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AREAL AND VERTICAL VARIATION OF HEAVY MINERAL COMPOSITION OF THE SURFACE SEDIMENTS, ROSS SEA, ANTARCTICA

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Abstract: In this paper are shown the results of heavy mineral analysis of ice-rafted sand fractions of muddy sediments from several gravity cores around the Ross Sea collected during the TH91 and TH92 Antarctic research cruises by the Technology Research Center, Japan National Oil Corporation, using the R/V HAKUREI-MARU. Samples for the analysis were collected from two levels of the cores, *i.e.* late Holocene S-group samples in the upper part and last glacial to early Holocene D-group samples in the lower part of the cores. Both the S-group and D-group samples are comprised of the same kinds of heavy minerals and show the nearly completely same distribution patterns of the frequency of those minerals. These patterns suggest the existence of at least two petrographic provinces, *i.e.* western and central-eastern areas, which must reflect the difference of the provenances of East Antarctica and West Antarctica. Especially, olivine and clinopyroxene with titanaugite, dominantly distributed in the western area, were probably supplied from the late Quaternary McMurdo alkaline basaltic volcanics fringing the eastern margin of the Victoria Land. The strong similarity of the distribution pattern of heavy mineral composition between the S-group and D-group samples suggests the long-term stability of flow patterns of icebergs in the Ross Sea. Such stability must be controlled by the submarine topography in the Ross Sea, which plays the most important role in the Ross Sea, controlling not only the types of sediments, but also the flow patterns of icebergs.

key words: Antarctica, Ross Sea, glacial marine sediments, heavy mineral analysis, ice-raft

1. Introduction

Glacial marine sediments and sedimentation dominate on the shelves around Antarctica as summarized by ANDERSON and MOLNIA (1989), ANDERSON (1991) and so on. Several authors have discussed the characteristics of sediments and sedimentation in the Ross Sea based on the sedimentological, geographical, oceanographical and micropaleontological data (*e.g.* STETSON and UPSON, 1937; JACOBS *et al.*, 1970; CHRISS and FRAKES, 1972; KELLOGG *et al.*, 1979; ANDERSON *et al.*, 1984; EDWARDS *et al.*, 1987).

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The Ross Sea is bordered on the south by the largest ice shelf in the world, the Ross Ice Shelf. The shelf break of the Ross Sea occurs at relatively great depth (approximately 800 m) and the greatest depths on the shelf occur on its landward rather than seaward side (CHRISS and FRAKES,1972). According to ANDERSON *et al.* (1984), the deeper (greater than approximately 300 m) portions or basin floors of the Ross Sea continental shelf are covered by muddy sediments (compound glacial marine sediments), whereas shallower (above approximately 300 m) portions or bank areas of the shelf are floored by coarser (sand and gravel) deposits (residual glacial marine sediments), reflecting effective sediment sorting by bottom currents to depth of up to nearly 300 m. The muddy sediments in the deeper portions consist of terrigeneous fine silt and clay, siliceous biogenic material, and poorly sorted ice-rafted debris. Therefore, heavy mineral composition of sand fraction of these sediments is expected to reflect the origin and flow pattern of the icebergs in the Ross Sea shelf area.

AGYINGI *et al.* (1995) showed the results of heavy mineral analysis of undisturbed surface sediments of several gravity cores in and around the Ross Sea shelf area, collected during the TH91 and TH92 Antarctic surveys conducted by the Technology Research Center, Japan National Oil Corporation, using the R/V HAKUREI-MARU, and discussed the origin of some characteristic heavy minerals and flow patterns of icebergs which deposited those minerals. In this paper, the authors first show the results of heavy mineral analysis of samples collected at two levels of the same cores, *i.e.* surface sediments (S-group samples) and deeper sediments (D-group samples), and then compare them to each other to discuss some petrographical and sedimentological problems.

2. Characteristics of Samples

Localities and short descriptions of gravity cores are shown in Fig. 1 and Table 1 respectively. NISHIMURA *et al.* (1996) divided the gravity core sediments in the Ross Sea into two parts, *i.e.* upper part and lower part. The sediments of the upper part are characterized by high water content (usually very rapid decrease downward from about 150% to 50%) and low sand content (usually less than 20%), but, on the other hand, the sediments of the lower part are characterized by low water content (relatively constant values usually less than 40%) and high sand content (usually more than 20%). NISHIMURA *et al.* (1996) found that the lower and upper parts of the core sediments were deposited during the last glacial to early Holocene ages and the late Holocene age respectively based on previous studies (KELLOGG *et al.*, 1979; ANDERSON *et al.*, 1991) and the characteristics of sediments. S-group samples for heavy mineral analysis belong to the upper part, collected near the surface of the core sediments, and D-group samples for heavy mineral analysis belong to the lower part of the core sediments.

Samples of GC1303, GC1304 and GC1305 in the eastern and central Ross Sea and samples of GC1204, GC1205 and GC1206 in the western Ross Sea were collected from basin floors of the Ross Sea shelf and they all consist of muddy sediments as pointed out by ANDERSON *et al.* (1984). Samples of GC1307 and GC1308, collected

