APPLICATION OF MULTIVARIATE STATISTICAL ANALYSIS TO CLASSIFICATION OF ANTARCTIC STONY METEORITES

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Abstract: Two standard multivariate statistical computer analyses, *i.e.* cluster and stepwise discriminant analyses, are applied to classification of antarctic stony meteorites of 1 E chondrite, 11 H chondrites, 14 L chondrites, 4 LL chondrites, 8 C chondrites, 15 achondrites and 1 mesosiderite. Six cases by changing combinations of several variables of magnetic, chemical and petrographical components give basically the same classification of sample grouping, except for a few samples. Also it is worthy of special mention that only two parameters of I_s and $I_s(\alpha)/I_s$ make a good classification of sample grouping.

1. Introduction

Magnetic characteristics of antarctic stony meteorites have been intensively studied by NAGATA (1979a, b), taking account of mineralogical and petrographical properties by examing a Urey-Craig-Mason diagram (UREY and CRAIG, 1953; MASON, 1962) and a Prior's rule (PRIOR, 1920) for chondrites, and he showed that stony meteorite groups can be satisfactorily identified on the basis of magnetic data alone.

Adding 16 samples to the above Nagata's study, two kinds of multivariate statistical analyses (*e.g.* BMDP, 1979) are applied to classification of antarctic stony meteorites; one is a cluster analysis which gives a grouping on the basis of n-dimensional Euclid distances of variables, and the other is a stepwise discriminant analysis based on the distribution of probabilities of samples belonging to each group. Effects of combination of variables on the classification are examined for 6 cases.

The main objective of this study is to clarify the differences of classification by magnetic characteristics, chemical and petrographical properties, and their combinations. Although two methods for 6 cases give basically the same classification, a few differences are found, and it has been proved that this kind of computer analysis is useful for classification and identification of magnetic, chemical and petrographical properties of antarctic stony meteorites.

2. Data of Antarctic Stony Meteorites

42 samples of antarctic stony meteorites have been used in Nagata's previous study (1979 a, b), and 16 samples are newly added in the present analysis, as shown in Table 1. Since a preliminary analysis indicates that 4 irons make a definite

Table 1. Samples of antarctic stony meteorites with their characteristics. Abbreviations are explained in the text.

ID	NO.		Sample ID	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14
E	1	1	1 Y-691 (a)	48.0	97	0	3	0	12	764	22.18	1.86	0.089	11.47	0.48	11.92	5.6
H	2	1	2 Y-694 (d)	32.3	94	6	0	0	23	685	12.45	1.52	0.081	5.32	12.32	8.19	6.8
		2	3 Y-7301 (j)	15.5	85	10	5	0		660	7.21	0.77	0.05	5.05	18.92	9.36	10.9
		3	4 Y-74371	33.5	95	5	0	0	10	635							7.7
		4	5 Y-74647	27.9	94	6	0	0	14	659							7.1
		5	6 Kesen	34.4	95	5	0	0	8	670							6.5
		6	7 Yonozu	24.2	87	13	0	0	42	654							10.2
		7	8 Seminole	24.3	94	6	0	0	18	627							8.2
		8	9 Mt. Baldr b	27.3	88	10	2	0	10	650							9.5
		9	10 Mt. Brown	40.0	90	5	5	0		640							9.9
		10	11 Y-74054	24.0	98	2	0	0	11.6								
		11	12 Y-74115	23.9	96	4	0	0	25.5								
L	3	1	13 Y-7305 (k)	14.3	38	0	0	0		624	7.64	0.96	0.06	7.57	13.10	7.96	10.3
		2	14 Y-7304 (m)	16.6	90	0	10	0	4	644	7.50	0.83	0.06	8.44	13.02	9.04	10.2
		3	15 Y-74191	6.8	79	21	0	0	30	671	5.66	0.85	0.03	5.01	14.68	6.66	11.6
		4	16 Y-74362	8.1	81	19	0	0	38	645							11.4
		5	17 Fukutomi	22.9	82	18	0	0	20	700	9.83	1.33	0.02	6.37	11.62	7.39	10.2
		6	18 Mino	11.0	80	20	0	0	3	653	7.86	1.16	0.05	5.88	14.48	6.78	12.1
		7	19 ALH-769	8.4	65	35	0	0	160	680							15.7
		8	20 Dalgety Down	9.7	85	14	0	0	117	648							10.5
		9	21 Bjurböle	13.0	85	10	0	0		660							10.8
		10	22 Barratta	12.0	80	15	3	0		655							11.6
		11	23 Homestead	10.0	80	15	5	0		650							12.3
		12	24 Y-74190	9.3	83	6	11	0	5.8								
		13	25 Y-74354	21.8	93	7	0	0	65.5								
		14	26 ALH-77260	2.0	70	25	5	0	115								
LL	4	1	27 Y-74442	6.0	45	35	20	0	85	680	2.48	0.99	0.015	4.84	17.89	2.51	22.6
		2	28 Y-74646	3.2	19	7	74	0	20	720	1.96	1.01	0.03	4.59	19.02	1.94	31.0

Table 1. (*Continued*).

