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Analysis on the crystals of sea ice cores derived from Weddell Sea, Antarctica

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Abstract In order to understand the sea ice types and its region of origin frozen in Weddell Sea, 27 ice cores were taken from Weddell Sea, Antarctica during September and October, 2006. Their crystals were analyzed, and their ice forming processes were evaluated based on the crystals. Photos of the thin sections from two whole ice cores, and from polygonal granular superimposed ice were taken as well as corresponding stratigraphy descriptions. Vertical profiles of salinity, density and grain size were also obtained. Based on ice core structural texture, the findings include that: 1) although large and smooth ice floes were selected as the investigation sites, the ice sheet at the sampling position may be formed by rafted ice, consolidated ice ridges and second-year ice which were affected by dynamic and thermodynamic processes together subsequently. Ice formed in pure thermal growth comprises minority. The polygonal granular superimposed ice from refrozen wetted dense snow is one type of the ice in Antarctica. 2) Of the all 27 ice cores, the granular, mixed granular-columnar and columnar crystals in sea ice occupy 28.7%, 14.4% and 55.2%, respectively. 3) The pure thermal growth ice is predominant in marginal sea ice zone; the rafted ice and consolidated ice ridges, even second-year ice and polygonal granular superimposed ice from dynamic and thermal effects were found in front of Larsen A Ice Shelf; the thermal growth ice froze in the polynyas of Larsen A, and was transferred outwards.

Key words Antarctic, sea ice, crystal, salinity, density.

1 Introduction

New ice, first-year ice, multi-year ice, ice ridge and superimposed ice are common in polar seas. Sea ice crystals change with ice forming processes. From the view of ice physics, the combination of crystal, temperature, salinity and density of sea ice dominates its other properties. During the physical and ecological investigations of sea ice, a quantity of ice cores were collected and the vertical profiles of crystal types, temperature, salinity and density were determined[1,2]. Chinese scientists also studied the crystals of Antarctic[3,4] and Arctic[5] sea ice, usually there were a few ice cores in a cruise which did not like others[6]. This paper presents the analysis on the crystal types from 27 ice cores and 2 superimposed ice samples obtained during the cruise of Winter Weddell Outflow Study in Weddell Sea, Antarctic (WWOS06) in 2006[7].

2 Field investigation

From 24th August to 29th October 2006, German Alfred-Wegener Polar and Ocean Institute organized the scientific expedition to investigate sea ice physics and oceanography in the Weddell Sea (WWOS06)[7]. During 41-days expedition, a total of 28 ice stations (22 ship-based and 6 helicopter-based) were performed (Fig. 1). In each ice station, an integral ice core from ice surface to bottom was drilled for ice texture analyses. Sea ice temperature was measured immediately after coring by drilling sideways into the core and measuring internal temperature using a hand held Pt-1000 thermometer, with a vertical interval of 5 to 10 cm. Then the core was brought into a freezing lab (−15°C) on board and spilt into two sections by a band saw along the longitudinal direction, and a thick section (about 0.5 cm in thickness) was cut from one part of the two sections for texture analysis, ice crystal observations and photography between cross polarizers. The structural ice types provide following evidences: the ice growth rate variations in ice thermal growth process, ice thickness increase in dynamic processes and snow contribution to sea ice thickness. Therefore, pieces of 7—11 cm in length were cut from the thick section fragments. These pieces covered

