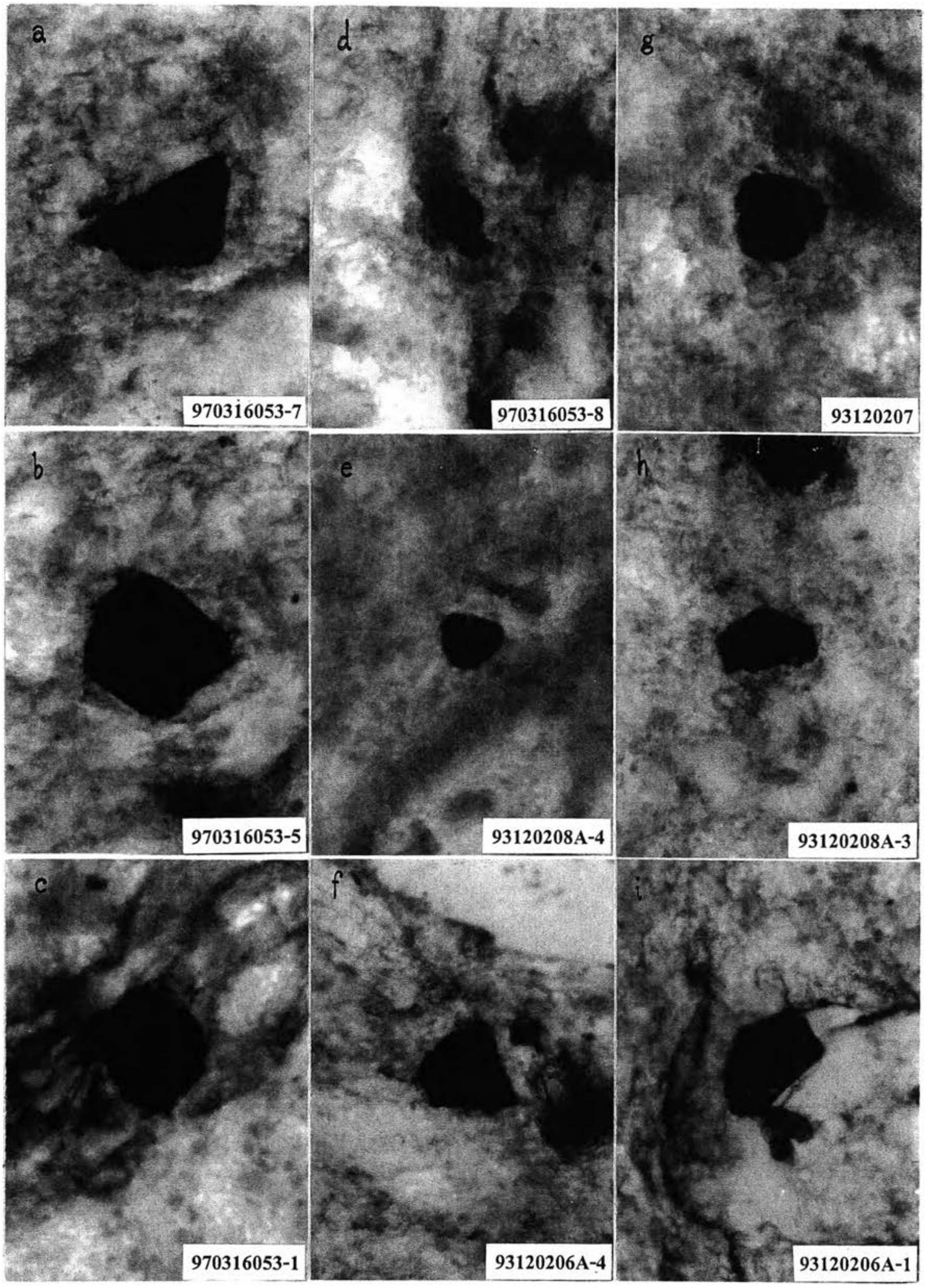

Figure 5.14 Characteristics of detrital chromian spinels from Carboniferous sandstones (a-d) and siltstones (e-i). 100 μ

a-g are spinel grains of the first group, h-i are of the second group.

Table 5.3 Major oxides of detrital chromian spinels from Carboniferous siltstones and sandstones analysing by EPMA.