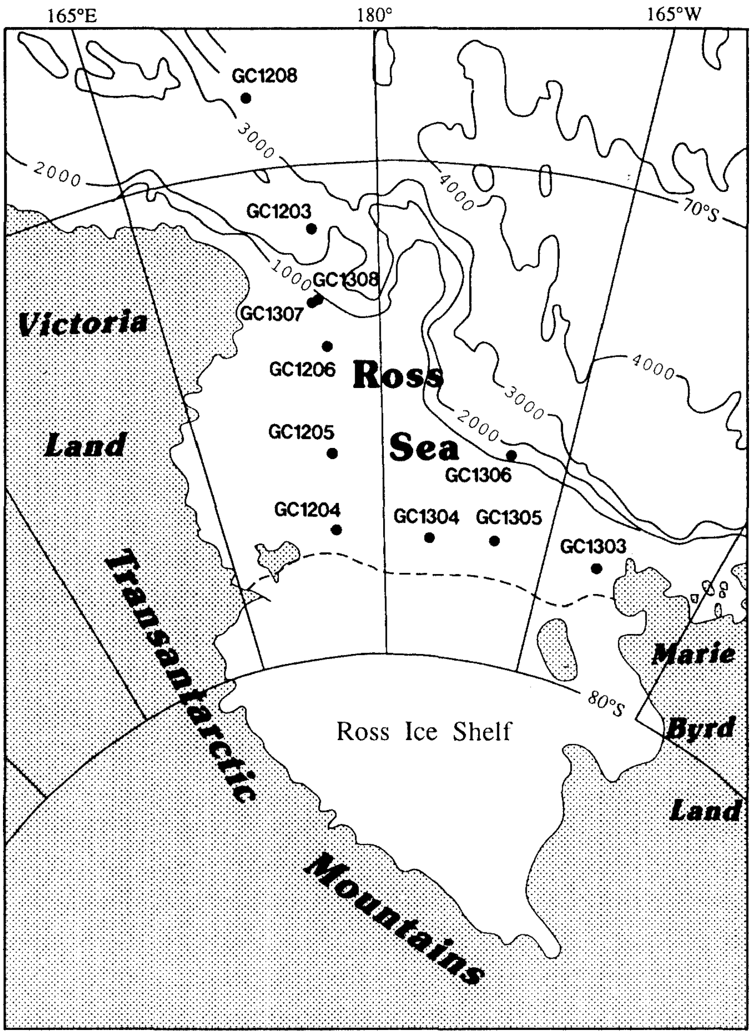


Fig. 1. Index map and sampling points.

Table 1. Short description of cores.

Core No.	Location (Long.)	Location (Lat.)	Water depth (m)	Topography	Lithology
GC1203	175°30′18″E	71°20′10″S	2224	Upper continental rise	Silty clay with diatom
GC1204	175°28′12″E	77°25′15″S	662	Basin floor in the Ross Sea	Diatom ooze
GC1205	175°29′35″E	75°55′55″S	543	Basin floor in the Rose Sea	Silty diatom ooze
GC1206	175°30′48″E	73°44′33″S	580	Basin floor in the Ross Sea	Clayey diatom ooze
GC1208	172°27′36″E	68°29′32″S	3405	Lower continental rise	Silty clay with diatom
GC1303	161°11′03″W	77°26′46″S	672	Basin floor in the Ross Sea	Silty clay with diatom
GC1304	175°54′30″W	77°26′26″S	571	Basin floor in the Ross Sea	Siliceous silty clay
GC1305	169°46′28″W	77°26′23″S	570	Basin floor in the Ross Sea	Siliceous clay
GC1306	169°59′36″W	75°46′11″S	1450	Continental slope	Silt siliceous clay
GC1307	175°27′54″E	72°31′04″S	527	Bank slope at the shelf break of the Ross Sea	Shell sand
GC1308	175°37′54″E	72°27′38″S	643	Bank slope at the shelf break of the Ross Sea	Calcareous sand

from the bank slope at the shelf break of the Ross Sea, are, on the contrary, composed of sand, reflecting the existence of bottom currents; seaward-flowing Antarctic Bottom Water (CHRISS and FRAKES, 1972) or geostrophic current impinging onto the shelf (ANDERSON *et al.,* 1984). Other samples were collected from deeper portions off the Ross Sea shelf, such as the continental slope (GC1306), upper continental rise (GC1203) and lower continental rise (GC1208). These sediments are composed of muddy sediments like those collected from basin floors of the Ross Sea shelf area.

3. Results of Heavy Mineral Analysis

3.1. Results of S-group samples

The method of laboratory experiment for heavy mineral analysis is the same as that explained by AGYINGI *et al.* (1995). The results of the analysis for S-group samples are summarized in Table 2. Major transparent heavy minerals observed are hornblende (brown, green, bluish green), clinopyroxene (brown, pale green-colorless), zircon, garnet, rutile, tremolite-actinolite, epidote, tourmalinie, andalusite, kyanite, glaucophane, olivine. The areal distributions of the frequency of individual transparent heavy minerals of S-group samples are shown in Figs. 2A and 2B. As indicated by AGYINGI *et al.* (1995), two petrographic areas, *i.e.* western part and central-eastern part, are recognized based on the characteristics of the distribution pattern of individual heavy minerals. Clinopyroxene, olivine, garnet, tremolite-actinolite, andalusite and kyanite are more abundant in the western part (westward from approximately long. 180°) than in the central-eastern part (eastward from approximately long. 180°) of the Ross Sea. Among them clinopyroxene and olivine are dominant in the western part of the sea. In the central-eastern part of the Ross Sea shelf area, on the other hand, hornblende, zircon, epidote and tourmaline are more abundant in the central-eastern part than in the western part of the sea. Especially, hornblende predominates in the central-eastern part of the sea.

3.2. Result of D-group samples

The results of the analysis for D-group samples are summarized in Table 2. The same kinds of transparent heavy minerals as those of S-group samples are observed. The areal distributions of the frequency of individual transparent heavy minerals of D-group samples are shown in Figs. 3A and 3B. It is a remarkable fact that the nearly completely same frequency distribution patterns of transparent heavy minerals are observed between S-group samples and D-group samples.

