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Self-organization phenomena of the nonequilibrium process in magmatism of the Fildes Peninsula, West Antarctica

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Abstract Volcanic geological, petrological and geochemical characteristics of the Tertiary volcanic rocks from the Fildes Peninsula, West Antarctica show that magma evolution was a process of dissipation of heat energy exchanged energy and mass occurring between the magma system and its surrounding environments, and with the feature of dynamic equilibrium and periodicity (stage). In the study volcanic rocks of different types commonly exhibit a multi-grade composite texture and the derivative magmas produced by differentiation of parent magmas in the magma chamber show a zonal structure in the high-level-magma chamber which represent self-organization phenomenon of the nonequilibrium process in magmatism. The self-organization phenomenon is dissipative structure formed under given conditions.
Key words West Antarctica, Fildes Peninsula, magmatism, self-organization phenomenon.

1 Introduction

When a system is situated in a nonlinear region far from thermodynamic equilibrium, under some conditions, through continuous exchange of material and energy between the system and the ambient environment and the irreversible process inside the system (energy dissipation process), the disordered state is possible to lose stability and some fluctuations may be amplified to bring about sudden change of the system, thus producing the ordered state in time-space and function, which is called dissipative structure (Glansdorff and Prigogine, 1971; Li, 1986).

Under the condition far from the equilibrium, the ultimate state of the development of the system is likely to be a nonequilibrium state. The behavior of the nonequilibrium state depends not only on thermodynamic conditions but also on kinetic conditions. When the interior of a system involves some appropriate nonlinear kinetic mechanism, the homogeneous time-independent nonequilibrium state may become unstable, thus probably giving rise to the self-organization phenomenon with temporally and spatially ordered structure (Glansdroff and Prigogine, 1971; Li, 1986; Nicolis and Prigogine, 1977; Shen *et al.*, 1987).

Controlled by boundary conditions (cooling surface, boundaries etc. of a magma body), most of the igneous processes are difficult to reach the equilibrium state. The igneous processes are largely chemical reactions, concentration diffusion and thermal diffusion, which change as a function of temperatures and pressures (Zhang and Li, 1991).

Here volcanic rocks (Li and Liu, 1987, 1991; Li *et al.*, 1991, 1992) of the Fildes Peninsula, West Antarctica, are taken as an example to study the self-organization phenomenon of the nonequilibrium process in magmatism. The self-organization phenomenon is dissipative structure formed under given conditions.

2 Geological Setting

The Fildes Peninsula is located at the southern tip of King George Island, South Shetland Islands, West Antarctica. During the last two million years, the expansion of the Bransfield Strait has caused South Shetland Island to migrate westward about 65 km (Ashcroft, 1972). The Meso-Cenozoic volcanism is related to the subduction of the Antarctic continental plate. The volcanic rocks of the Fildes Peninsula are of Eocene age and may be divided from older to younger into five lithologic members and tectono-magmatism largely involves two phases. The rocks formed in the first phase consist of basaltic volcanic rocks of the Jasper Hill Member and Agate Beach Member, and the rocks formed in the second phase, basalt-andesite and andesitic and dacitic volcanic rocks of the Fossil Hill Member, Black Hill Member and Long Hill Member. There occurred a relatively long eruption interval of an erosion sedimentary hiatus and a low-angle unconformity between the two phases. Rocks are mainly represented by basaltic and basalt-andesitic rocks with subordinate andesitic rocks and minor amount of dacitic rocks, belonging to the subalkaline series. The REE distribution patterns of different rocks show relatively good parallelism and a relatively low slope. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ of the volcanic rocks are 0.70320～0.70384 and 0.512913～0.512949 respectively, the large-ion lithophile elements and light REE are rich, ε_{Nd} is +2.77～+0.63, and the dark-colored index of basalt is low, being 21(V)%～28(V)%, which indicate that the primitive magma of the volcanic rocks in the study area is the product of partial melting of the mantle and closely associated with the subduction of the oceanic plate toward the Antarctic plate. The magma, which derived from the primitive magma by differentiation process, such as fractional crystallization in the deep magma chamber, entered the high-level magma chamber (shallow source).

3 Self-organization phenomenon of the ascent of magma far from equilibrium

3.1 Multi-grade complex texture of volcanic rocks of different types

In the study area volcanic and subvolcanic rocks of different types commonly exhibit a multi-grade complex texture, including five components, megaphyric-glomeroporphyric phenocrysts, seriate phenocrysts, matrix microlites, interstitial glass and microamygdales, representing five temperature-decreasing and crystallization stages of magma in the whole process of localization from the high-level magma chamber through conduits to the near-surface portion or surface. This texture represents the nonequilibrium process and self-organization phenomenon of exchange of heat energy and material betweem magma and its surrounding environment, heat energy dissipation and inhomogeneous nucleation-crystallization that took place in the process far from the equilibrium state (Table 1).

Table 1. Comparison of complex texture of different rock types

Rock types		Basalt	Basalt-andesite	Andesite	Dacite
Megaphyric-glomero-porphyric phenocrysts	V%	0.2~2	0.2~3	2~7	2~7
	mm	2~5	2~5	3~8	3~8
Seriate phenocrysts	V%	65~26	68~28	20~30	15~25
	mm	1.6~0.48	1.3~0.32	2.5~0.27	2.1~0.38
Matrix microtites	V%	28~64	24~61	65~56	70~65
	mm	0.21~0.036	0.24~0.041	0.23~0.032	0.28~0.037
Interstitial glass	V%	0.5~3	0.5~3	0.5~5	0.5~5
Microamygdales	mm	0~3	0~3	0~2	0~2
Texture		diabasic and intergranular	intergranular, pilotaxitic and tholeiitic	intergrnular and pilotaxitic	pilotaxitic and hyalophitic