ID	NO.		Sample ID	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14
LL	4	3	29 St. Severin	4.7	45	55	0	0	500	700							20.5
		4	30 ALH-764	5.1	88	12	0	0	87.5								
C	5	1	31 Orgueil	11.9	0	0	0	100	(3.4)								
		2	32 Ivuna	11.2	0	0	0	100	(3.4)								
		3	33 Y-693 (c)	10.8	0	0	0	100	157	540	0.06	0.00	0.08	3.62	27.95	999.00	4.0
		4	34 Y-74662	0.81	5	0	85	10	149	580	0.00	0.00	0.06	7.38	22.53		
		5	35 Leoville	10.3	6	0	0	94	34	575							4.0
		6	36 Allende	0.61	0	0	95	5	143	576							
		7	37 Karoonda	7.8	0	0	0	100	155	548							
		8	38 Makoia	8.0	0	0	0	100	(2)	570	0.00	0.00	0.00	6.74	25.43		
AA	6	1	39 ALH-78113	5.33	100	0	0	0	24								
AD	7	1	40 Y-692(b)	0.19	81	0	19	0	42	780	0.66	0.004	0.003	1.34	12.58	165.00	4.0
		2	41 Y-74013	0.17	56	0	44	0	10	792							4.0
		3	42 Y-74037	0.32	100	0	0	0									
		4	43 Y-74097	0.32	100	0	0	0	13								
		5	44 Y-74648	0.20	100	0	0	0	85								
		6	45 Y-75032	0.042	100	0	0	0	93								
AE	8	1	46 Y-74159	0.061	100	0	0	0	265								
		2	47 Y-74450	0.22	100	0	0	0	58								
		3	48 ALH-765	0.076	100	0	0	0	15								
		4	49 ALH-78040	0.83	98	2	0	0	90								
		5	50 ALH-77302	0.012	100	0	0	0	24								
AH	9	1	51 Y-7308 (1)	0.53	100	0	0	0	13	792	0.39	0.012	0.007	0.75	16.00	32.5	4.0
AU	10	1	52 ALH-74123	6.45	93	7	0	0	41								
		2	53 Y-74659	2.23	84	9	7	0	76								
M	11	1	54 ALH-77219	45.00	92	8	0	0	46.3								
I	12	1	55 ALH-77255	184.50	98	2	0	0	9								
		2	56 ALH-762	210.00	100	0	0	0	6								
		3	57 DRP-78003	199.00	100	0	0	0	7.5								
		4	58 DRP-78007	176.50	100	0	0	0	4								

group well-separated from others, these are not adopted to this study. These samples are identified chemically and petrographically as 1 enstatite (E) chondrite, 11 olivine-bronzite (H) chondrites, 14 olivine-hypersthene (L) chondrites, 4 olivine-pigeonite (LL) chondrites, 8 carbonaceous (C) chondrites, 15 achondrites (A) sub-classified into 1 aubrite (AA), 6 diogenites (AD), 5 eucrites (AE), 1 howardite (AH), and 2 ureilites (AU), and 1 mesosiderite (M).

14 variables are defined as; Il is a saturation magnetization (usually denoted by I_s), I2 to I5 are ratios of the saturation magnetization to α-phase (kamacite), $(\alpha+\gamma)$-phase, γ-phase and the total saturation magnetization (conventionally denoted by $I_s(\alpha)/I_s$, $I_s(\alpha+\gamma)/I_s$, $I_s(\gamma)/I_s$, and $I_s(Mt)/I_s$, respectively), I6 is a magnetic coercive force (H_c) as a representative of the structure-dependent magnetic parameter, and I7 is a main magnetic transition temperature (Θ_c) in the cooling branch of thermomagnetic curve, in the case of stony meteorite, representing Curie point of magnetite in C chondrite, Curie point of Ni-poor α-phase FeNi in E chondrite and some achondrites, and γ to α transition temperature in H and L chondrites and some other achondrites. I8 to I14 are the weight per cent of abundances of metalic iron (Fe°), Ni°, Co°, FeS, FeO, and the ratios of Fe° to Ni° and Ni° to Fe°+Ni°, respectively. In the analysis, the samples whose adopted variable values are not available are omitted.

3. Computer Multivariate Statistical Analysis

Several methods of computer multivariate statistical analyses have been developed well recently. A cluster analysis is one of intuitively perceivable methods, which uses, as a measure for grouping, N (number of valuables)-dimensional distances, such as a p-root of summation of distance to the power of p ($p=2$ for a Euclid distance being used in this analysis), etc. The distance between adjacent samples or between a center of an adjacent group and a sample is called an amalgamation distance which is used for this classification.

On the other hand, a stepwise discriminant analysis calculates a probability P_{ij} that a sample j belongs to i group, and finds a maximum value of the distribution of P_{ij} ($i=1, 2, \cdots, M$: present number of groups); if $P_{Ij}=\max(P_{ij})$, then a sample j is most likely to be a member of a group I (For definition of P_{ij} and analysis procedure, see BMDP, 1979). The result P_{ij} ($i=1, 2, \cdots, M$, and $j=1, 2, \cdots, N$, N: total number of samples) is an $M\times N$ matrix or presented by M-dimensional structure for each sample. However, this paper employs a two-dimensional presentation by introducing a new coordinate system with two canonical variables in the following way. The linear combinations of variables in each set that have maximum correlation are the first coordinates in the new systems. Then a second linear combination in each set is sought such that the correlation between these is the maximum of correlations between such combinations as are uncorrelated with the first linear combinations. The procedure is continued until the two new coordinate systems are

completely specified (*e.g.* ANDERSON, 1958).