4. Discussion

4.1. Inferred source rocks of heavy minerals

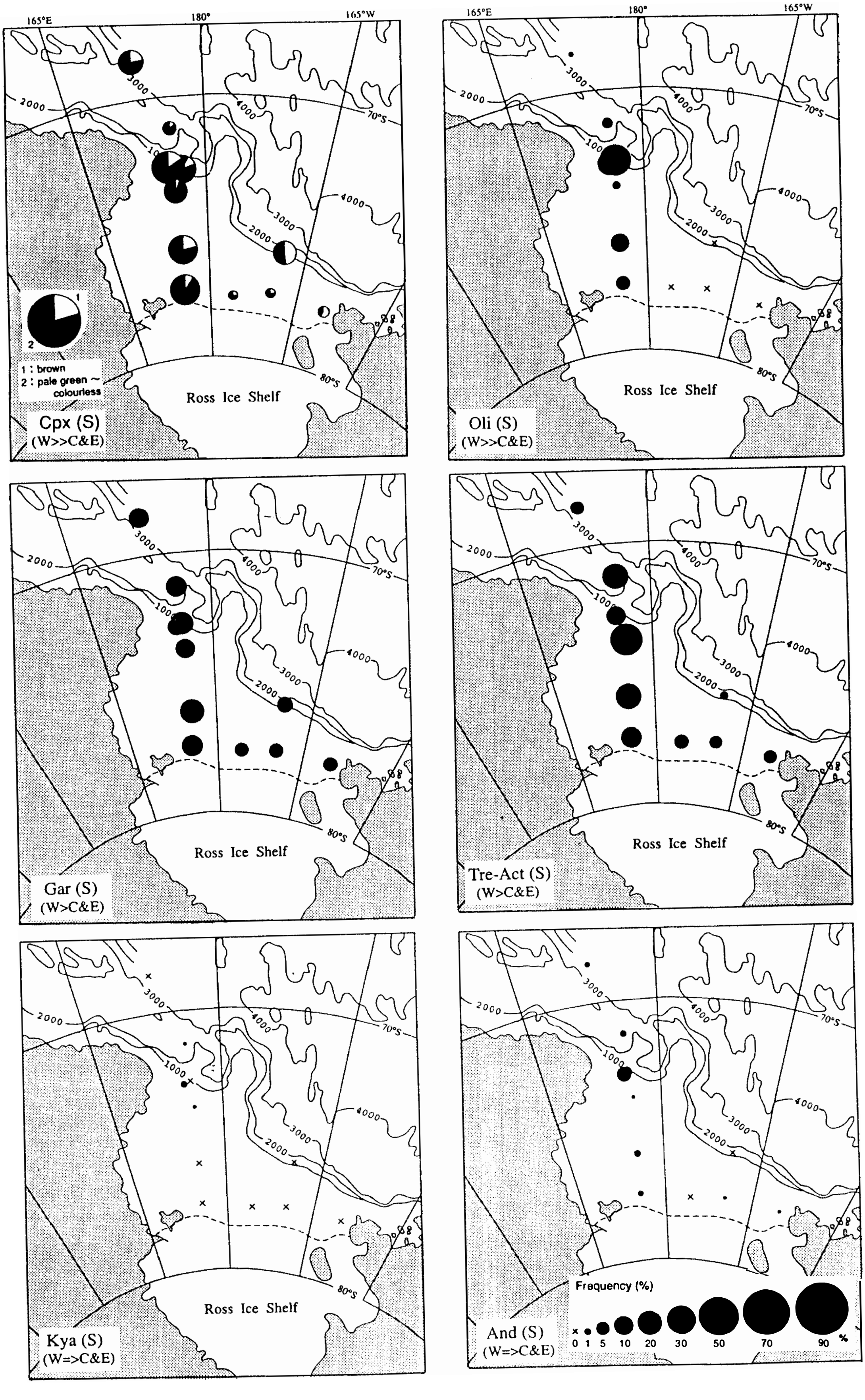
ANDERSON *et al.* (1984) pointed out the existence of the distinct petrologic province of the western Ross Sea and the broadly similar but still distinct petrologic province of the central and eastern Ross Sea based on the petrography of sand fractions of surface sediments collected from many piston and gravity cores in the

Table 2. Results of heavy mineral analysis of S-group samples (upper) and D-group samples (lower). Sample GC1306D is omitted due to the scarcity of the heavy mineral fraction within the sample.