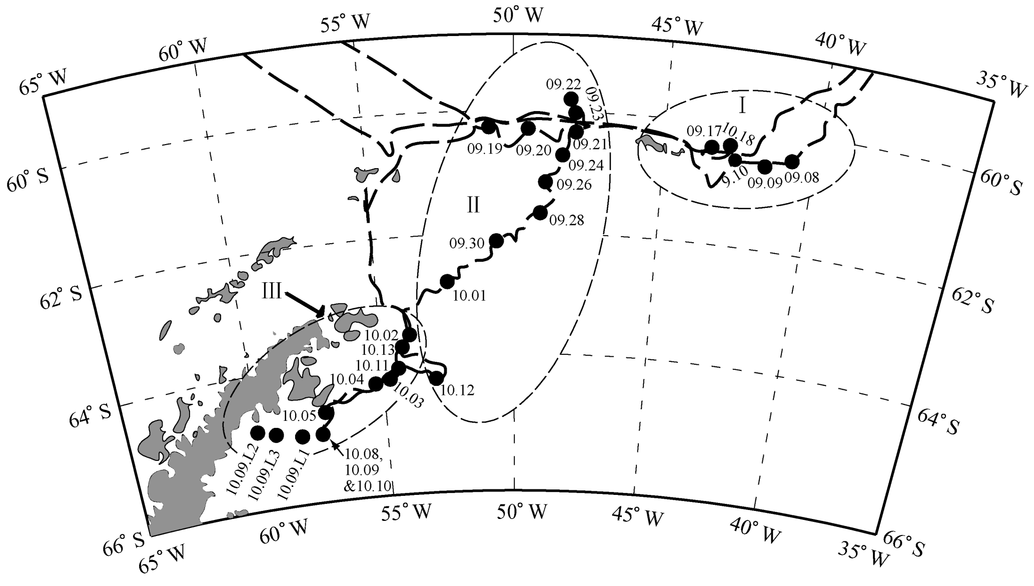


Fig. 1 Map of sampling stations, navigational tracks and geographical sub-regions (station number is sampling date, month and date).

whole ice core or the parts with special ice crystals. Then each piece of the cut thick section was frozen on a glass of 12 cm×12 cm by cold fresh water. Later the piece of thick section with the glass was frozen on microtome and was cut into thin sections with 0.05—0.1 cm in thickness. The crystal types of the thin sections were observed and taken photographs between cross polarizers and the air bubbles in the thin sections were observed and taken photographs under diffuse light. Based on the observation, the stratigraphy of ice types can be determined. Then the other section of the two sections was cut into small blocks of 2 to 10 cm in thickness and melted for salinity, density measurements according to stratigraphic units. Totally, 27 ice cores from 28 ice stations were collected and performed the analyses of crystal, temperature, salinity and density. In addition, 46 thin sections from 15 ice cores were cut and used for observation of crystals and photographs.

3 Ice crystals in Weddell Sea

3.1 Ice crystals forming in pure thermal growth ice sheet

In calm water, the surface layer of sea ice is the granular crystals because sea water is frozen rapidly in thermodynamic process. With the decreasing ice growth rate, ice grains have enough time to grow. Their crystals are held by others beside. The corresponding growth rate downward is faster than others, and crystals become columnar formation. The grain size of columnar crystal in the horizontal plane increases with the increase of ice depth and decrease of growth rate. Between the granular and columnar crystals, there is a transition zone of granular-columnar crystal. Usually, there are several cold snaps in a winter, which result in the fast growth rate, making the formation of granular crystal and columnar crystal alternatively from surface to bottom in an ice sheet. With the increase of ice thickness, the ice growth rate slows down and the cold air snaps affect little on the growth rate, and the granular and columnar crystals alternation is rare. This case occurred in the Bohai Sea and the Arctic sea ice which formed in pure thermal frozen process[5]. The pure thermal frozen ice crystal in Weddell Sea, Antarctic is similar to that in the Bohai Sea and Arctic. The stratigraphy and crystal photographs of an integrated first-year ice core (060910TEX) from the pure thermal process are shown in Fig. 2, which is collected in the marginal area of floating ice. And its vertical profiles of salinity, density and grain size are given in Fig. 3. The density profile of this core is in line with the "?" shape of the Antarctic ice[8], while outside of the surface layer the salinity profile agrees with the "C" shape and mean gain size of ice crystals increases with the ice depth.

3.2 Ice crystals from dynamic growth ice sheet

In winter, ice sheet crushes easily because of the forces from ocean current, wave, wind and the movement discrepancy among the broken ice sheets. The fractured ice undergoes the dispersion and the aggregation that can lead to a sudden increase in ice thickness. Then owing to the influence of cold air snaps, the cracked ice refreezes and the consolidated rafted ice, ice ridge and so on form. While the consolidated ice goes over summer, its surface looks like a plane and the ice cores collected seem to be integral. The differences of rafted ice crystal and stratigraphy compared to the pure thermal frozen ice are discovered in the thin section between cross polarizers. The characteristics of the rafted ice crystal are clear interfaces between granular crystal and columnar crystals, even the crystals have inclined angles in some parts which are broken ice blocks. The water in the space of ice blocks was frozen and formed fine granular crystal. Simultaneously, these processes result in the abnormity of the salinity, density in cores and there is no comparability among the cores in different positions of one ice sheet.