Sample No.	93120206A-1	93120206A-4	93120206A-5	93120206B-1	93120207	93120208A-1	93120208A-3	93120208A-4
SiO2	0.369	0.052	0.249	0.302	0.018	0.43	0.14	0.412
Al2O3	20.856	8.106	2.078	28.259	29.358	10.282	10.365	3.699
TiO2	0.372	0.183	0.274	0.6	0.35	0.247	0.174	0.132
Cr2O3	40.285	55.47	44.059	32.98	32.478	52.805	55.184	51.819
FeO	21.655	20.54	29.894	24.409	23.884	21.804	18.552	22.626
NiO	0.01	0.105	0.102	0.084	0.157	0.033	0.094	0
MnO	0.205	0.343	0.386	0.485	0.298	0.433	0.343	0.713
MgO	16.044	11.908	1.541	7.58	15.532	10.629	12.353	1.645
CaO	0.084	0.025	0.257	0.113	0.133	0.093	0.121	0.296
Na2O	0.174	0.027	0.08	0.171	0.069	0.085	0	0.036
K2O	0.048	0.061	0.035	0.026	0.017	0.052	0.036	0.066
Total	100.104	96.82	78.954	95.008	102.295	96.892	97.361	81.444

Table 5.3 Continued.

Sample No.	93120208A-5	970316053-1	970316053-5	970316053-7	970316053-8	97112217	97112302
SiO2	0.692	0.249	1.01	0.149	0.079	0.096	0.038
Al2O3	6.827	2.142	7.3	10.274	6.433	7.266	15.668
TiO2	0.175	0.292	0.263	0.232	0.248	0.103	0.224
Cr2O3	54.067	45.98	47.514	51.398	60.042	53.28	48.128
FeO	17.962	29.916	25.309	27.664	22.156	29.455	21.541
NiO	0.07	0.099	0	0	0.047	0.035	0.097
MnO	0.251	0.386	0.371	0.422	0.303	0.333	0.279
MgO	7.506	1.676	5.473	9.091	9.944	0.359	10.634
CaO	0.092	0.323	0.193	0.042	0.074	0.076	0
Na2O	0	0.037	0.085	0.006	0.011	0.145	0.043
K2O	0.094	0.028	0.088	0.01	0.024	0.002	0.005
Total	87.737	81.129	87.607	99.285	99.36	91.15	96.657

5.3 Chromian spinels from Carboniferous basalt

Besides detrital chromian spinels detected from sandstones and siltstones, the author also detected chromian spinels from Carboniferous basalt in the Karosawa Formation at Omata district (see Fig. 3.11). Most of the chromian spinel crystals were found in association with altered olivine crystals in the thin-sections. Under microscope, many chromian spinel crystals were detected in two thin-sections of basalt sample number 97112104. The sketches of distributions, sizes, and shapes of these spinel crystals on the thin-sections are shown in Figures 5.15 and 5.16.

Chromian spinels from basalt of Karosawa Formation are, similar to the first group of detrital ones, characterized by high relief, isotropic, and dark reddish brown in color. Sizes of these chromian spinel crystals vary from less than 10 up to 110 microns, with the average of 40 microns. These crystals often show subhedral crystals of the octahedral form. The dark color of most chromian spinel crystals may suggest that they were the xenocrysts in basalt, which had occurred originaly in the higher temperature ultramafic rocks. Figure 5.17 shows the characteristics of these chromian spinel crystals within the Carboniferous basalt of Karosawa Formation.

Major oxides of 14 selected chromian spinel crystals from Carboniferous basalt analysed by EPMA are shown in Table 5.4. These chromian spinels contain high Cr_2O_3 content, they are in the range of 38.704 to 53.193 %. The Al_2O_3 values are lower than 20 % that are comparatively lower than Cr_2O_3 content. This suggested, like those of the detrital ones, that there was a strong Cr^{3+}-substitution. TiO_2 of these chromian spinels are in the range of 0.263 to 0.536 %. These chemical compositions show the similarlity between these chromian spinel crystals and detrital chromian spinels from clastic sedimentary rocks, especially the first group, which indicate the high temperature during their crystallizatin.