Generally speaking, the megaphyric-glomeroporphyric phenocrysts are larger in size and more in number in andesites and dacites than those in basalts and basaltic andesites. The seriate phenocrysts in andesites and dacites are dominated by medium-and fine-grained ones, while those in basalts and basaltic andesites by fine-and very fine-grained ones. They may be easily discriminated in the field and on hand specimens. The groundmass plagioclase microlites may show different textural relationships. Generally, basalts and basaltic porphyrites are diabasic and intergranular; basaltic andesites are intergranular and pilotaxitic and may exhibit a tholeiitic texture in the presence of more glass; andesites are intergranular and pilotaxitic; dacites are pilotaxitic or hyalopilitic. The interstitial glass tends to be metasomatized by postmagmatic hydrothermal fluid to varying extent, and its content is difficult to estimate accurately. Microamygdales, irregular in shape, mostly occur in the interstices betweem plagioclase crystals in association with interstitial glass. The minerals filled in the interstices are very similar to those replacing glass.

3.1.1 Megaphyric-glomeroporphyric clusters of phenocrysts

Megaphenocrysts are mainly represented by plagioclase, and subordinate clinopyroxene. The glomeroporphyric clusters sometimes also contain a few pseudomorphs of orthopyroxene or olivine.

Plagioclase, as megaphenocryst, exhibits a zonal structure. The rhythmic zoning is clearer and denser on the outer side than that in the interior. The plagioclase composition varies from An=85% or so (bytownite) in the center to An=64% or so (labradorite) on the edges. A few corrosion surfaces are often recognized in the interior of the grains. The core is sometimes composed of several smaller plagioclase aggregates, and the patchy texture of different degrees can be found.

The composition of pyroxene megaphenocrysts is intermediate between diopside, endiopside and augite. Its Wo and En elements are reduced gradually from the core to the edges. The grain surface sometimes displays a resorption phenomenon. The glomeroporphyritic aggregates of clinopyroxene phenocrysts sometimes contain or enclose euhedral olivine and orthopyroxene grains, which are usually replaced by iddingsite, saponite or vermiculite and occur as pseudomorphs.

The crystallization stage represented by megaphenocrysts and glomeroporphyritic clusters was considered to have started in the high-level magma chamber and continued in the conduits along which magmas ascended. As the pressure and temperature changed with depth, the equilibrium conditions were away gradually from original equilibrium conditions so that the minerals were crystallized and subjected to resorption, reaction and autometasomatism.

3. 1. 2 Seriate-porphyritic texture

The feature of this kind of texture is that the sizes of phenocrysts of plagioclase, clinopyroxene and some orthopyroxene vary in a continuous series. Phenocrysts in this kind of texture account for about 1/4 to 1/3 of the whole rock and their sizes may differ by 8 to 15 times. The plagioclase varies from bytow-labradorite to labra-andesine. Rhythmic dense zoning is developed, which is clearer on edges.

A majority of clinopyroxene found in rocks is augite, and orthopyroxene is represented by hypersthene or bronzite. The grains of pyroxenes range from medium through fine to very fine ones. In seriate phenocrysts the content of forsterite increases as compared with glomerophenocrysts. Orthopyroxene is mostly replaced by saponite, vermiculite or chlorite, and displays pseudomorphs.

The occurrence of seriate phenocrysts in rocks may result from their continuous crystallization with decreasing temperature and pressure when magmas ascended along the conduits after their departure from the high-level magma chamber. Therefore it may be considered that they represent a stage of crystallization in the volcanic conduits.

3. 1. 3 Matrix microlites

Depending on different rock characters, groundmass plagioclase and pyroxene microlites may be gabbro-diabasic, diabasic, intergranular, tholeiitic, pilotaxitic or hyalopilitic. The groundmass microlites may make up 1/3 to 2/3 of the whole rock. Microcrystalline plagioclase varies in composition from andesine to andeclase, depending on different rock characters. Clinopyroxene, represented by augite, usually has lower content of Wo norms and higher Fs norms than seriate phenocrystic pyroxenes. Titanic magnetite is equant granular with a grain size of 0.04×0.032 to 0.004×0.0004 mm^2. Apatite is acicular or slender prismatic, 0.048×0.004 to 0.016×0.002 mm^2 in grain size. They occur in the interstices of plagioclase and pyroxene grains in association with interstitial glass. The fact that the microlites are present in the groundmass of both lavas and subvolcanic rocks implies that they crystallized near or on the surface. It is noteworthy that although the pressure decreased abruptly when magmas ascended near the surface or reached the surface, the formation of microlites could still last for a relatively long period of time so long as the magmas were in an overheated state.

3. 1. 4 Interstitial glass

Interstitial glass can be considered as an indicator of the primary consolidation of the magmas at the end of magmatism. The interstitial glass observed in thin sections is light brown, light brownish yellow or nearly colourless, usually accompanied by microamygdales, most magnetite and slender prismatic apatite and the microcrystalles are enclosed by the interstitial glasses. Besides, microvesicles are always closely associated with it. The content of the interstitial glass occurring in the groundmass of lavas is slightly higher than that in the groundmass of subvolcanic rocks. The appearance of interstitial glass evidently represents the consolidation of more acid residual melts at the ultimate stage in the process of magmatic crystallization. This kind of glass contains abundant water and various volatiles. When magmas ascend to a certain height along the conduit and the internal pressure of the volatiles in residual melts exceeds the external pressure, the melts (from which volatiles have been released) were moved between the plagioclase and pyroxene crystals and cooled and solidified rapidly into glass at a relatively low pressure and temperature.