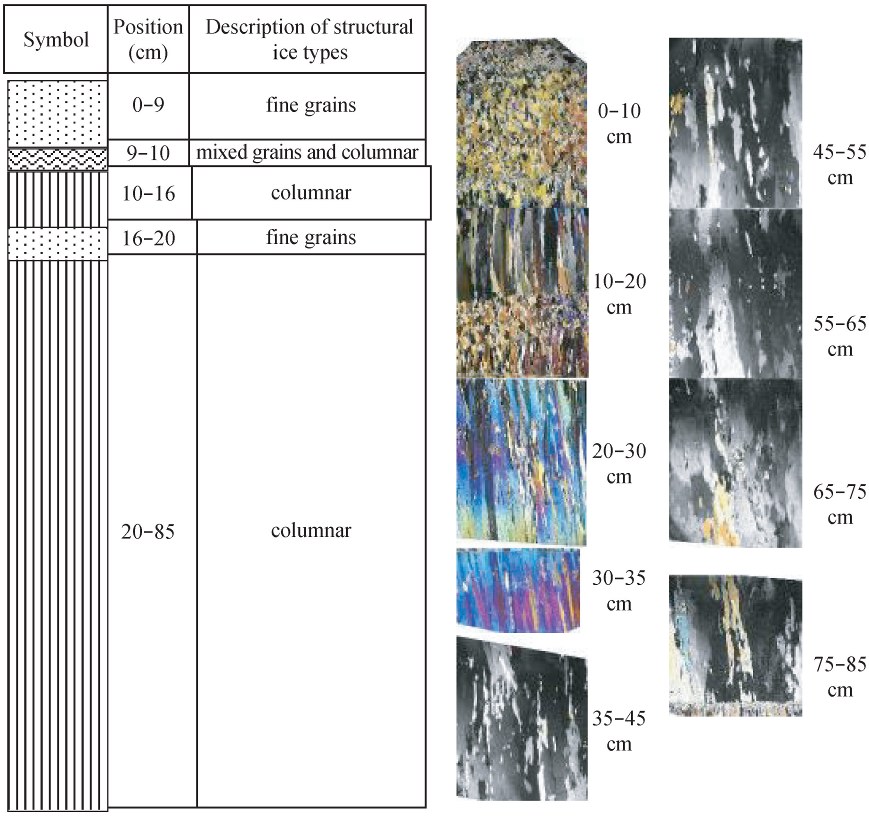


Fig. 2 The stratigraphy and crystal photographs between cross polarizers of ice core 060910TEX.

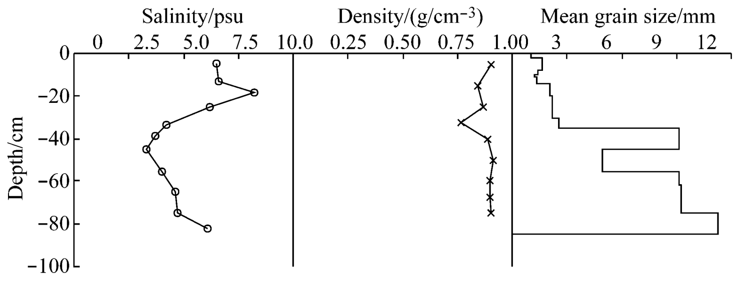
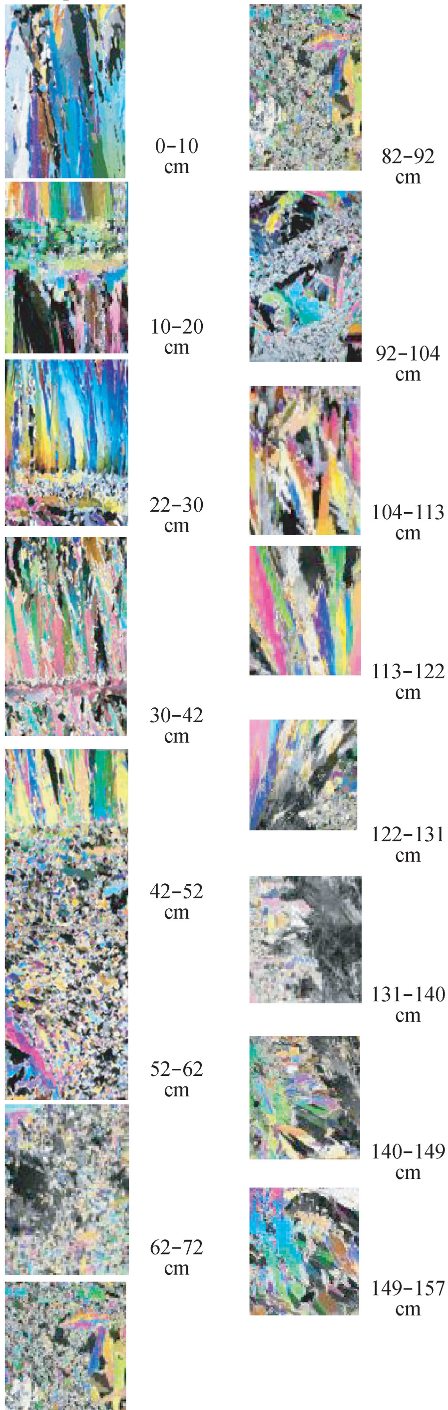