Sample no.	Sample interval from surface (cm)	Hor total	(Hor) (brown)	(Hor) (green)	(Hor) (blui-green)	CPX total	(CPX) (brown)	(CPX) (pale green/col-less)	Zir	Gar	Rut	Tre-Act	Epi	Tou	And	Kya	Gla	Oliv	Un-cert.	Total numb. of CHMG	Hy(%)	Mg(%)	Opq(%)
GC1203S	0--15	83.1	(0.6)	(73.8)	(8.7)	4.1	(0.4)	(3.6)	2.8	4.7	0.1	2.0	2.0	0.3	0.6	0.0	0.0	0.1	0.1	765	3.2	2.2	19.2
GC1204S	0--12	87.2	(0.5)	(71.7)	(14.9)	2.7	(0.9)	(1.9)	1.2	1.7	0.3	6.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	569	2.3	2.6	20.4
GC1205S	0--12	86.7	(1.7)	(60.8)	(24.2)	2.2	(0.4)	(1.8)	1.4	3.4	0.1	4.3	0.7	0.8	0.3	0.0	0.0	0.0	0.0	611	7.5	1.6	22.4
GC1206S	0--15	85.7	(0.7)	(74.5)	(10.5)	0.5	(0.1)	(0.3)	7.0	4.3	0.0	0.7	1.5	0.3	0.0	0.0	0.0	0.0	0.0	802	4.9	0.3	31.7
GC1208S	0--15	17.8	(4.0)	(13.8)	(0.0)	38.8	(6.2)	(32.6)	1.8	8.2	0.0	9.9	0.1	0.1	6.0	1.0	0.0	16.2	0.0	735	2.2	10.3	7.0
GC1303S	7--17	72.1	(3.0)	(68.5)	(0.6)	4.4	(2.6)	(1.8)	5.7	5.7	0.2	5.0	1.7	1.5	0.3	0.0	0.3	0.0	3.2	1363	1.6	3.9	51.4
GC1304S	0--15	77.4	(0.7)	(74.4)	(2.2)	2.4	(0.6)	(1.8)	2.4	5.5	0.0	5.1	0.7	1.9	0.0	0.0	0.0	0.0	4.5	1207	2.3	3	21.9
GC1305S	0--15	78.2	(0.8)	(75.3)	(2.2)	2.7	(0.9)	(1.7)	6.6	5.9	0.1	3.8	1.3	0.7	0.3	0.0	0.0	0.0	0.4	1133	1.1	3.5	34.3
GC1306S	5--15	64.4	(3.8)	(58.7)	(2.0)	19.0	(9.2)	(9.8)	5.4	7.0	0.5	2.1	0.5	1.0	0.0	0.0	0.0	0.0	0.0	938	2.1	6.3	35.0
GC1307S	5--15	17.8	(4.0)	(13.8)	(0.0)	38.8	(6.2)	(32.6)	1.8	8.2	0.0	9.9	0.1	0.1	6.0	1.0	0.0	16.2	0.0	731	7.4	1.5	7.0
GC1308S	0--10	4.2	(0.8)	(3.4)	(0.0)	29.0	(3.2)	(25.8)	0.4	17.3	0.0	1.2	0.0	0.0	3.4	0.0	0.0	34.7	9.9	519	15.5	0.6	2.9

Sample no.	Sample interval from surface (cm)	Hor total	(Hor) (brown)	(Hor) (green)	(Hor) (blui-green)	CPX total	(CPX) (brown)	(CPX) (pale green/col-less)	Zir	Gar	Rut	Tre-Act	Epi	Tou	And	Kya	Gla	Oliv	Un-cert.	Total numb. of CHMG	Hy(%)	Mg(%)	Opq(%)
GC1203D	50--60	82.4	(0.0)	(65.9)	(16.4)	2.3	(0.3)	(2.0)	5.2	3.4	0.1	3.8	0.9	0.8	0.3	0.0	0.0	0.8	0.0	997	2.3	3.3	25.5
GC1204D	143--153	56.0	(3.1)	(48.9)	(4.0)	9.9	(0.6)	(9.3)	2.5	15.2	0.4	10.8	1.0	0.4	0.4	0.0	0.0	0.9	2.6	1178	3.4	0.1	32.3
GC1205D	78--88	14.1	(2.8)	(11.3)	(0.0)	40.0	(8.1)	(31.9)	0.4	17.1	0.0	19.3	0.9	0.6	3.0	0.2	0.0	3.9	0.6	594	7.8	1	10.3
GC1206D	78--88	64.3	(2.7)	(56.3)	(5.3)	13.0	(5.0)	(8.0)	1.8	6.1	0.2	11.0	1.2	0.2	0.8	0.0	0.0	1.5	0.0	720	5.2	1.3	16.4
GC1208D	70--80	31.4	(3.6)	(27.8)	(0.0)	23.7	(3.4)	(20.3)	0.2	10.9	0.0	24.9	0.2	0.2	1.4	0.0	0.0	7.2	0.0	569	1.7	4.6	11.6
GC1303D	97--107	42.1	(5.2)	(36.9)	(0.0)	4.8	(1.7)	(3.1)	39.2	4.2	0.4	2.7	1.0	4.8	0.4	0.0	0.0	0.0	0.4	4688	1.1	0.8	89.0
GC1304D	50--60	83.1	(0.6)	(73.8)	(8.7)	4.1	(0.4)	(3.6)	2.8	4.7	0.1	2.0	2.0	0.3	0.6	0.0	0.0	0.1	0.1	852	2.8	4.3	19.2
GC1305D	130--140	85.7	(0.7)	(74.5)	(10.5)	0.5	(0.1)	(0.3)	7.0	4.3	0.0	0.7	1.5	0.3	0.0	0.0	0.0	0.0	0.0	1258	2.7	1.1	31.7
GC1307D	37--47	17.0	(3.8)	(13.1)	(0.0)	39.4	(2.1)	(37.3)	1.1	9.9	0.6	3.2	0.2	0.2	4.0	0.2	0.0	24.2	0.0	582	7.6	1	9.8
GC1308D	48--58	19.5	(1.5)	(17.7)	(0.4)	32.7	(2.6)	(30.1)	3.0	10.0	0.4	10.4	0.2	0.4	2.0	0.6	0.0	20.8	0.0	564	5.4	0.5	4.6

A


165°E
180°
165°W
70°S
80°S
2000
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4000
1000
Ross Ice Shelf
1 : brown
2 : pale green ~ colourless
Cpx (S)
(W>>C&E)
Oli (S)
(W>>C&E)
Gar (S)
(W>C&E)
Tre-Act (S)
(W>C&E)
Kya (S)
(W=>C&E)
And (S)
(W=>C&E)
Frequency (%)
0 1 5 10 20 30 50 70 90 %