3. 1. 5 Microamygdales and auto-alteration minerals

Microamygdales and auto-alteration minerals account for at most 4 vol. % of the rock, or are simply absent. The microamygdales, very irregular in shape, occur in the interstices of feldspar crystals , which are accompanied by auto-altered interstitial glass. They exhibit an encrustation structure. From the walls of the vesicles to the center , the infillings are successively gel-chlorite, scaly chlorite and carbonates or saponite, and carbonates. Interstitial glass is often partly or entirely replaced by postmagmatic products, which are commonly saponite, chlorite and carbonates. The auto-alteration of interstitial glass and the formation of encrusted infilling minerals in microvesicles represent the beginning of postmagmatic processes.

The above-described complex textures, commonly existing in volcanic and subvolcanic rocks of different kinds, suggested that the process of crystallization and consolidation of magmas in study region would be divided into five stages. The rocks may be different in characteristics, but their processes of crystallization are almost identical, i. e. from crystallization in the high-level magma chamber through continuous crystallization in the ascent conduits to rapid crystallization, cooling and removal of postmagmatic fluids and volatiles near the surface and on the surface.

3. 2 The processes of the ascent of magma far from equilibrium

The further ascent and crystallization of high-Al basaltic magma from the upper mantle in the area after 10%～15% of partial melting were controlled by the following factors.

(1) Temperature gradient. The normal temperatures of the magma source region — upper mantle — should be greater than 1000 ℃, and under the water — saturation condi-

tion the temperatures of partial melting of garnet lherzolite in the mantle were greater than 1250℃. Owing to the temperature contrast between the mantle and the crust, the heat energy of the mantle might be dissipated rapidly through the ascent and eruption of the molten magma besides the mode of normal and slow heat conduction.

(2) Pressure gradient. The Moho depth of the area is 23 km and the lower crust and upper crust are about 13 km and 10 km thick respectively. According to the thermodynamic calculation, the depth of condensation of basaltic magma in the area might be greater than 25～35 km. When the regional (compressive) stress field underwent local relaxation and decompression or was in an extensional stage, magma might rise or even erupt along deep fracture systems, and when decompression or extension occurred periodically, there occurred the change by stages in the velocity of the magma movement.

(3) Density contrast between magma and its surrounding medium. The density of the magma after partial crysallization decreased with the fractional crystallization of the magma and dissipation of heat energy in the deep condensation space, and when the density of the new magma was lower than that of its surrounding medium, so long as there appeared or existed conduits of migration, the magma would migrate toward the medium till the densities of the magma and its surrounding medium were close to or in dynamic equilibrium; then the magma stagnated at a certain depth of the crust and accumulated gradually in a certain space to form a high-level magma chamber.

(4) Viscosity and volatiles of magma. The viscosity and volatiles of magma had significant influence on the ascent velocity of the magma, and the contents of water and volatiles also affected the interaction between the magma system and its surrounding environments. The magma stagnated for a longer time in the high-level magma chamber; especially in the case of groundwater infiltration the exchange of energy and mass occurring between the magma and the surrounding medium became stronger than in the conduits of migration. When the density of the derivative magma that had undergone fractional crystallization and other differentiation was lower than that of the surrounding medium, so long as there were extensional environments or fractural systems, the derivative magma would continue to migrate upward and intrude or erupt under appropriate tectonic conditions. The textures of the rocks have recorded and reflected related crystallization and condensation conditions.

The process of generation of magma by partial melting in the source region and its subsequent accumulation, ascent and condensation was generally a process of dissipation of heat energy as well as a process far from equilibrium. Although there appeared a relative and temporary equilibrium between the removed crystals and the melts and between the magma system and its surrounding environments and frequent alternation of this equilibrium and destruction of this equilibrium in the process, the non-equilibrium state occupied a dominant position as far as the entire process is concerned. Except for the inner cores of macrophyric plagioclase and pyroxene that might start crystallization at greater depths, the bulk part of macrophyric minerals in the multi-grade complex texture was formed in the high-level magma chamber, while the outer rims of the macrophyric phenocrysts became increscent in the ascent of conduits. The inner core in large-graded grains of seriate phenocrysts were also crystallized in the high-level magma chamber, while their outer rims also incremented in the ascent of conduits. The crystallization of microlites might start at a certain depth of the conduits but close to the surface, while the crystallization ended in the solidification of the magma after it erupted out of the surface. To sum up, the bulk of the multi-grade complex texture reflects the thermodynamic process of the magma from its localization in the high-level magma chamber to its crystalization and solidification after its eruption on the sruface; more explicitly, the multi-grade complex texture occurring in the crystallization and solidification of magma in the nonequilibrium process of its ascent from the high-level magma chamber is a self-organization phenomenon in the process of magmatic crystallization under a given condition; so it is also a dissipative texture.

4 Self-organization phenomenon in the high-level magma chamber

Magmatic differentiation is a very slow, sustained geological process, but volcanic eruption is a very rapid, transient geological "interval". So it is generally considered that the principal process of differentiation begins before eruption; whereas the earlier the differentiation begins, the higher the degree of differentiation and the more pronounced the diversity of rocks formed by eruption will be. The differentiation reflecting the self-organization in the high-level magma chamber in the area is mainly manifested in the following two aspects.

4. 1 Mineral assemblages and contents of dominant oxides in different rock types

The essential mineral assemblages of various rock types in the area are similar, whereas the relative contents of the minerals therein vary with different rocks. From basalt—basaltic andesite—andesite to dacite, the mineral contents show regualr variation (Table 2). Among these minerals, the normative mineral quartz does not appear in actual rocks, especially in basalt and basaltic andesite, and part of SiO_2 might occur in various forms in interstitial glass, micro-amygdaloids and auto-altered silicate minerals.