Fig. 3 The vertical profiles of salinity, density and mean grain size of ice core 060910TEX.

The ice core 061005TEX was drilled from the first-year hummocked ice in front of the Larsen A Ice Shelf in Weddell Sea. From surface to bottom, the core has four layers of rafted ice about 15 cm in thickness, hummocked ice with different directions and new columnar ice due to the refrozen and consolidation. It is common that the rafted ice only appears in the thin ice areas, while ice ridge only creates in the thick ice area. It is obvious that the alternation of granular and columnar crystals in the upper section of the ice core is created by rafting. The stratigraphy and crystal photographs of ice core 061005TEX are shown in Fig. 4. Its vertical profiles of salinity, density and grain size vary erratically within the depth of 0—80 cm. Below the depth, the salinity profile almost follows the "C" shape and

Symbol	Position (cm)	Description of structural ice types
	0-13	columnar, 13 cm boundary, rafting
	13-16 13-19	coarse granular, 15-16 large grained
	19-27	columnar, 27 cm boundary, rafting
	27-30	granular, 29-30 cm, coarse
	30-38	columnar, 38 cm boundary, rafting
	38-40	granular, 38-39 cm, coarse
	43-43	columnar
	43-47	columnar, 47 cm boundary
	47-81	mixed granular and columnar
	81-107	mixed granular and columnar, slanted layers
	107-123	columnar
	123-154	columnar with different direction
	154-157	columnar, skeleton layer



the mean grain size of crystal increases with the depth (Fig. 5).

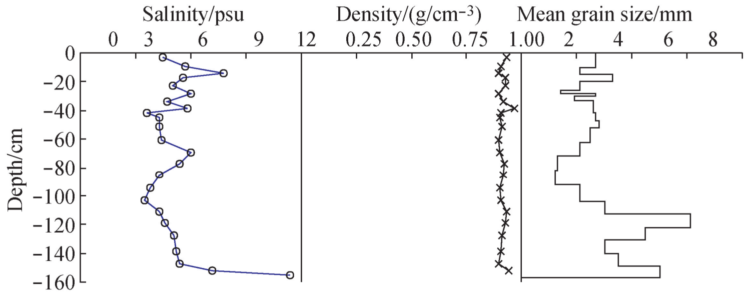
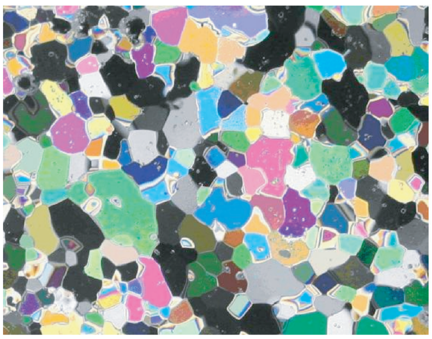


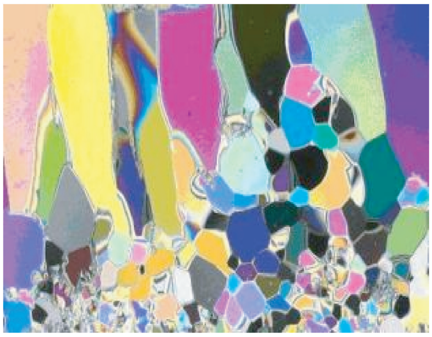
Fig. 5 The vertical profiles of salinity, density and mean grain size of ice core 061005TEX.