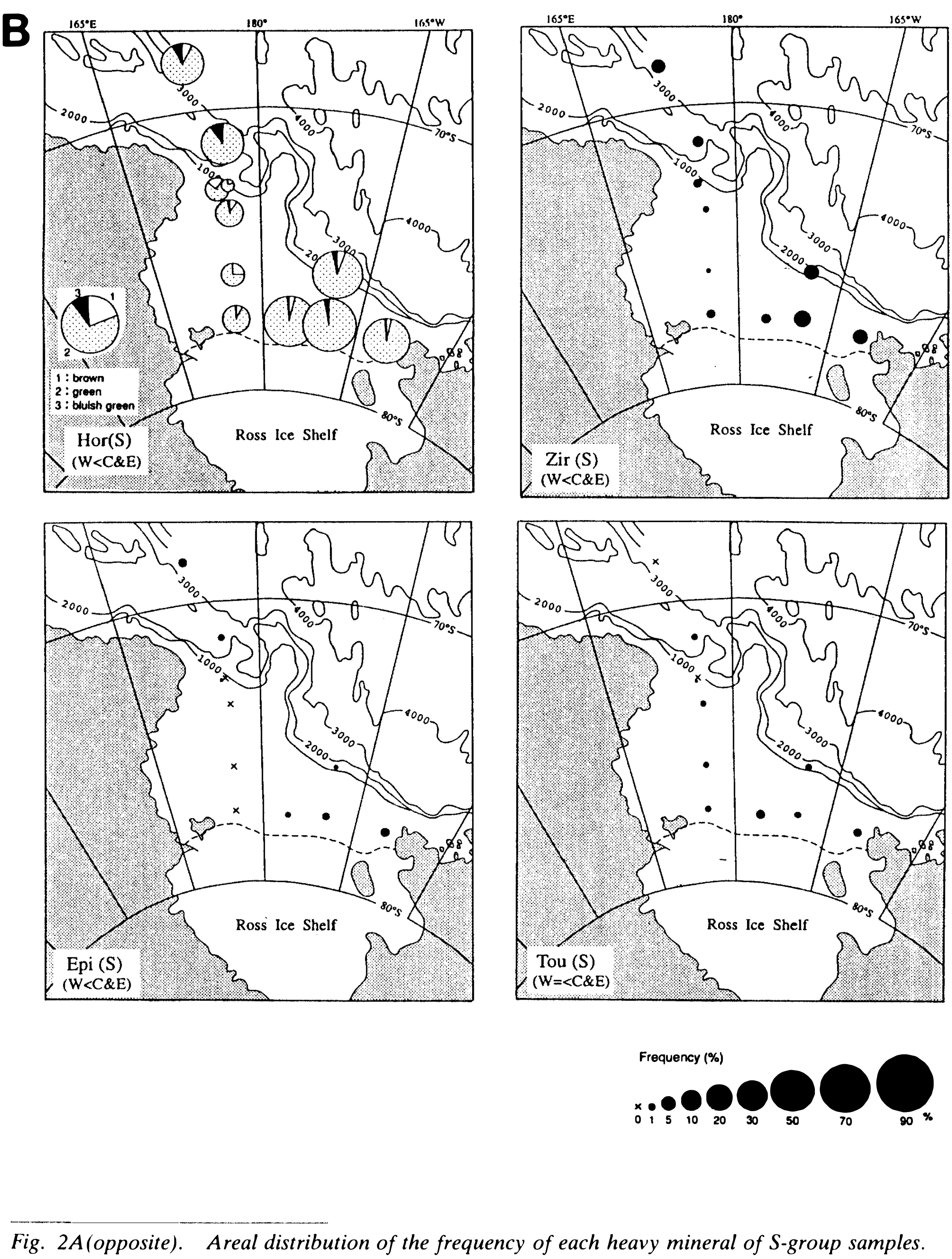
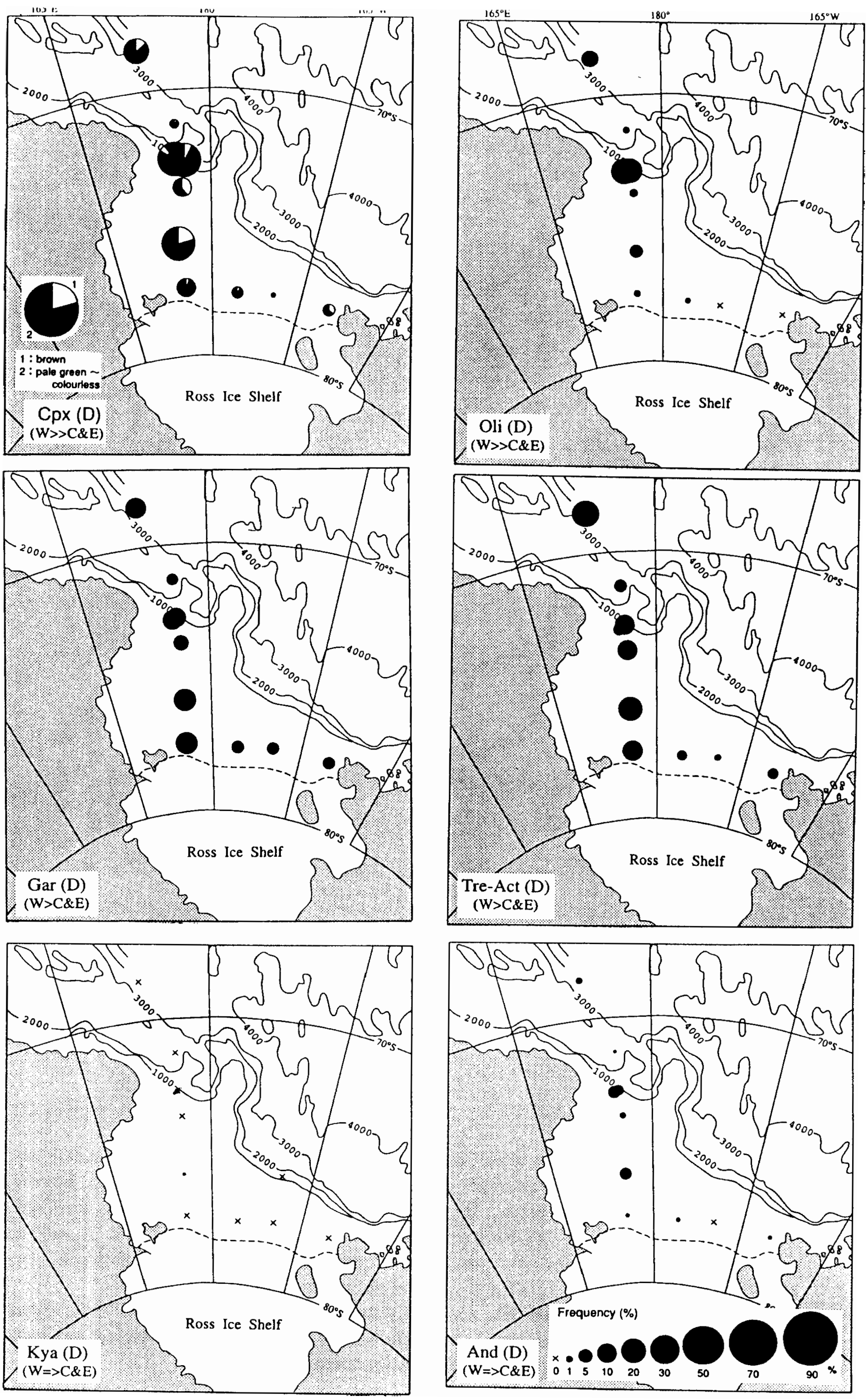