Table 2. IPW norms in different types of rocks (V%)

Rock types	Picritic -basalt	Basalt	Basaltic-andesite	Andesite	Dacite
Colour index	33～22	28～21	24～17	20～9	11～8
An	75～69	69～55	52～43	49～34	39～26
Plagioclase	78～67	75～68	70～65	73～64	78～67
Pyroxene	18～28	18～22	14～20	8～16	3～12
Apatit	0. 17～0. 19	0. 21～0. 32	0. 26～0. 48	0. 36～0. 56	0. 55～0. 73
Magnetite	2. 99～3. 65	2. 88～3. 86	2. 31～4. 65	2. 13～5. 44	5. 08～6. 23
Quartz	—	0. 3～4. 2	5. 4～12. 8	7. 9～15. 8	15. 4～19. 8
Olivine	1. 6～3. 9	—	—	—	—

The contents of dominant oxides in different rock types also vary regularly (Table 3). The chemical and mineral compositions show the same regularity of variation, i. e. from picrite-basalt, basalt, basaltic andesite and andesite to dacite, the normative mineral quartz, total alkalis (ALK), K_2O, apatite and P_2O_5 increase progressively with increasing of SiO_2 content, both showing positive correlation; while the color index, pyroxene content and MgO and CaO contents all decrease accordingly, showing negative correlation. The variation of the ($FeO+Fe_2O_3$) content is distinctive, i. e. , when the SiO_2 content increases from 45% to about 53%, the TFeO content also increases, both showing positive correlation; but when SiO_2 increases from about 53% to 65%, TFeO decreases accordingly. The SiO_2 content at this inflection point of the evolutionary trend is just in agreement with the average composition of volcanic rocks in the whole area. These features indicate that the different rocks showing regular variation in the area might be the products of crystallization of related magmas derived from consanguineous differentiation.

Table 3. Contents of major oxides (%)

Major oxides	SiO_2	Al_2O_3	MgO	CaO	TFeO	ALK	K_2O	P_2O_5	δ
Picritie-basalt	45.35～47.92	21.00～19.32	7.03～5.54	12.66～12.51	8.57～8.49	1.90～2.51	0.26～0.19	0.08～0.13	0.73～1.13
Basalt	48.12～52.00	22.35～17.99	5.84～3.97	12.19～8.68	10.10～8.37	2.84～3.62	0.63～0.16	0.14～0.19	1.15～1.85
Basaltic-andesite	52.27～54.83	18.40～16.19	4.96～3.11	9.78～6.15	11.24～8.77	3.49～4.98	1.68～0.20	0.16～0.21	1.11～1.98
Andesite	55.04～60.07	18.38～15.56	3.51～1.69	8.34～4.71	9.64～5.68	4.45～6.12	1.42～0.85	0.19～0.25	1.33～2.23
Dacite	63.29～65.03	16.91～14.85	1.54～1.05	4.17～2.91	6.33～5.18	6.37～7.34	2.40～1.93	0.25～0.35	1.99～2.45
Averages	53.63	18.96	4.46	9.36	8.07		0.75		

An intensive analysis of the mineralogical and chemical compositions of various types of volcanic rocks, particularly basalts, in the area indicates that the color index of basalt in the area is lower than the lower limit (35 vol. % or 40 wt. %) of the color index of oceanic ridge basalt (ORB) that was formed directly by partial melting of the mantle but has not undergone strong differentiation, being only 21 vol. %～28 vol. % and that even the color index of picrite basalt is only up to 22 vol. %～33 vol. %. In the bulk composition, the plagioclase in basalt of the area is more basic with an An content up to 69%; olivine is not observed in thin sections and also absent in the normative minerals. The plagioclase in picrite basalt has an An content as high as 75%, while the olivine has only a normative molecular content of 1.6%～3.9% and is still less in thin sections. This implies that basalt and even picrite basalt in the area are also "leucocratic basalt" formed by crystallization of basaltic magma derived from magmatic differentiation. Likewise, the color indices of basaltic andesite, andesite and dacite are commonly low too, which is not in agreement with the bulk average composition of the plagioelase. This case may occur only after deep-seated differentiation, i. e. after deep-seated separation of early-formed ferromagnesian minerals from derivative magma.

In summary, the magmas corresponding to picrite basalt, basalt, basaltic andesite, andesite and dacite are the product of consanguineous differentiation, while the initial magmas of various derivative magmas produced by magmatic differentiation in the high-level magma chamber are not primitive magmas but were derived by fractional crystallza-tion in the deep-seated magma chamber of the primitive magmas originating by partial melting of the mantle. The composition of the initial magmas that began to enter the high-level (shallow) magma chamber might be high-Al basaltic, but closer to the marginal values of basalt and basaltic andesite; andestic and dacitic rocks are their acid differentiates. The composite fabrics of various types of volcanic rocks also suggest that different derivative magmas all underwent the same stage of crystallization and cooling and went through close or similar channel-ways of migration, so should have come from the same magma chamber region.