3.3 The polygonal crystal in superimposed ice

For the sea ice is coverd by snow, the snow cover can decrease the growth rate of sea ice and also transform into superimposed ice, therefore increasing the ice thickness[9]. Although the amount of superimposed ice is quite few, scientists have paid much attention to its physical forming processes and its contributions to the ice thickness[6,10]. After snow falls on ice surface, its density and grain size increase through aggradation and consolidation with time. When the snow melts, the water inside migrates to the interface between snow and ice, the snow crystals change with the process and refreeze into superimposed ice with polygonal crystals. Between cross plarizers, the horizontal thin section of superimposed ice shows angular grains crystals, while the vertical thin section shows granular or columnar crystals. The corresponding crystal size decreases with the depth below superimposed ice. In this case, the salinity in superimposed ice is close to 0. A case of similar crystals was found in the thin section, the salinity in ice is much higher than that in upper section of sea ice. A possible explanation is that the ice results from a kind of slush. Its higher salinity comes from the sea water which flows through ice cracks while snow was thicker and the free board was negative. If the snow absorbs the upwelling sea water little and there is enough time for snow crystals changing and refreezing, it is possible to form the polygonal crystals as well. Photographs of polygonal crystals of superimposed ice are shown in Fig. 6, and



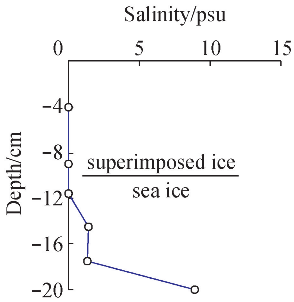
a) 061018TEX (snow)-group1 crystal in horizontal section



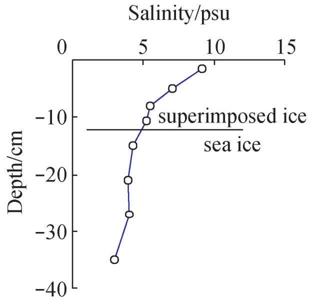
b) 061001SURF crystal in vertical section

Fig. 6 Photographs of polygonal crystals of superimposed ice.

their vertical salinity profiles of the two ice cores are given in Fig. 7.



a) 061018TEX(snow)-group1 ice core



b) 061001TEX ice core

Fig. 7 The vertical salinity profiles of two superimposed ice cores.

4 The distribution of sea ice crystal types in Weddell Sea

According to the texture and crystal types of 27 ice cores, it is easy to find out that the crystals in upper section of ice cores are granular crystals primary; the crystals in middle section of ice cores are granular crystals or the alternate granular and columnar crystals at random because of the growth rate variation faster or the cases of rafted ice within the ice; and columnar crystals are common near the bottom of ice sheet. If the ice core drilled from a refrozen tilted ice block, the crystal is granular or columnar in a large range of the core. If the ice core drilled from the frozen sea water among the spaces of small broken ice pieces, the ice crystal shows the non- orientation mixture of frozen water crystal and granular and/or columnar sea ice crystals. The statistical results reveal that the total length of 27 ice cores is 3477 cm, the granular, mixed granular-columnar and columnar crystals in ice occupied 28.7%, 14.4% and 55.2% respectively, and especially the proportion of polygonal crystal is only 0.66%.