Fig. 2A(opposite). Areal distribution of the frequency of each heavy mineral of S-group samples. Cpx: clinopyroxene, Oli: olivin, Gar: garnet, Tre-Act: tremolite-actinolite, Kya: kyanite, And: andalusite, S: S-group samples, W: western area , C&E: central-eastern area, W>C&E: More abundant in the western area than in the central-eastern area, W=>C&E: Equally to more abundant in the western area than in the central-eastern area, W>>C&E: Much more abundant in the western area than in the central-eastern area.

Fig. 2B(continued). Hor: hornblende, Zir: zircon, Epi: epidote, Tou: tourmaline, W<C&E: More abundant in the central-eastern area than in the western area, W=<C&E: Equally to more abundant in the central-eastern area than in the western area.

A


165°E
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(W>C&E)
Tre-Act (D)
(W>C&E)
Kya (D)
(W=>C&E)
And (D)
(W=>C&E)
Frequency (%)
0 1 5 10 20 30 50 70 90 %

B

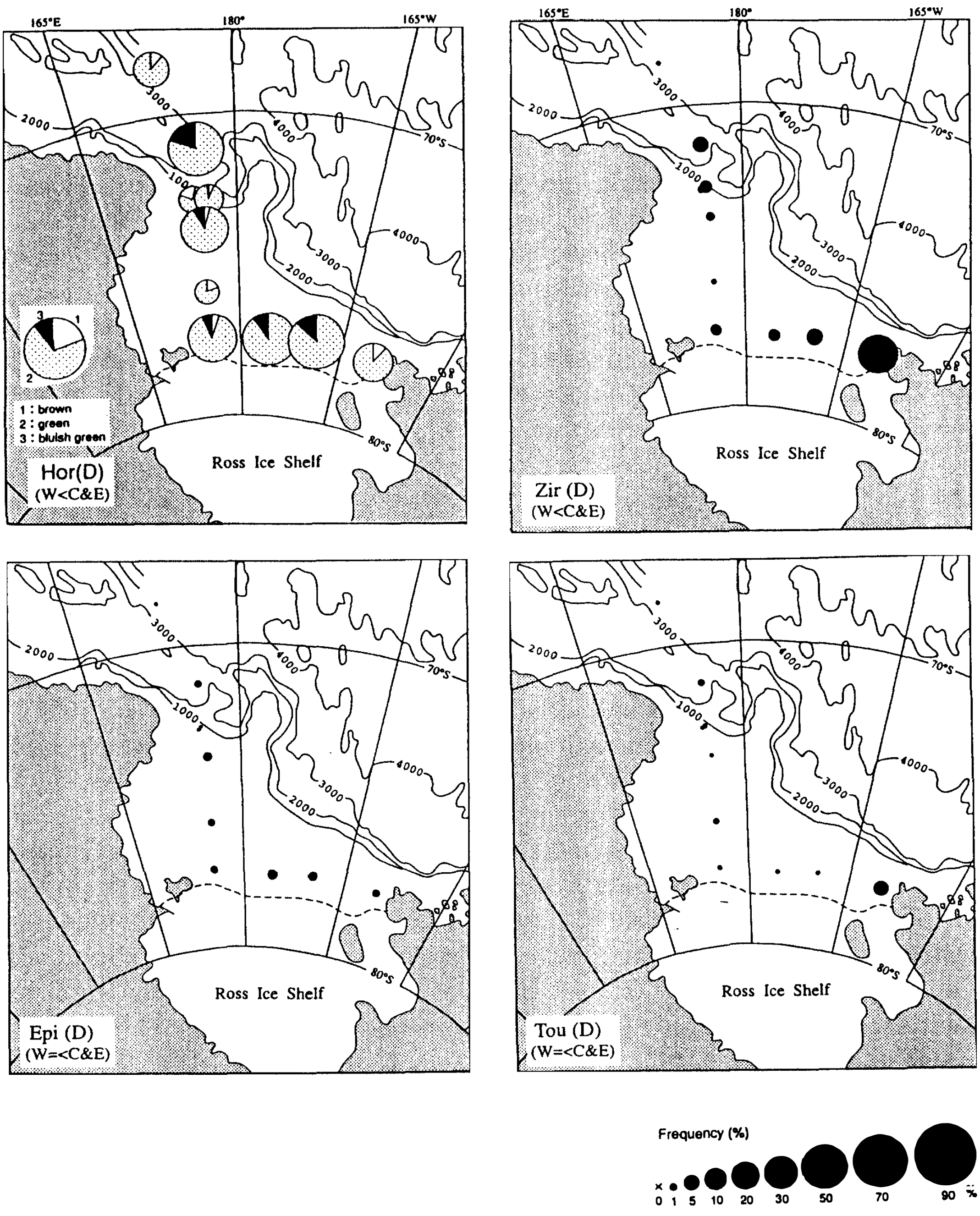

Fig. 3A(opposite). Areal distribution of the frequency of each heavy mineral of D-group samples. D: D-group samples. For other abbreviations, see Fig. 2A.

Fig. 3B(continued). For abbreviations, see Fig. 2B.

Ross Sea, though no data were shown there, and attributed the existence of such petrologic provinces to the flow patterns of icebergs in the Ross Sea.

According to ANDERSON *et al.* (1984), east of approximately 180°, glacial ice is derived from West Antarctica, most of which flows into the Ross Ice Shelf. West of approximately 180°, the Ross Ice Shelf consists of ice that has flowed from East Antarctica. Along the mountaineous north Victoria Land coast, outlet glaciers flow directly into the sea. Therefore, the existence of western and central-eastern petrographic provinces in the Ross Sea must reflect the difference of provenance between East Antarctica and West Antarctica.

Figure 4 is a simplified geologic map of the Ross Sea. As pointed out above, same kind of transparent heavy minerals and nearly completely the same frequency distribution patterns of those minerals between S-group and D-group samples are observed. Clinopyroxene and olivine, which predominantly or exclusively occur in the western area of the Ross Sea, must be derived from the late Quaternary McMurdo Volcanics which are mostly comprised of alkaline rocks such as olivine basalt, basaltic andesite, trachyandesite, phonolite