4. 2 Trace element and isotope geochemistry

The $^{87}Sr/^{86}Sr$ ratios of volcanic rocks both mantle-derived oceanic ridge and oceanic island rocks are known to be 0. 7028 and 0. 7039 respectively (Faure, 1977). The mea-sured $^{87}Sr/^{86}Sr$ values of volcanic rocks in the areas range from 0. 70320 to 0. 70384. According to these ratios and the corresponding K-Ar age data, the initial $^{87}Sr/^{86}Sr$ ratios are estimated to be 0. 70319~0. 70363 (on the basis of 13 samples). Except for a few samples of basalt whose initial $^{87}Sr/^{86}Sr$ ratio is 0. 70319, generally it is 0. 70335~0. 70352 for basalt, 0. 70350 for basaltic andesite, 0. 70356~0. 70357 for andesite and 0. 70361~0. 70363 for dacite. These data indicate that the initial $^{87}Sr/^{86}Sr$ ratios of different rock types in the area are all very low, approximating to the value of oceanic ridge basalt, which not only demonstrates that the magmatic materials of volcanic rocks in the area were mainly derived from the mantle but also rules out the possibility that the andesitic and dacitic magmas were generated by mixing of crustal materials. The measured values of $^{87}Sr/^{86}Sr$ and the calculated values of ($^{87}Sr/^{86}Sr$) have a very narrow variation range, and the ratios increase regularly from basalt to dacite and radioactive ^{87}Sr increases with increasing acidity. Then the Sr isotopic composition once again proves that the derivative magmas of different compositions in the area are the product of consanguineous differentiation. Before magmatic eruption, the zonal structure of derivative magmas of different compositions formed by differentiation had already existed in the high-level magma chamber. The correlation between $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ suggests that radioactive ^{87}Sr was mainly derived from subducted oceanic crustal materials and has little relation with continental crust.

In comparison with chondrite, the light rare earth element (LREE) in the volcanic rocks of the area are moderately enriched and the total REE amount is 70~300 times as high as in chondrite; in comparison with oceanic ridge basalt, the large-ion lithophile elements (LILE) Rb, Ba, Sr and Th in the volcanic rocks of the area are also enriched to different degrees. The enrichment of these incompatible elements was related to subducted oceanic crust. Dehydration and partial melting during the subduction caused the above-mentioned elements to concentrate in hydrous fluids and ascend with the fluid to the wedge-shaped mantle; the primitive magma orginating by partial melting of the mantle modified by hydrous fluids is also characterized by moderate enrichment of the above-mentioned elements. The primitive magma underwent fractional crystallization in the deep-seated magma chamber. Appreciable amounts of the aforesaid incompatible elements entered the high-level magma chamber along with the differentiated ascending derivative magmas, forming initial magmas or "parent magma" (in a relative sense) in the high-level magma chamber. The differences among basalt, basaltic andesite, andesite and dacite in respect to the contents of the REE, LILE and part of high-field strong elements (Table 4 and 5) are due to consanguineous differentiation in the high-level magma chamber. With the rise of the differentiation index, the content of the major element SiO_2 increases from 46% to 65% and the $\sum$REE amount also increases from 33×10^{-6} to 164×10^{-6}. The $\sum$LREE increases from 26×10^{-6} to 143×10^{-6} and the $\sum$HREE from 6×10^{-6} to 21×10^{-6}. The chondrite-normalized REE characteristic values reflect more markedly that various normalized REE characteristic values increase from basalt to dacite with inceransing degrees of differentiation, of which the normalized $\sum$REE increases from 110 times to 363 times that in chondrite, the $\sum$LREE from 70 timesto 302 times,

Table 4. REE data in different types of volcânic rocks (10^{-6})

REE data	Nonstandard				Chondrite-normalized			
	$\sum$REE	$\sum$LREE	$\sum$HREE	La/Yb	$\sum$REE'	$\sum$LREE'	$\sum$HREE'	La'/Yb'
Basalt	32.73 ~55.39	26.25 ~48.42	6.48 ~6.97	3.78 ~5.69	110.05 ~162.02	69.86 ~119.35	40.19 ~42.67	2.80 ~6.26
Basaltic -andesite	50.87 ~88.17	42.29 ~76.78	8.59 ~11.39	5.22 ~7.27	161.04 ~258.62	107.44 ~188.34	53.60 ~70.28	5.87 ~7.60
Andesite	83.16 ~112.12	68.14 ~95.27	15.32 ~16.85	5.38 ~7.26	273.25 ~338.42	176.80 ~232.91	108.61 ~105.50	3.19 ~4.31
Dacite	104.84 ~163.96	88.00 ~142.86	16.84~ 21.10*	6.76 ~8.06	235.95 ~367.64	189.56 ~302.37	116.45~ 185.75*	4.02 ~4.78

*: inferred

and the $\sum$HREE from 40 times to 185 times. On the other hand, the normalized and non-normalized values of La/Yb in different rocks of the area are relatively low and show narrow variations, indicating that their normalized patterns have relatively low slopes. The parallelism of the patterns of different rock types is relatively high, which also suggests that they are the product of consanguineous differentiation.

The contents of LILE and parı of high-field strong elements also show a trend of regular increase from basalt to basaltic andecite to andecite to dacite(Table 5), i. e., except the Sr content which decreases, the contents of other elements all increase regularly. This likewise reflects the differentiation of initial magmas in the high-level magma chamber.

Table 5. Averages of large ion lithophile elements and high-field strong elements in different types of volcanic rocks(10^{-6})

Volcanic rocks	Basalt	Basaltic-andesite	Andesite	Dacite
Sr	606	517	443	336
Rb	3.61	17.00	32.80	39.90
Ba	145	235	349	413
Th	1.41	2.08	3.15	4.03
Ta	0.50	0.60	1.24	1.26
Hb	1.25	3.58	6.33	-
Zr	54.25	9.40	1.23	1.90
Hf	1.04	2.35	3.60	5.25
Y	12.25	16.48	22.66	28.00

5 Zonation in the high-level magma chamber and its formation mechanism

5.1 Geological grounds for zonation

In discussing the zonal features of the high-level magma chamber, an analysis of the spatial and temporal distributions and associations of volcanic and subvolcanic rocks in the area are conducive to our understanding of the zoning in the magma chamber.

(1) The total volume of the eruptive materials from the Fildes Peninsula is roughly estimated at about 4.5 km^3, from which it may be inferred that the size of the high-level magma chamber was small, its volume possibly not exceeding 10 km^3.