Among many possible combinations of variables I1 to I14, six cases are chosen with a view to investigate the effects of magnetic characteristics, chemical and petrographical properties on classification of antarctic stony meteorites.

Case 1 (I1 to I5) treats pure magnetic components of variables, neglecting other quantities. Case 2 (I1 to I5, and I6) adds I6 (H_c) to case 1. Case 3 (I1 to I5, and I7) adds I7 (Θ_c) to case 1. Case 4 (I1 and I2) is a special case to study how only two variables I1 (I_s) and I2 ($I_s(\alpha)/I_s$) act effectively on the classification. Case 5 (I8 to I14) studies chemical and petrographical components of variables. Finally, case 6 (I1 to I5 and I8 to I14) is a combination of case 1 and case 4, trying to use characteristics of the both. Comparison among all cases reveals not only toles of each component of classification, but also properties of each antarctic stony meteorite.

4. Results and Discussions

A total of 58 samples of antarctic stony meteorites are used in this study. As previously mentioned, a preliminary analysis indicates that 4 irons make one definite group well-separated from others, and so these are omitted in this result.

The results of a stepwise discriminant analysis (hereinafter abbreviated to STW) for 6 cases are illustrated in Figs. 1 to 6, respectively in the form of the canonical variable coordinate system. As for a cluster analysis (hereinafter abbreviated to CLT), one example of case 2 is depicted in the amalgamation distance vertical tree diagram (Fig. 7) and its shaded form (Fig. 8).

Note that in the following a suffix indicates an identification number within a group, *e.g.* L_{14} means a 14th sample of a group L listed in Table 1.

4.1. Case 1: I1 to I5 (Fig. 1)

One E chondrite Y-691 (a) and one mesosiderite ALH-77219 make one group by themselves. This is true for all cases and analyses.

H_2 Y-7301 (j) belongs to L-chondrite group and is near L_2 Y-7304 (m), L_9 Bjurböle, L_{10} Barratta and L_6 Mino by STW or nearest to L_9 by CLT. H_9 Mt. Brown is placed between H and M groups.

L_1 Y-7305 (k) belongs to LL-chondrite group by STW but it is in-between an achondrite, L- and LL-chondrites groups and has long amalgamation distances to all groups by CLT. L_5 Fukutomi belongs to H-chondrite group and is near H_6 Yonozu but show a long amalgamation distance by CLT. L_{13} Y-74354 belongs to H-chondrite group and is near H_{10} and H_{11} Homestead by STW and near H_7 Allan Hills-769 by CLT. L_7 Allan Hills-769 and L_{14} ALH-77260 are in-between L- and LL-chondrites groups, and have long amalgamation distances to both groups.

LL_2 Y-74646 belongs to C-chondrite group but is in-between LL-chondrite and C-chondrite groups by STW, and CLT indicates the long amalgamation distance to