and kenyte (GAIR *et al.,* 1969; WARREN, 1969). These volcanic rocks, occurring in the belt along the east coast of northern and southern Victoria Lands, commonly include olivine and clinopyroxene as phenocrysts. The fact that the clinopyroxene observed includes brown clinopyroxene, or a kind of titanaugite, also supports this inference, because the McMurdo volcanic rocks commonly include titanaugite as phenocryst (KURASAWA, 1977). Such minerals as garnet, tremolite-actinolite, kyanite and andalusite, which are more abundant usually in the western area than in the central-eastern areas, may have come mostly from the older Precambrian metamorphic rocks such as the Nimrod Group and the late Precambrian metamorphic rocks such as the Wilson Group in the Transantarctic Mountains (GAIR *et al.,* 1969; WARREN, 1969; GRINDLEY and LAIRD, 1969; DAVEY, 1987). It must be much more difficult to estimate the origin of hornblendes in the western area of the Ross Sea, because some McMurdo volcanic rocks, some early Paleozoic Granite Harbour Intrusives, some middle-late Paleozoic Admiralty Intrusives and some Precambrian metamorphic rocks in the Transantarctic Mountains all include hornblende (GAIR *et al.,* 1969; WARREN, 1969; GRINDLEY and LAIRD, 1969; DAVEY, 1987). The contribution of the late Precambrian to the early Paleozoic sedimentary rocks such as the Beardmore and Robertson Bay Groups and the Bowers Supergroups, and the Devonian to Jurassic Beacon Group and the Ferrar Dolerite as a source rock to these heavy minerals is not certain.

The inference of origin of heavy minerals which occur in the central-eastern part of the Ross Sea is more difficult, because most of the provenance in West Antarctica is covered by a thick ice sheet except for the coastal area of Marie Byrd Land. Hornblende, which predominates there, may have derived from such intrusives as the middle-late Paleozoic Ford Granodiorite and/or the late Mesozoic (Cretaceous) Byrd Coast Granite in the western Marie Byrd Land (WADE, 1969; WEAVER *et al.,* 1991). Zircon, epidote and tourmaline, which are more abundant usually in the central-eastern area than in the western area, may also supplied from those intrusive rocks in the western Marie Byrd Land (WADE, 1969; WEAVER *et al.,* 1991). Garnet, tremolite-actinolite and andalusite in the central and eastern areas may have been