(2) The older volcanic rocks in the area —— the volcanic rocks of the Jasper Hill Member —— are only distributed at the southwestern end of the peninsula, whose volume accounts for about 11.04% of the total volume of volcanic rocks of the whole area (Table 6). The rocks consist of lava and pyroclastic rocks of picrobasaltic to basaltic composition, which are the most basic rocks in the area. They have an average SiO_2 content of 49.99%. Among the rocks of all the lithologic members, their MgO and CaO contents are the highest, being 5.33% and 11.78% respectively, and their K_2O content

is the lowest, being only 0.43%.

Table 6. Volumes (%) and averages (%) of the chemical compositions of different lithologic members

Member	Jasper member	Agate beach member	Forissil Hill member	Block Hill member	Long Hill member	Averages
SiO_2	49.99	53.42		57.29	53.30	53.11
TiO_2	0.69	0.78		0.89	0.78	0.77
Al_2O_3	20.45	18.92		16.11	18.49	19.13
Fe_2O_3	2.90	3.04		2.61	2.98	3.09
FeO	5.62	5.20		3.09	6.34	5.15
MnO	0.15	0.16		0.15	0.17	0.16
MgO	5.33	4.72		1.36	4.24	4.70
CaO	11.78	9.51		3.69	9.61	9.68
Na_2O	2.54	3.31		4.98	3.02	3.25
K_2O	0.43	0.77		1.98	0.90	0.73
P_2O_5	0.11	0.18		0.31	0.18	0.17
V%	11.04	82.44	2.41	4.06	0.05	100

(3) The volcanic rocks of the Agate Beach Member are the most widespread and thickest in the area, making up about 82.44% of the total volume of volcanic rocks. Volcanic rocks of this member show great variations in lithology in different places of the peninsula. In general basalt and basaltic andesite are the main rock types. Andesite and dacite occur locally. From southwest to northeast there is a trend of variation from basic rocks to intermediate and intermediate-acid rocks. Andesite and dacite are mainly distributed in the north-by-east part of peninsula. The average SiO_2 contents of basalt, basaltic andesite, andesite and dacite are 50.08%, 53.13%, 60.65% and 64.84% respectively. The MgO and CaO contents are a bit lower than those of the Jasper Hill Member. The TFeO content in basaltic andesite reaches the highest value in the area.

(4) Volcanic rocks of the Fossil Hill Member account for about 2.41% of the total volume of volcanic rocks in the whole area. The rocks are basalt-andesitic to andesitic pyroclastic rocks and pyroclastic-sedimentary rocks, yielding fossil plants. They are concentratedly distributed in the eastern part of the peninsula.

(5) The volume of volcanic rocks of the Block Hill Member is slightly larger than that of the Fosssil Hill Member, representing 4.06% of the total volume of volcanic rocks in the whole area. Like the Fossil Hill Member, they are only observed in the eastern part of the peninsula. The rocks are mainly andesitic and partly basalt-andesitic and dacitic. The SiO_2 content ranges from 54 to 60%, being notably higher than that of the Agate Beach Member; the MgO, CaO and TFeO contents are relatively low.

(6) Exposed only on the southern coast of the Ardley Bay in the eastern part of the peninsula, the Long Hill Member has a very limited distribution, accounting for only 0.05% of volcanic rocks.

(7) For the same lithologic member, lavas of the main stage are more basic than

lavas or subvolcanic rocks(including volcanic necks) of the late or terminal stage. For example, the average SiO_2 content of basalt of the Jasper Hill Member is 49.99%, but that of the lavas of its last layer is 54.83% and that of the last-intruded necks is 54.63%; another example, agglomeratic lavas of the Block Hill Member contain 49.40% SiO_2, while the Shanhaiguan Peak subvolcanic body intruded into them has 58.35% SiO_2.

(8) Subvolcanic bodies (including volcanic necks) show a regular distribution in space. They are largely distributed in the NWW and NE directions, with the necks mostly occurring near the intersection points of the two directions.

A comprehensive analysis of petrology and geochemistry, as mentioned above, may lead us to the following understandings about the high-level magma chamber in the area.

(1) The main portion of magmas in the high-level magma chamber was of basaltic and basalt-andesitic compositions. It covered a wide area and had a large volume, occupying over 90% of the total volume of the magma chamber.

(2) Andesitic and dacite magmas were not able to form independent zones as they accounted for a very small proportion in the magmas chamber. Owing to marked difference in density between magmas of different composition (e.g. the density of basaltic magma is 2.79 g/cm^3 at 1200℃, that of andesitic magma is 2.45 g/cm^3 at 1100℃, that of rhyolitic magma is 2.2 g/cm^3 at 900℃), andesitic and dacitic magmas in the area could be concentrated only at a relatively high level in the magma chamber in local regions (the eastern and north-eastern parts of the area), forming zones with a limited thickness.

(3) The high-level magma chamber or magma chamber system was a system made up of a main magma chamber and several interconnected small magma chamber. The main magma chamber extended along the southwest-directed long axis and was narrow in the NW—SE direction. From its volume and distribution area, it may be deduced that the thickness of the magma chamber was smaller than its width. The chamber occurred as a plate with its top convex upwards. The top surface was uneven and domed up at the northeast end along the southwest-directed long axis; it was higher in the east than in the west in the NW—SE direction. Therefore, the ridge axis of the magma chamber lay along the line of Shanhaiguan Peak to the Suffield Point, on the eastern side of the peninsula.

5.2 The zonation in the high-level magam chamber and its formation mechanism

According to the features of the temporal and spatial distribution of volcanic rocks in different parts of the Fildes Peninsula and the results of petrological and geochemical studies, it is considered that there might be five basic zones in the high-level chamber in the area (Fig. 1).