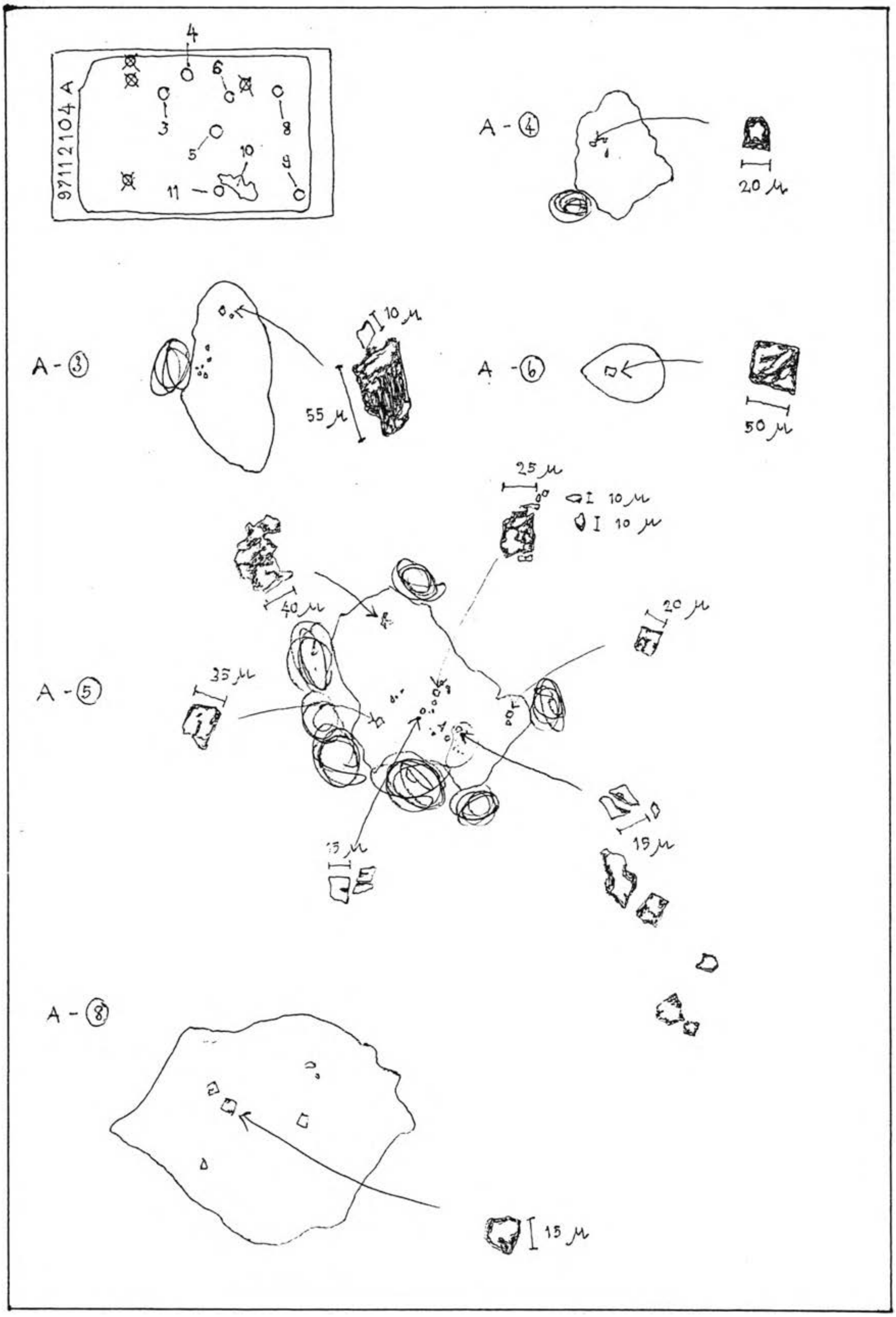

Figure 5.15 Sketches for distributions, sizes, and shapes of chromian spinel crystals within the thin-section No. 97112104A of basalt in Carboniferous Karosawa Formation.