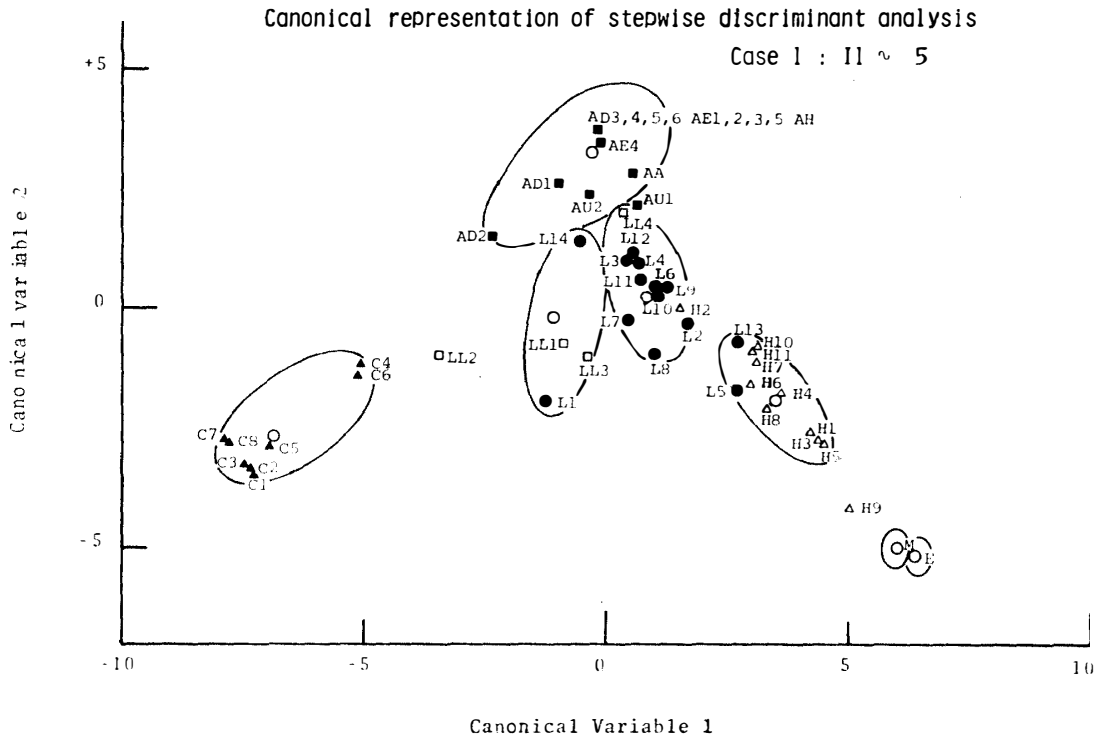

Fig. 1. Canonical representation of stepwise discriminant for case 1: I1 to I5. A circle indicates a center coordinate of each group.

both groups.

4.2. Case 2: I2 to I5, and I6 (Figs. 2, 7 and 8)

Since H_2 Y-7301 (j), H_9 Bjurböle and L_1 Y-7305 (k) have no data of I6, no examinations of these samples are made in this case.

L_5 Fukutomi and L_{13} Y-74354 belong to H-chondrite group. L_5 is near H_6 and L_{13} is near H_{10} and H_{11} by both STW and CLT.

L_7 Allan Hills-769 and L_{14} ALH-77260 are still in-between L- and LL-chondrites groups.

LL_2 approaches to C-chondrite group compared with case 1, but still has a long amalgamation distance. LL_4 is now belonging to the achondrite group apart from LL-chondrite group.

4.3. Case 3: I1 to I5, and I7 (Fig. 3)

H_2 Y-7301 (j) belongs again to L-chondrite group and is near to L_9 Bjarboele by both STW and CLT. H_9 Mt. Brown is existing in-between H and M groups.

STW shows L_5 Fukutomi belongs to H-chondrite group and is near H_6 Mino, but L_5 belongs to its own L-chondrite group by CLT. L_1 Y-7305 (k) and L_7 Allan

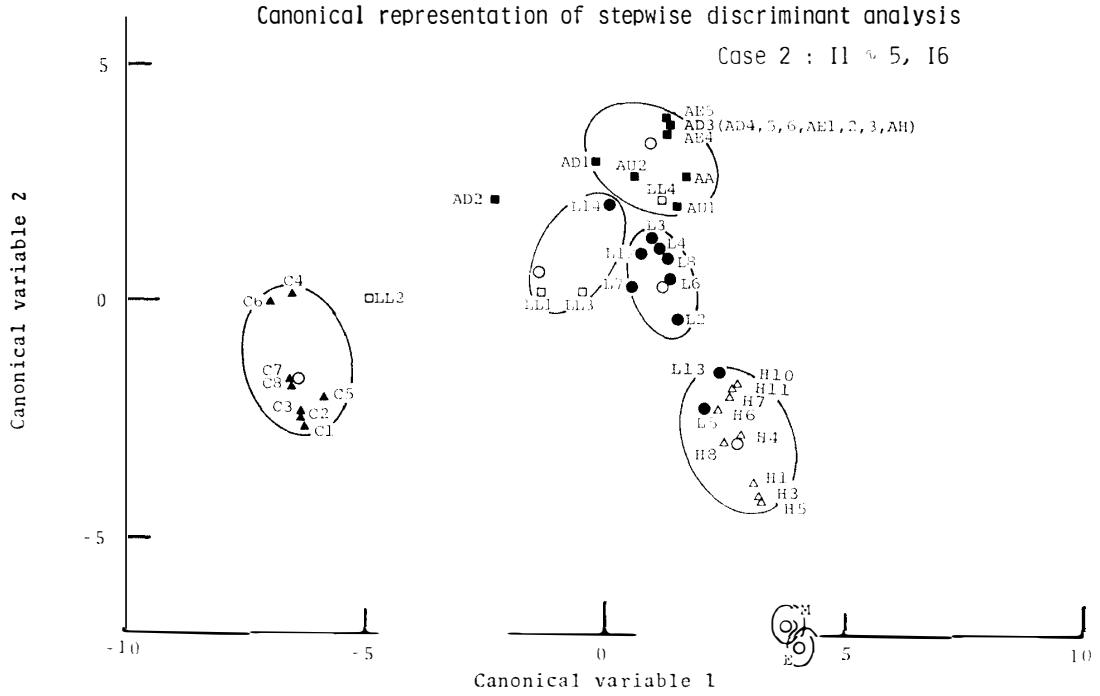

Fig. 2. Canonical representation of stepwise discriminant analysis for case 2: I1 to I5, and I6.