Although a large flat ice floe was selected as the ice sampling site, it is uncertain that the flat ice floe is formed from the pure thermal growth, because the ice floe surface usually was rebuilt by ice dynamic process, and reformed by thermal process. These processes make the surface of first-year rafted ice, the second-year reformed ice or consolidated ice ridge smoother than that of the ice in the young stage. Only according to the stratigraphy of ice core texture, vertical profiles of salinity, density and oxygen isotope[11], the type of ice could be determined exactly. All 27 ice cores information and ice forming processes are summarized in Table 1. This table gives the ice crystal distribution in plane along the cruise track. Based on the investigation sites and the dependence of ice formation upon the growth condition, three areas were divided, which are shown in Fig. 1[7]. They are: AREA I, the marginal area of the floating ice; AREA II, the first-year and second-year ice areas from dynamic process; AREA III, the first-year ice area from polynyas Larsen A. Only four cores in the total 27 ice cores in the cruise track are second-year ice, which demonstrates that first-year ice dominates the ice in Weddell Sea. In the AREA I, all of four cores are first-year ice. In them, three ones are formed by the pure thermal growth and one is superimposed ice with polygonal crystal. They reveal that although in the marginal area of the floating ice the influence of ocean wave is obvious, the rafting and ridging hardly occur because of the ice concentration is lower in AREA I. In the AREA II, three of ten cores are second-year ice. Among them, three cores are formed by the pure thermal growth and other seven cores exhibit the evidences of dynamic effect. These demonstrate that ice dynamic process contributes to the sudden increase of ice thickness, and there is ice which not melted completely in last summer and the ice refroze in the winter. In the AREA III, among the thirteen ice cores, one is second-year ice, five cores are formed in the pure thermal growth and eight cores have the evidences of dynamic effect. These are the evidences that the speed differences between icebergs and ice floes in front of Larsen A supply the dynamic force to ice deformation, and the polynyas in front of Larsen A are the original place of new ice forming where a large amount of pure thermal growth ice is transferred outward.

Table 1. Summary of ice cores information and ice formation processes

Area	Name of ice cores	Length of cores /cm	Position and type of cores	Area	Name of ice cores	Length of cores /cm	Position and type of cores
I	060908TEX	62	first-year ice, with two times of fast growth	III	061001TEX	216	second-year ice, consolidated ice ridge
I	060909TEX	106	first-year ice, with two times of fast growth	III	061002TEX	124	first-year ice, rafted
I	060910TEX	85	first-year ice, with two times of fast growth	III	061003TEX	132	first-year ice, with two times of fast growth
I	061018TEX	132	superimposed ice, rafted ice and regrowth first-year ice	III	061004TEX	151	rafted ice and regrowth first-year ice
II	060919TEX	175	second-year ice, consolidated ice ridge	III	061005TEX	157	first-year ice, multilayer rafted
II	060920TEX	73	first-year ice, rafted	III*	061008TEX	125	first-year ice, with one time of fast growth
II	060921TEX	137	first-year ice, with two times of fast growth	III*	061009TEX1	122	rafted ice and first-year ice with three times of fast growth
II	060922TEX	237	second-year ice, consolidated ice ridge	III*	061009TEX2	151	first-year ice, with three times of fast growth
II	060923TEX	113	first-year ice, with one time of fast growth	III*	061009TEX3	68	first-year ice from broken ice pieces refrozen
II	060924TEX	88	first-year ice, consolidated ice ridge	III*	061009TEX	122	first-year ice, with one time of fast growth
II	060926TEX	97	first-year ice, rafted	III	061011TEX	97	first-year ice, with one time of fast growth

II	060928TEX	195	second-year ice, consolidated ice ridge	III	061012TEX	228	first-year ice, consolidated ice ridge
II	060930TEX	126	first-year ice, rafted	III	061017TEX	130	superimposed ice and first-year ice with three times of fast growth
II	061013TEX	132	first-year ice, with three times of fast growth				

Note: The first part of ice core name is the date of sampling (year, month and date) and the sampling position is in Fig. 1; the * ice cores were drilled from the area in front of Larsen A.

5 Conclusions

1) The Antarctic Weddell Sea has superimposed ice with polygonal crystal besides the sea ice with granular crystal, columnar crystal, mixed granular and columnar crystals and ice needle. The superimposed ice has polygonal granular crystals in the horizontal thin sections, while it is columnar crystal or granular crystal in the vertical thin sections. Its crystal size decrease with the ice depth and its salinity has much difference based on the water original resources in snow.

2) Among the 27 ice cores, the granular, mixed granular-columnar and columnar crystals in sea ice occupied 28.7%, 14.4% and 55.2% respectively. The proportion of superimposed ice with polygonal crystal is only 0.66%.

3) First-year ice is primary in Weddell Sea. The thermal growth ice is predominant in the marginal area. Most of first-year ice and second-year ice are influenced by the dynamic process. In front of Larsen A, the speed differences between icebergs and ice floes cause the dynamic force which results in ice deformation. Also there is much thermal growth ice with granular and columnar crystals which is transferred outwards continually by winds and currents in the large area of polynyas.

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