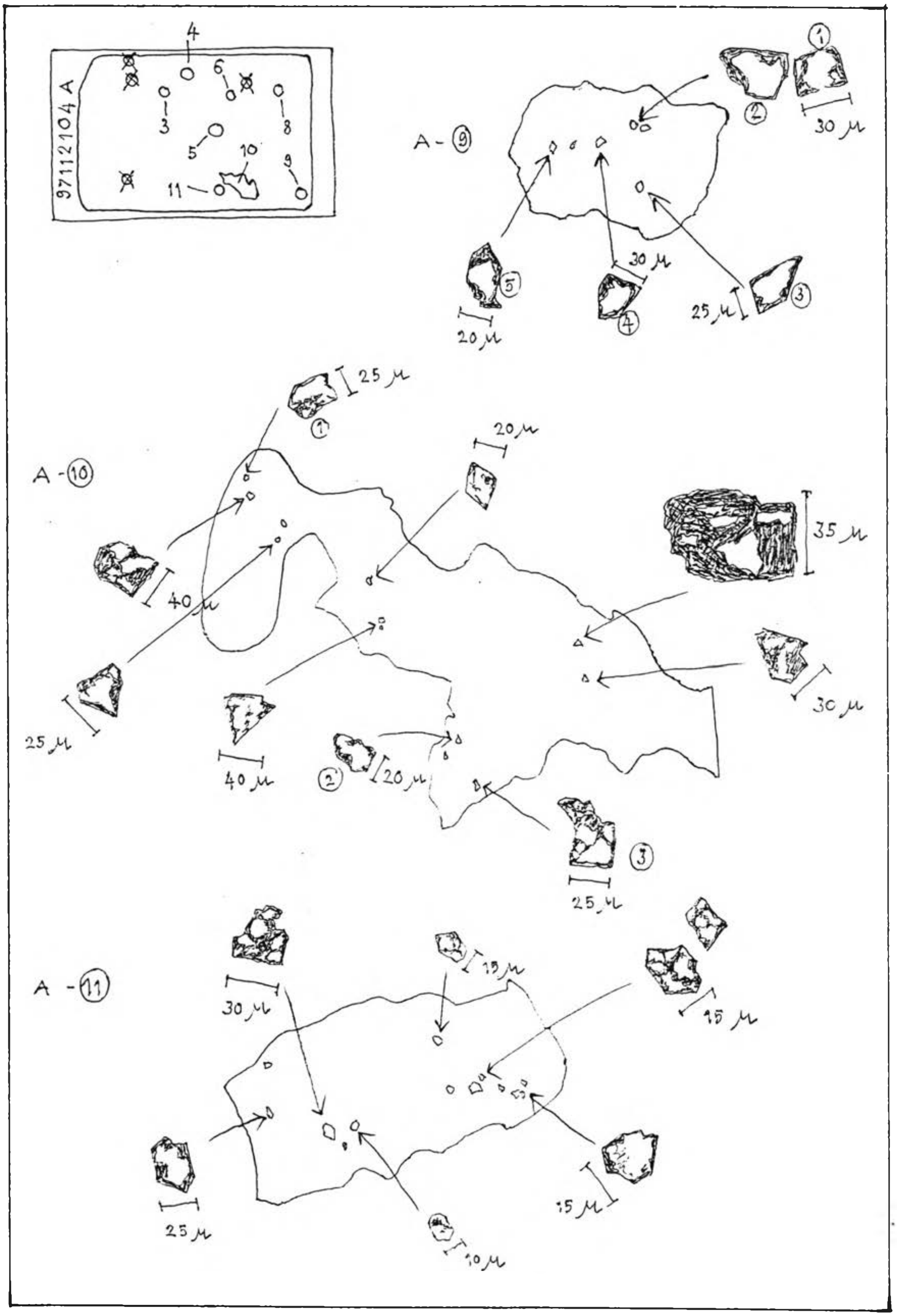

Figure 5.15 Continued.