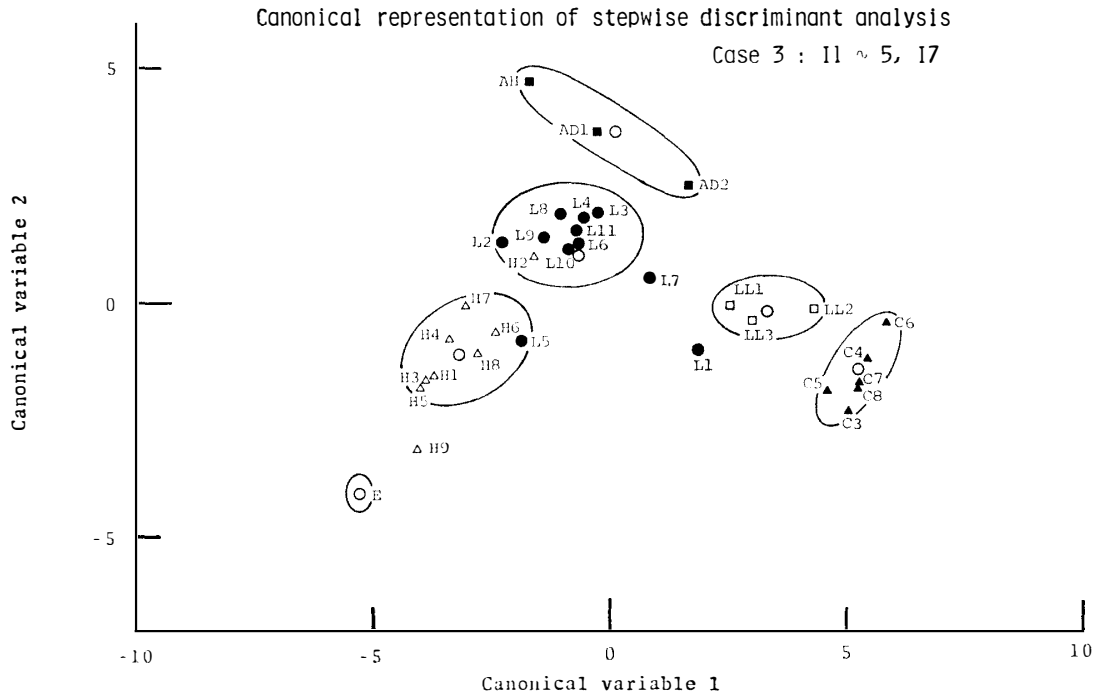

Fig. 3. Canonical representation of stepwise discriminant analysis for case 3: I1 to I5, and I7.

Hills-769 are in-between L- and LL-chondrite groups and have long amalgamation distances. L_2 Y-7304 (m) is in-between H- and L-chondrites groups by STW, but still belongs to L-chondrite groups by CLT.

LL_2 Y-74646 is in-between C- and H-chondrites groups.

4.4 Case 4: I1 and I2 (Fig. 4)

This case uses only two variables, but the results of classification by both STW and CLT are almost the same as that of case 1, except that AD_2 Y-74013 gets near LL-chondrite group.

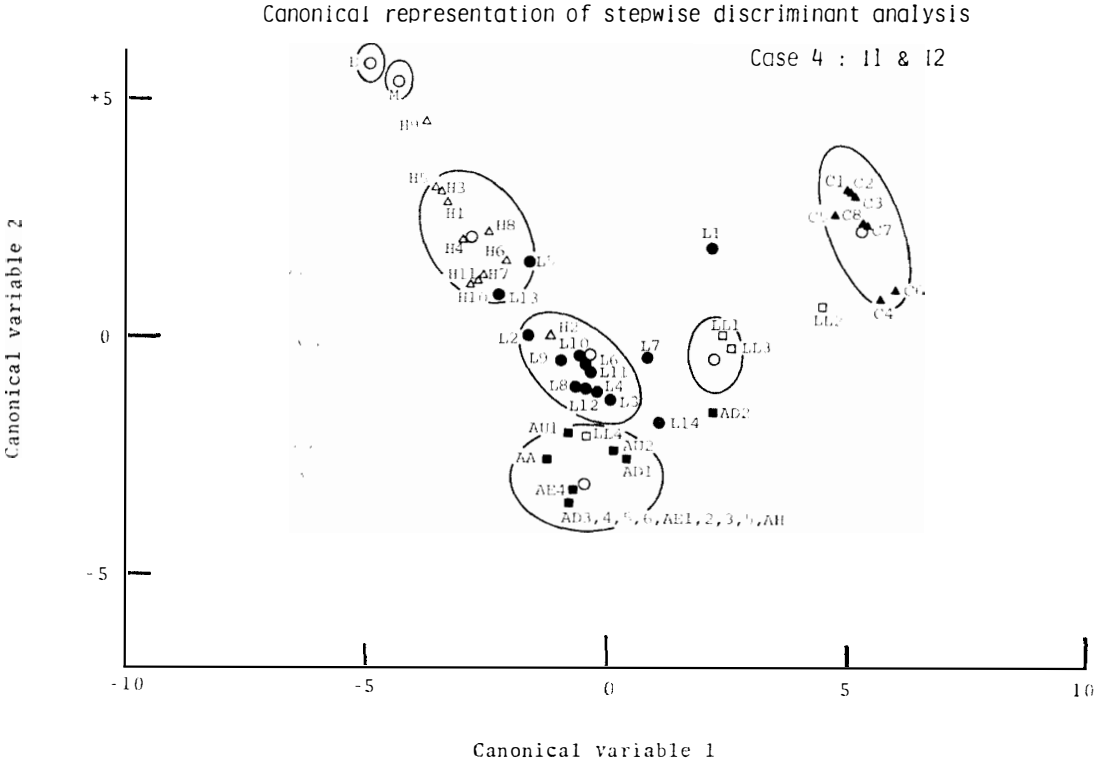

Fig. 4. Canonical representation of stepwise discriminant analysis for case 4: I1 and I2.