5.2.1 Central zone

It was located in the central part of the magma chamber, occupying about 2/3 to 4/5 of the total volume of the magma chamber. Its main portion had the composition of

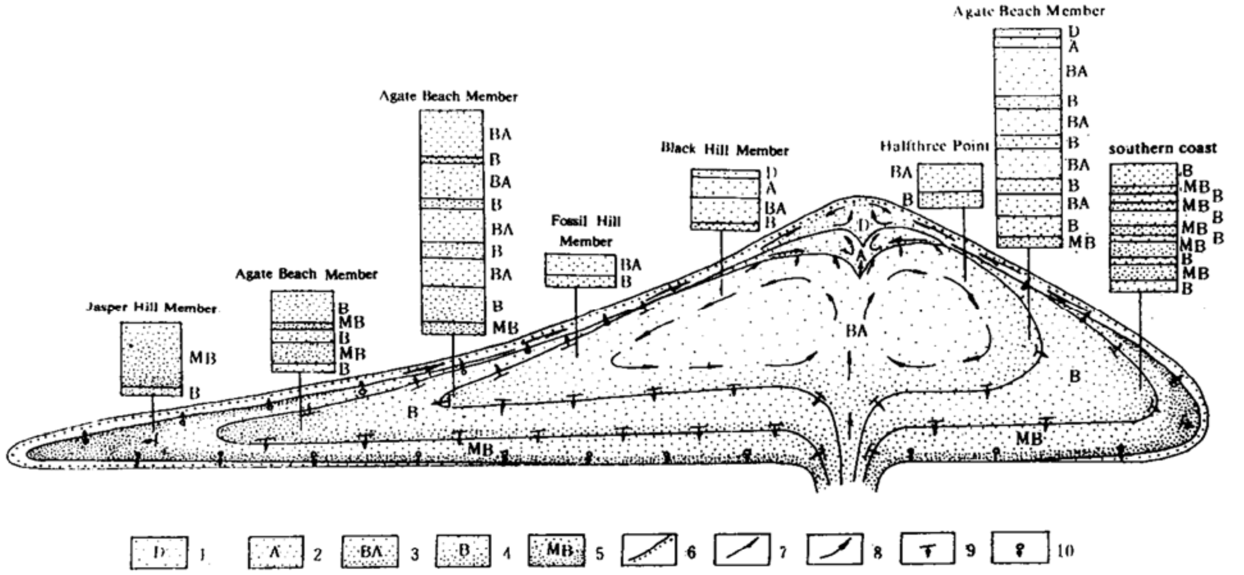

Fig. 1. Schematic model of the high-level magmatic chamber in the Fildes Peninsula.
1. dacitic magma (SiO_2=62%~66%); 2. andesitic magma (SiO_2=55%~62%); 3. basalt-andesitic magma (SiO_2 = 52%~55%); 4. basaltic magma (SiO_2 = 50%~52%); 5. picritic magma (SiO_2 = 48%~50%); 6. condensational border; 7. border circulation; 8. convective circulation; 9. thermodensity (thermogravitational) diffusion; 10. fractional crystallization. Volume percent of various magmas: dacitic and andesitic magmas~4%; basalt-andesitic and basaltic magmas~82%; picritic magma~11%.

parent magma from the deep magma chamber, with a SiO_2 content of some 52%. As the magma lay in the central part of the magma chamber, the temperature there was the highest in the magma chamber. On the edges of the central zone, the temperature was relatively low; there existed gradients of variations in temperature, density, composition and volatiles, which caused basic components in magmas to migrate from high to low temperature regions through thermodensity diffusion (or thermogravitational diffusion) and meanwhile brought about convective circulation of magmas.

5. 2. 2 Border zone

It was situated at the top and periphery of the magma chamber. As the temperature of the country rocks is lower than the magma chamber, there existed appreciable temperature and density contrasts between the border zone and central zone. Owing to the diffusion effect and convective circulation, magmas underwent liquid density and compositional differentiation and the basic components in magmas diffused towards the low-temperature borders and were concentrated there, thus forming the border zone that was more basic than the central zone. The composition of the border zone was picrobasaltic, with a SiO_2 content of about 48%~50%. Convective circulation occurring under the influences of the temperature and density gradients caused basic components to migrate down along the border zone; therefore the border zone was thin at the top of the magma chamber and became thick at the periphery of the magma chamber. The basic magma was cocentrated particularly in the pinch-out part of the magma chamber where its thickness reached a maximum.

5. 2. 3 Transition zone

The transition zone was located between the central zone and the border zone, with the SiO_2 content ranging from 50% to 52%. The formation of this zone was also related to the combined actions of liquid thermo-graviational diffusion and convection. As its density and temperature were intermediate between those of the central zone and the border zone, its composition also showed a transitional nature.

5. 2. 4 Updomed zone

This zone was located in the updomed part of the magma chamber. From the above-mentioned morphological analysis of the magma chamber, it is known that the magma chamber had a ridge-shaped swell in a NE—SW direction in the eastern part of the area. The updomed region of the ridge-shaped swell was mainly filled with andesitic and dacitic magmas. Andesitic and dacitic magmas were liquid acid differentiates in the magma chamber, with a SiO_2 content of about 55%~66%. Its formation was due to liquid thermogravitational diffusion superposed by circulation in boundary layers and vapour transport. Crystals grew from outside inwards near the cool walls of the magma chamber in the border zone. The decrease in temperature resulted in crystallization of refractory iron and magnesium minerals and basic plagioclase from basic magmas in the border zone, and the fractional crystallization in the border zone led to evolution of magma near the cool walls of the magma chamber towards acid ones and lowering of their density. Such low-density, intermediate-acid to acid melts migrated upwards along the edges to the upper part of the magma chamber concentrated in the updomed region at the top of the magma chamber, forming layered liquid phases. In the presence of abundant water and volatiles, such circulation in the boundary layers further caused part of readily molten substances such as Si, K, Na, F, Cl, LREE and LIL elements to be separated from magmas and migrated towards the top of the magma chamber.