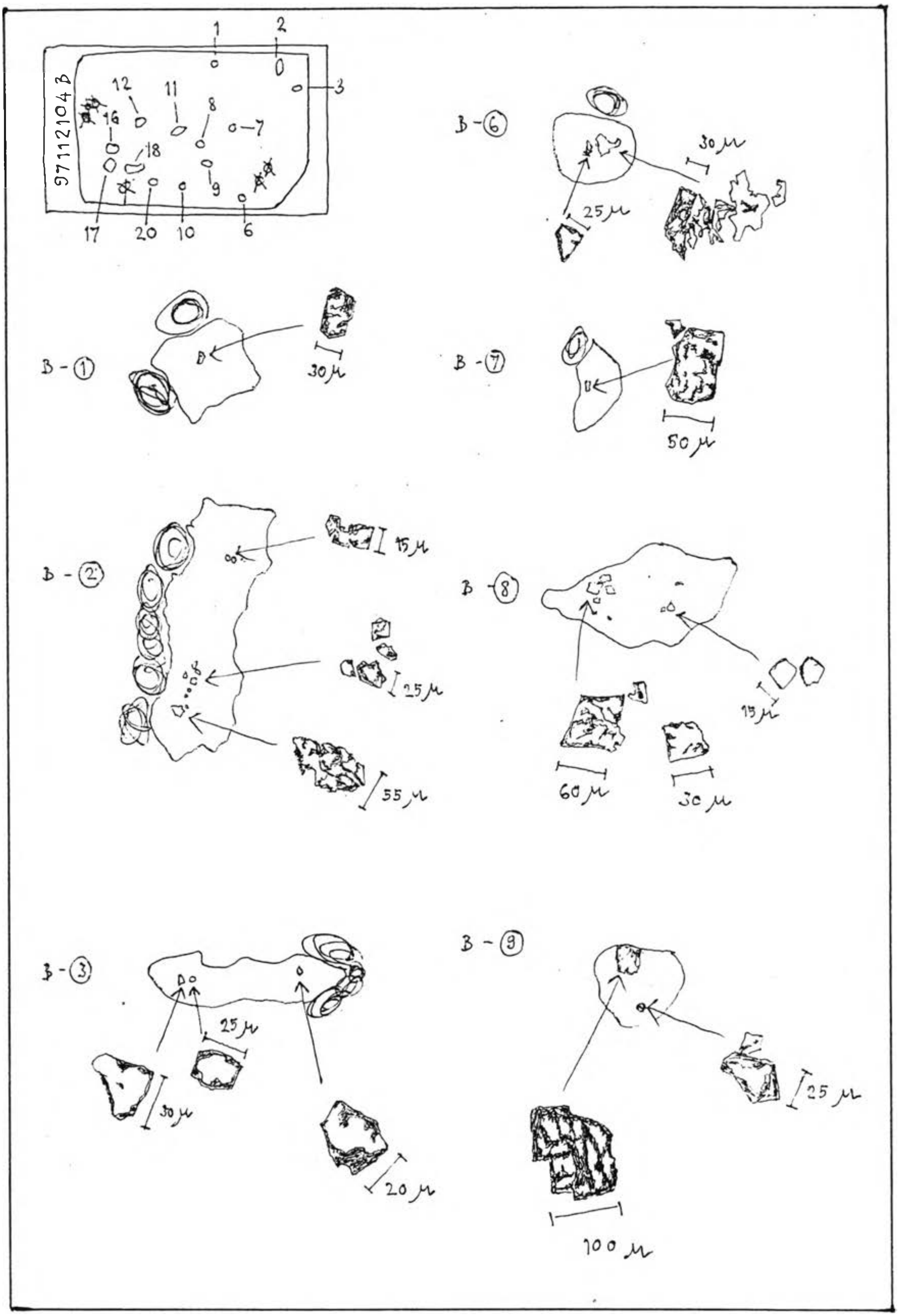

Figure 5.16 Sketches for distributions, sizes, and shapes of chromian spinel crystals within the thin-section No. 97112104B of basalt in Carboniferous Karosawa Formation.