4.5. Case 5: I8 to I14 (Fig. 5)

There are 12 samples which have data corresponding to I8 to I14. STW shows that all samples are classified with good separation for themselves, but CLT indicates only H_2 Y-7301 (j) belongs to the different group (L-chondrite group) from its own.

4.6. Case 6: I1 to I5 and I8 to I14 (Fig. 6)

Classification in this case by both STW and CLT is almost the same as case 5.

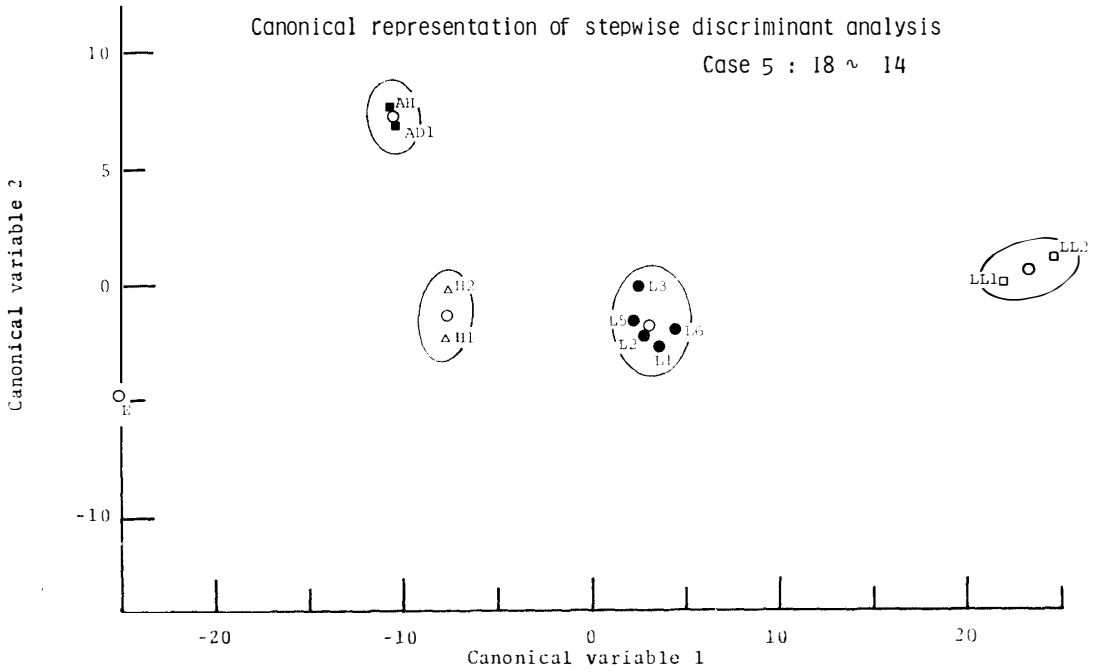

Fig. 5. Canonical representation of stepwise discriminant analysis for case 5: I8 to I14.