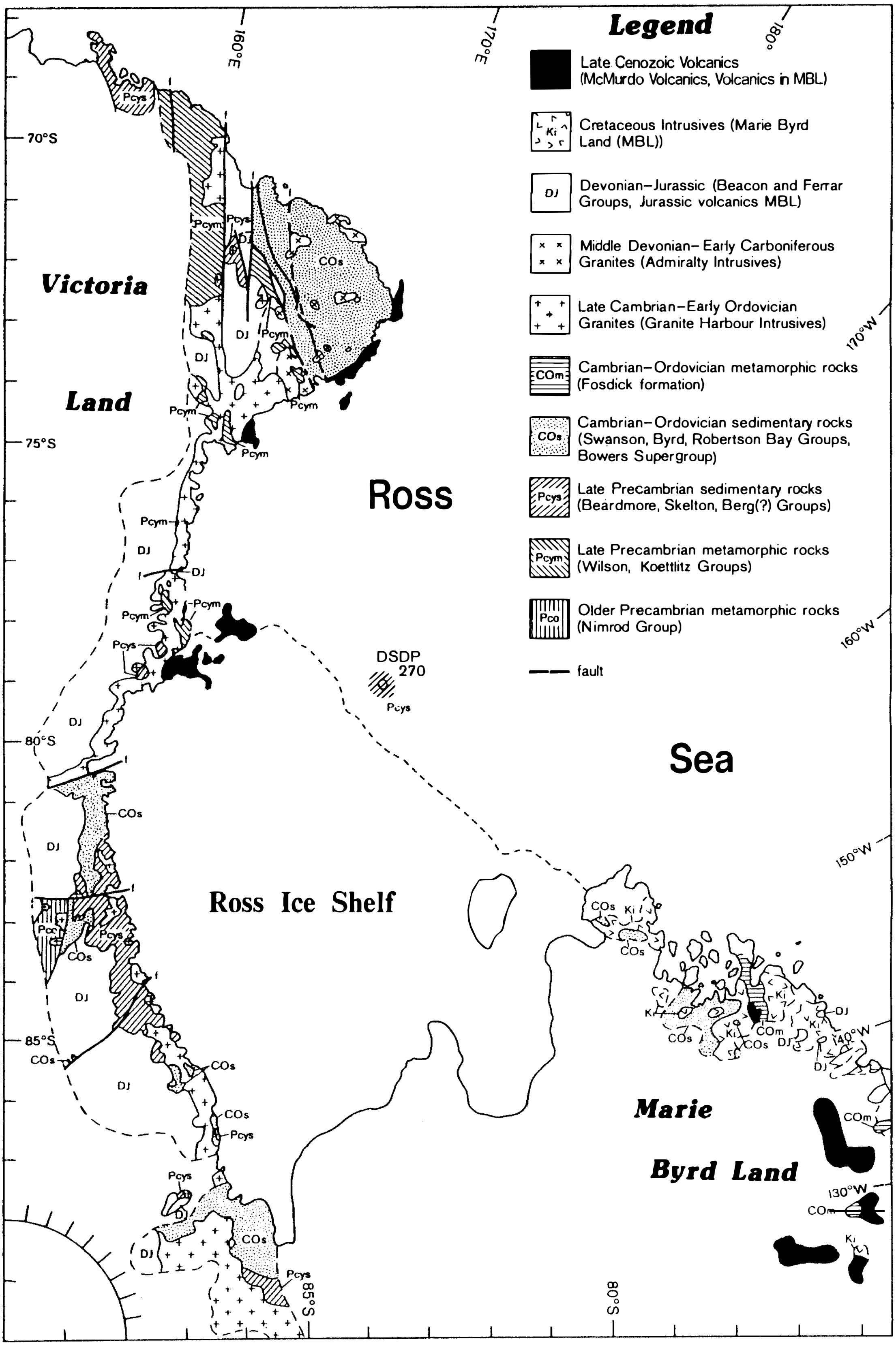

Fig. 4. Simplified geological map around the Ross Sea. Modified from DAVEY *(1987).*

supplied from the early Paleozoic metamorphic rocks such as the Fosdick Formation or Fosdick Complex in western Marie Byrd Land . The contribution of the Swanson Group, the early Paleozoic sedimentary rock in western Marie Byrd Land, as source rocks to those heavy minerals is not certain.

4.2. Inferred flow pattern of icebergs

The existence of western and central-eastern petrographic zones in the Ross Sea based on the areal distribution pattern of the heavy minerals of S-group samples strongly suggests the northward flow of icebergs which transported and deposited these heavy minerals. As the boundaries of several petrographic provinces suggested by ANDERSON *et al.* (1984) are nearly parallel with the trends of submarine topography such as basins and banks, such northward movement of these icebergs must have been contolled by the submarine topography. The strong similarity of the distribution pattern of heavy mineral composition between S-group and D-group samples shown in this paper suggests the long-term stability of flow patterns of icebergs in the Ross Sea. Such long-term stability must be controlled by the characteristic submarine topography in the Ross Sea, which is inferred to have been formed by erosion at the bottom of ice sheet or glaciers during the glacial ages. Therefore, the submarine topography plays the most important role in the Ross Sea, which controls not only the types of sediments such as compound glacial marine sediments (siliceous mud with sand and gravel) in the basins and residual marine sediments (sand and gravel) on the banks, but also flow patterns of icebergs which transport and deposit coarse materials.

5. Concluding Remarks

Ice-rafted sand fractions both of the late Holocene S-group samples and the last glacial to early Holocene D-group samples collected from several gravity cores in the Ross Sea shelf area show the same kinds of heavy mineral composition and nearly completely same areal distribution patterns in frequency of those minerals each other. The patterns suggest the existence of at least two petrographic provinces, *i.e.* western and central-eastern areas. Such existence of western and central-eastern petrographic provinces in the Ross Sea must reflect the difference of provenances of East Antarctica and West Antarctica. Especially, olivine and clinopyroxene with titanaugite, which are exclusively or dominantly distributed in the western area, were probably supplied from the late Quaternary McMurdo alkaline basaltic volcanics fringing the eastern margin of the Victoria Land. The strong similarity of the distribution pattern of heavy mineral composition between S-group and D-group samples suggests the long-term stability of flow patterns of icebergs in the Ross Sea. Such long-term stability must be controlled by the characteristic submarine topography in the Ross Sea. The submarine topography plays the most important role in the Ross Sea, which controls not only the types of sediments, but also the flow patterns of icebergs.

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