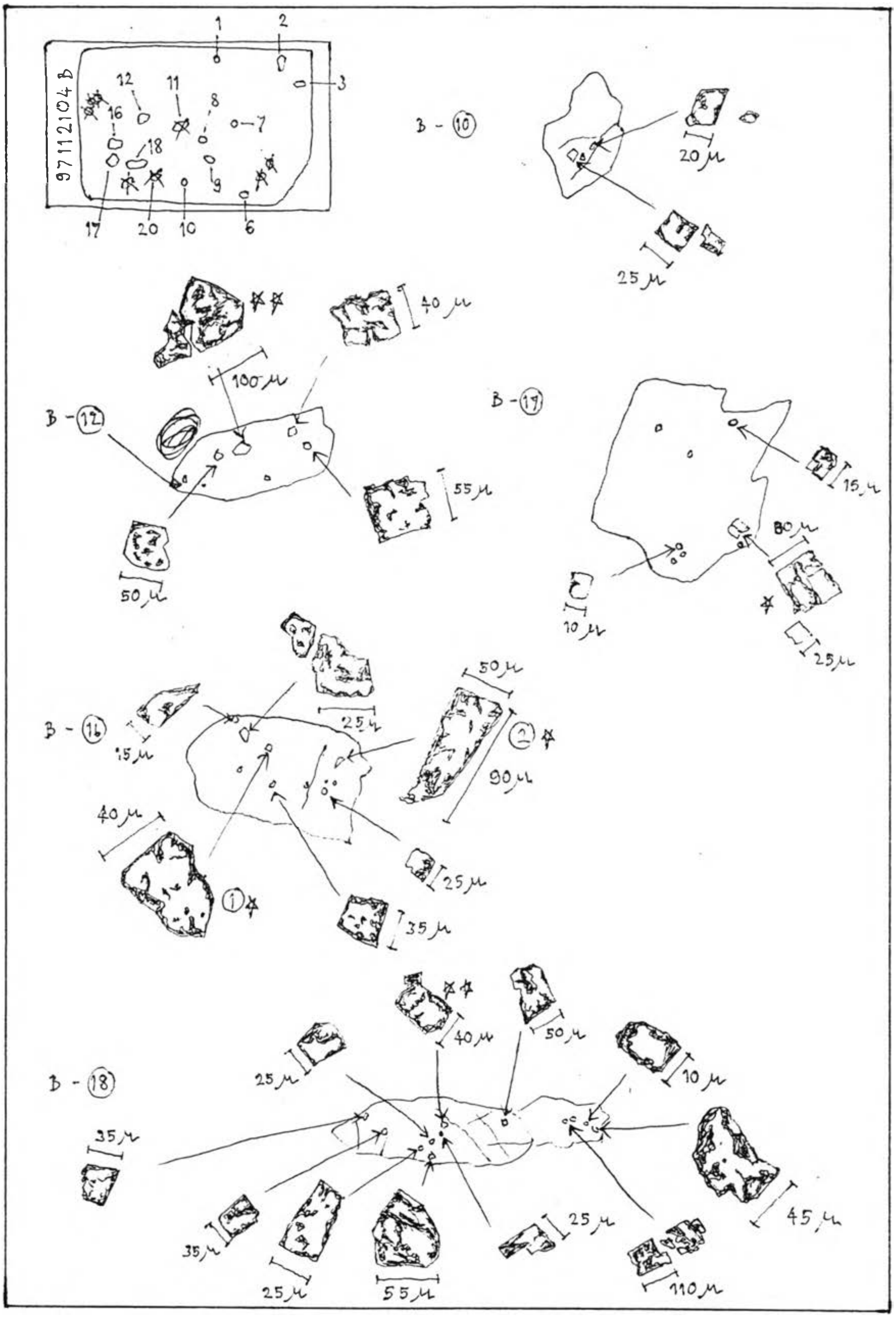

Figure 5.16 Continued.

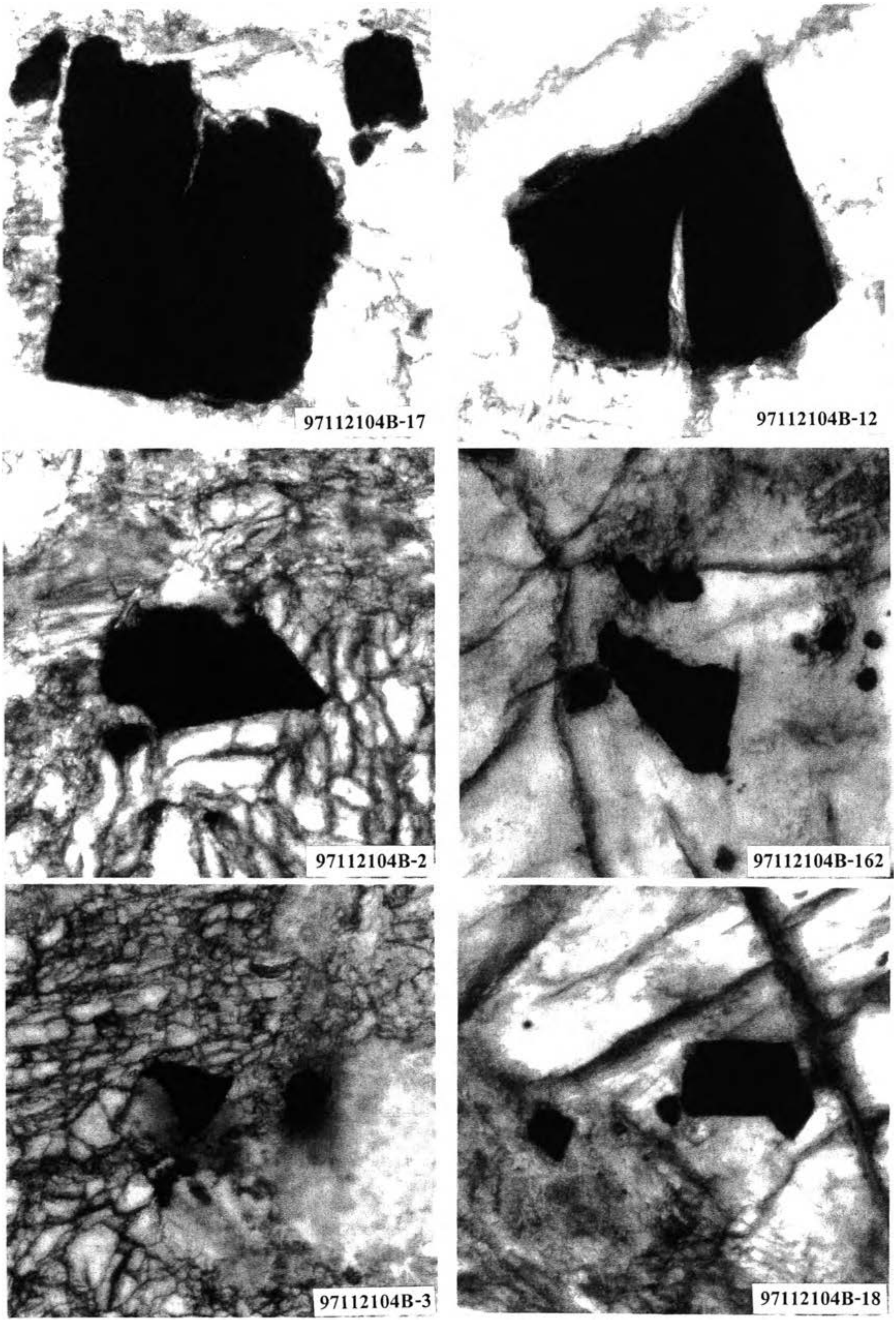

Figure 5.17 Characteristics of chromian spinel crystals from basalt in Carboniferous Karosawa Formation.