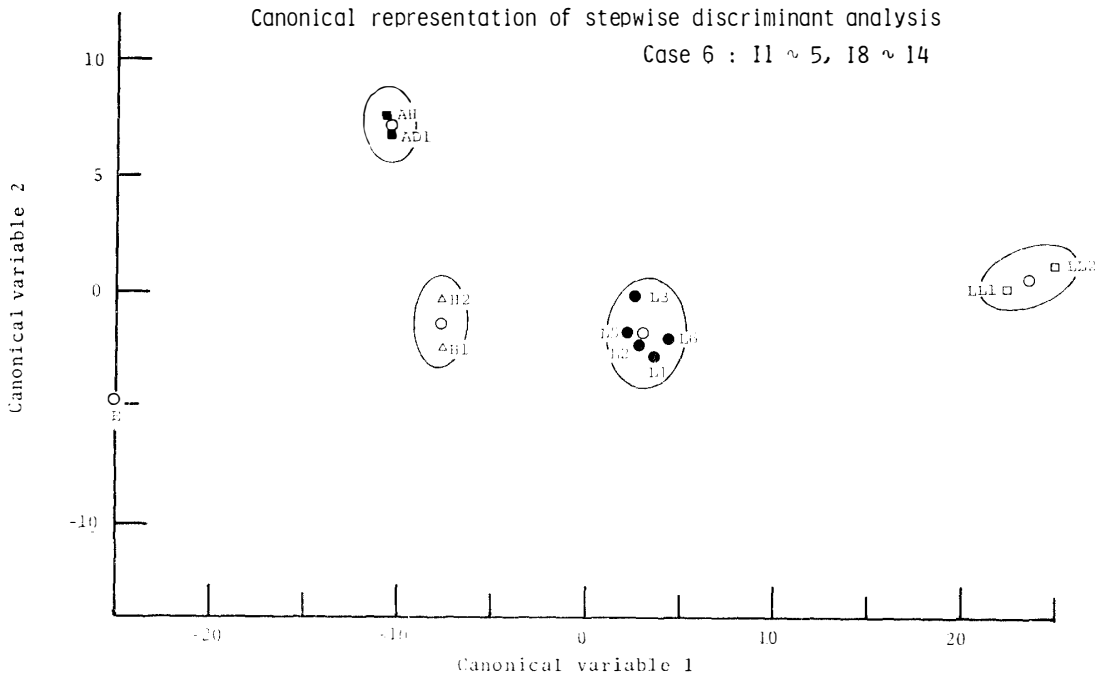

Fig. 6. Canonical representation of stepwise discriminant analysis for case 6: I1 to I5 and I8 to I14.

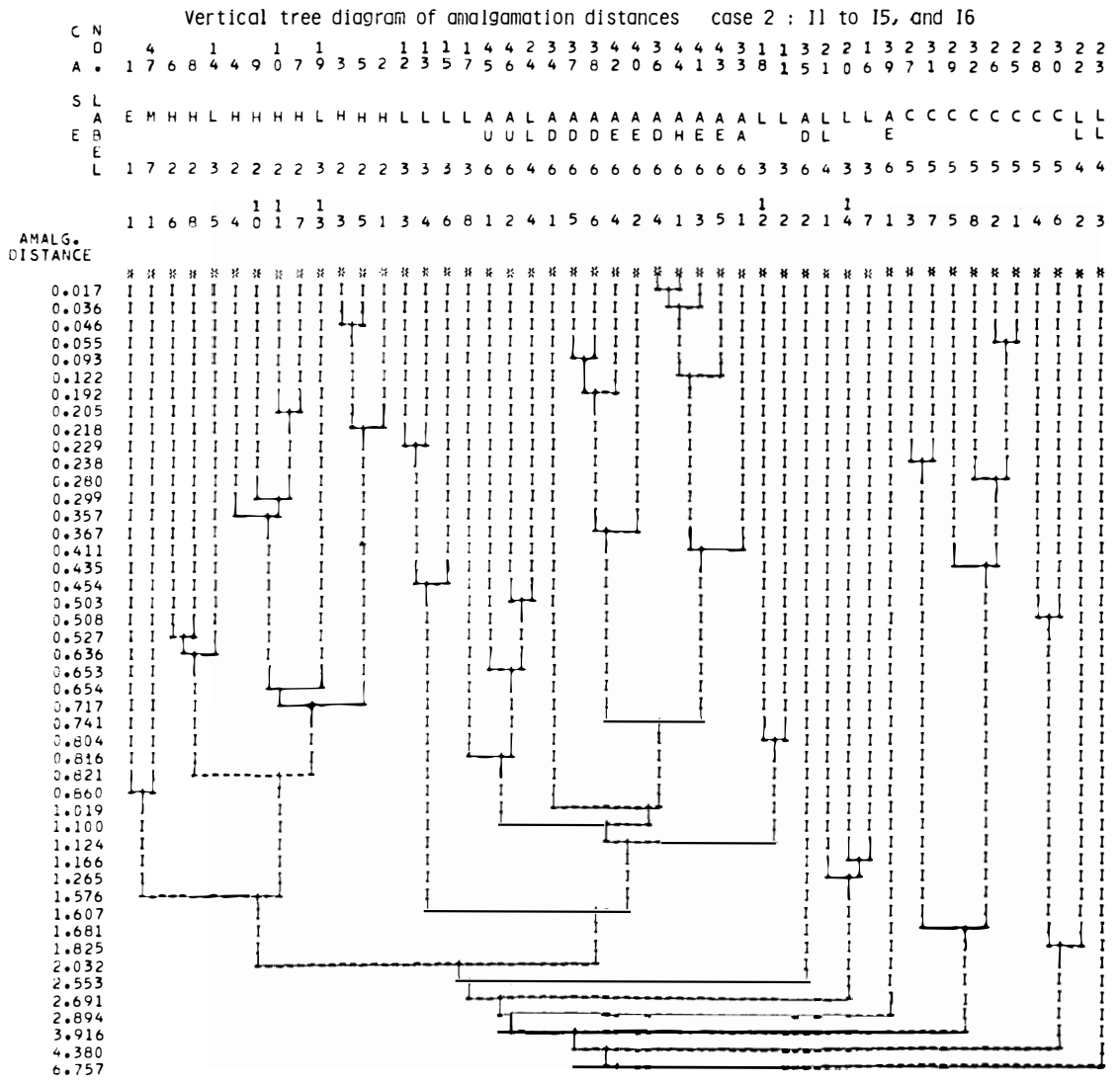

Fig. 7. Cluster amalgamation distance vertical tree diagram for case 2: I1 to I5, and I6.

5. Concluding Remarks

Two kinds of multivariate statistical analyses are applied to classification of the total 58 antarctic stony meteorites. Two methods, *i.e.* a cluster analysis and a stepwise discriminant analysis, give basically the same classification except for a few differences.

Six cases are selected so as to easily distinguish the effects of variable combinations of magnetic components and chemical and petrographical components on the classification of antarctic stony meteorites.