100 μ

Table 5.4 Major oxides of chromian spinels from Carboniferous basalt analysing by EPMA.

Sample No.	97112104B-12	97112104B-3	97112104A-4	97112104A-8	97112104B-8	97112104A-91	97112104A-101
SiO2	0.068	0.05	0.208	0.257	0.18	0.186	0.108
Al2O3	15.678	13.008	19.073	16.601	16.117	17.332	17.518
TiO2	0.445	0.395	0.536	0.5	0.498	0.418	0.524
Cr2O3	46	46.979	42.389	38.704	41.147	44.666	43.985
FeO	20.653	20.283	22.679	30.511	29.879	21.771	22.476
NiO	0.14	0.129	0.1	0	0.081	0.091	0.151
MnO	0.288	0.329	0.238	0.601	0.4	0.281	0.269
MgO	12.91	11.311	14.024	6.116	6.785	12.901	12.368
CaO	0.049	0.166	0.436	0.405	0.356	0.097	0.244
Na2O	0	0.027	0	0.006	0.069	0.053	0
K2O	0	0.052	0	0.008	0.007	0	0.007
Total	96.231	92.73	99.683	93.71	95.52	97.795	97.65

Table 5.4 Continued.

Sample No.	97112104A-4	97112104A-92	97112104A-93	97112104B-161	97112104B-17	97112104B-18	97112104B-162
SiO2	0.113	0.111	0.091	0.088	0.07	0.1	0.076
Al2O3	17.922	16.83	11.435	14.49	14.982	16.619	14.822
TiO2	0.529	0.494	0.263	0.325	0.48	0.491	0.359
Cr2O3	40.488	44.347	53.193	48.399	47.347	43.467	47.051
FeO	29.752	23.7	20.164	17.713	20.202	21.448	18.635
NiO	0.068	0.072	0.114	0.095	0.108	0.11	0.074
MnO	0.447	0.26	0.226	0.208	0.254	0.228	0.187
MgO	8.206	11.943	12.011	13.62	13.028	13.066	13.739
CaO	0.347	0.149	0.125	0.218	0.052	0.181	0.301
Na2O	0.056	0	0	0.079	0.053	0	0.016
K2O	0	0.004	0	0.008	0.008	0	0.002
Total	97.927	97.911	97.622	95.241	96.585	95.709	95.26

5.4 Detrital chromian spinels from Triassic sandstone

Detrital chromian spinels that found in Triassic sandstone are from sample number 97031703. This sample is arkose from Osawa Formation of the Inai Group collected at Utatsu district (see Fig. 3.14). Under microscope, 10 chromian spinel grains were detected, their sketches of distributions, size, and shapes are shown in Figure 5.18. Unfortunately, these detrital chromian spinels have not been analysed by EPMA yet.

Optical properties of these detrital chromian spinels are, similar to those from sandstones and siltstones of the Devonian and Carboniferous periods, high relief, isotropic, and dark reddish brown in color. Sizes of these detrital chromian spinel grains are very small, vary only in the narrow range of 20 to 30 microns. These Chromian spinel grains also show subhedral crystals of the octahedral form. The dark color of these detrital chromian spinels suggest the high content of Cr ion or low content of Al and Ti ions, which probably be derived from the host rocks occurring at high temperature. The small sizes of these subhedral chromian spinel grains partly indicate the rapid crystallization of these chromian spinels in the host rocks.