As the previous study by NAGATA (1979a, b) made remarks on H_2 Y-7301 (j)

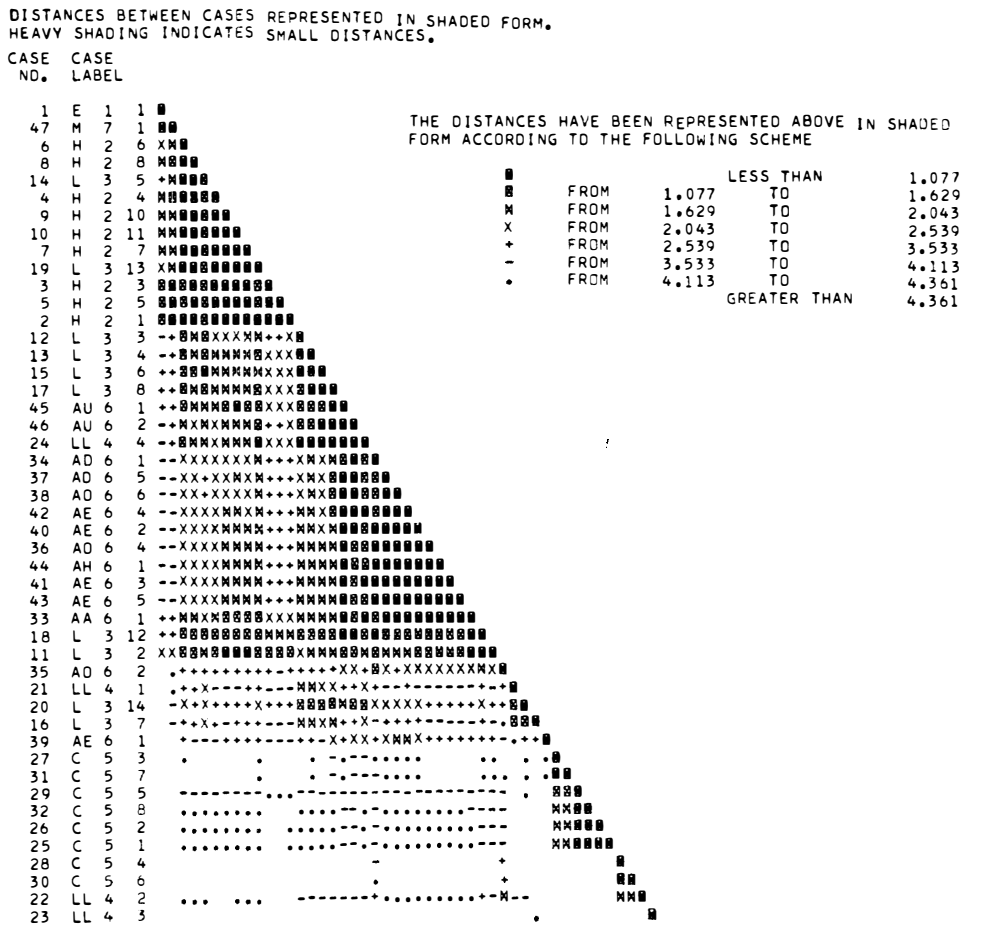

Fig. 8. Shaded form of amalgamation distance tree diagram for case 2: I1 to I5, and I6. Gray levels of shading are shown in the figure.

sample that the metalic phases of this chondrite are strongly weathered and metals are oxidized or hydro-oxidized, the present study also shows that H_2 belongs to the L-chondrite group near L_9 Bjurböle, although the stepwise discriminant analysis with the chemical and petrographical components indicates H_2 Y-7301 (j) is an H chondrite.

Magnetic characteristics including Θ_s of H_9 Mt. Brown are in-between H and E chondrites L_5 Fukutomi with magnetic components belongs to H-chondrite group near H_5 Yonozu in cases 1 and 2, whereas the cluster analysis of case 3 shows this sampe belongs to its own L-chondrite group. L_{13} Y-74354 is also belonging to H-chondrite group near H_{10} Y-74054, H_{11} Y-74115, and H_7 Seminole. It is, however, not elucidated physically that L chondrite belongs to H chondrite, even taking account of weathering or oxidizing. Among samples described in the previous section, there are several which exist in-between their own groups and other groups depending on the analysis methods and the cases. One of partly possible reasons is that some stony

meteorites are generally brecciated and the pieces from a sample are different ones for magnetic and petrographical tests.

Chemical and petrographical properties as shown in case 5 classify the samples into their own groups with good separation except for H_2 Y-7301 (j) belonging to L-chondrite group by the cluster analysis.

That the combination of case 1 (I1 to I5) and case 5 (I8 to I14) shows almost the same result as case 5 implies that the effects of chemical and petrographical properties on the classification dominate over the effects of magnetic components.

A more important fact is that even though case 4 uses only two variables, I_s and $I_s(\alpha)/I_s$, the result shows almost identical classification as derived from cases 1, 2 and 3. This means I_s and $I_s(\alpha)/I_s$ are good enough parameters to classify the antarctic stony meteorites as has been pointed out by NAGATA (1979b).

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