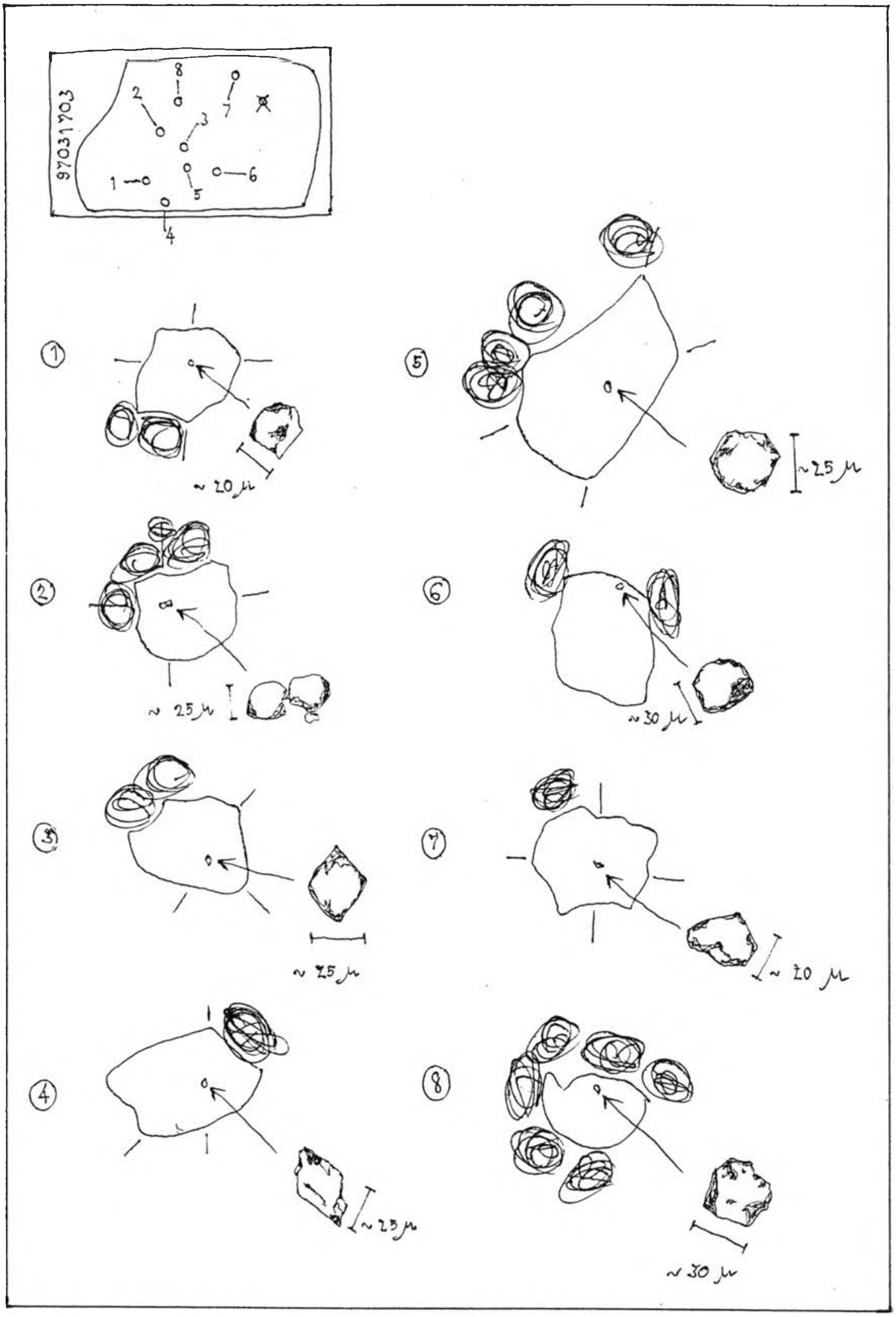

Figure 5.18 Sketches for distributions, sizes, and shapes of detrital chromian spinel grains within the thin-section No. 97031703 of sandstone in Triassic Inai Group.

5.5 Petrochemical characteristics of detrital chromian spinels

As stated in the previous sections, it is important to point out, in general, that there exists a certain relationship between petrography and geochemistry among the investigated (detrital) chromian spinels. It seems likely that dark-colored spinels always give rise to high content of Cr values (e.g., spinel numbers 97031604A-8, 97031604A-9, 93120206-4, 970316053-1, and 970316053-5) the mineral. And it is possible that the higher the TiO_2 content in the spinel, the lighter its color is. Based on these relationships, it is concluded that in thin-section of most equi-thickness the fragmental and rather anhedral-shape grains with dark colors represent the spinels related to the more mafic plutonic rocks. On the other hand, the lighter-colored grains with the subhedral- to rather euhedral-shaped spinel point to the spinel association with basaltic volcanic affinity. Moreover, it is also supported from the chemistry of spinel that the low contents of Cr and relatively higher contents of TiO_2 advocate the provenance of spinel from the less mafic, gabbroic or basaltic rocks. And the higher contents of Cr and lower contents of TiO_2 infer the existence of spinel in association with the more mafic to ultramafic varieties. Thus, both petrographic and geochemical investigations of spinels suggest the provenance of the rocks, which bear spinels as detrital grains.