5. 2. 5 Basal zone

In the border zone at the bottom of the magma chamber, the refractory components in the magma underwent fractional crystallization with decreasing temperature. The crystals settled down and accumulated at the bottom of the magma chamber. The fractional crystallization in the basal zone made bulk composition of the erupted magma a bit more acid than parent magma.

In summary, the high-level magma chamber in the area was a small, elongate, plate-shaped one with its top doming up. The top of the magma chamber was undulated; and in general, it was slightly higher in the east than in the west, and as far as the eastern part is concerned, the top was higher in the northern segment than in the southern segment. Before surface eruption of magmas, in the magma chamber there had already occurred magmatic differentiation dominated by liquid immiscibility accompanied by fractional crystallization, thus forming compositional zonation of derived magmas. The picrobasaltic magma was mainly distributed in the lower part on the southwestern margin of the magma chamber, the main part of the chamber was occupied by basaltic-basalt-andesitic magmas; andesitic and dacitic magmas were concentrated within the space of the updomed region at the top of the magma chamber. The zonation of magmas in the western part of the peninsula is characterized by a relatively thin basalt-andesitic zone in the upper part and a relatively thick basaltic zone in the lower part. The magma chamber in the eastern part of the peninsula domed up and had relatively complex zonation: the topmost updomed region was filled with the derived dacitic magma, below it occurred the andesitic zone, and still downwards occurred successively the basalt-andesitic and basaltic zones. Of them the dacitic zone was the thinnest, the andesitic zone was slightly thick, and the basalt-andesitic and basaltic zones were the thickest.

5. 3 The process of volcanism with relation to the regional structure

The history of volcanism in the area is closely related to the zonation in the high-level magma chamber and the regional tectonic evolution. The first phase of volcanism took place in the Paleocene. In this phase, the NE-trending faults on the western side of the peninsula were subjected to extensional stresses and magmas were erupted from the crater of Flat Top-the point of intersection between the NE-trending fault and the Mt. Flat Top-Horatio-Shanhaiguan fault, which cut the more basic border zone in the western part of the chamber. The basalt of the Jasper Hill Member was formed. As the top of the magma chamber in the western part of the peninsula was relatively low, magmas were under loading conditions and in an overheated state. so they were more basic and less viscous. The velocities of their ascent and eruption were both rapid and there was no distinct break of eruption. The amygdaloidal structure begins to appear in lavas in the upper part of the Jasper Hill Member and the volcanic rocks have higher $\delta^{18}O$—these indicate that large amount of meteoric water (ground water) has been introduced. At the early stage of the first phase (which is equivalent to the time interval when the Jasper Hill Member was deposited), only extension of basement faults in the western part caused the southwestern corner of the magma chamber to be connected with the surface, resulting in eruption of magmas. After a not too long time intermission and energy accumulation, especially infiltration of ground water into the magma chamber, the vapour pressure in the magma chamber exceeded the critical point and thus magmas were erupted again, forming volcanic rocks of the Agate Beach Member. This eruption started from Flat Top and Horatio Stump to its east in the southwestern part of the peninsula. At the early stage, explosion predominated, forming agglomerate lavas and breccia lavas. Afterwards the extension of the NE-ternding basement faults shifted gradually eastwards. The faults cut the transition zone and central zone, and several eruption centres were formed at the sites of their intersection with the NWW-trending faluts. Therefore the eruption occurred throughout the area. As magmas were derived from the transition and central zones of the magma chamber, their SiO_2 content ranges from 50% to 55%. A large amount of ground water was introduced into the overheated magmas, so eruption was strong. This eruption was the largest in scale in the area, giving rise to a series of basaltic and basalt-andesitic amygdaloidal lavas. At the late stage of this eruption, when the extension of the basement fractures shifted to the domed ridge in the eastern part of the magma chamber, the faults cut the updomed region in the east-by-north part of the magma chamber and then andesitic and dacitic magmas in the updomed region ascended along the faluts, thus forming andesite and dacite with SiO_2 content of 57%～66% in the northeastern part of the peninsula. The first phase of magmatism was the main phase of eruption. The total amount of eruptive materials in this phase makes up 92% of the volcanic rocks of the whole area. The eruptive materials consist mainly of basaltic and basalt-andesitic lavas. At the early stage there occurred explosive clastic lavas, while at the late stage occurred andesitic and dacitic rocks. The sequence of eruption and lithologys of extrusive rocks were closely related to the zonation in the magma chamber and variation in the regional stress field.

There was a relatively long intermission of eruption between the end of the first phase and the begining of the second phase in the area. During this intermission, volcanic rocks of the Agate Beach Member formed on the surface in the first phase were subjected to weathering and erosion, forming a "red top" and meanwhile the whole area was elevated together. The velocity of elevation was higher in the southwestern part than in the northeastern part, resulting in appearance of a low-angle volcanic unconformity between volcanic rocks of the this phase and volcanic rocks formed later in the second phase. During this long intermission differentiation of residual magmas progressed in the high-level magma chamber. As a very large amount of materials had been erupted in the first phase, the volume of the magma chamber was reduced greatly and differentiation proceeded more thoroughly. In the ridge region of the magma chamber, particularly in the updomed region, the composition of magmas was mainly andesitic and dacitic, containing more H_2O, volatiles and LIL elements. At the beginning of eruption in the second phase, there occurred extension of NE-trending faults in the eastern part of the peninsula, and magmas were erupted along conduits at several intersections between them and NWW-trending faults. The eruption at the early stage still showed the feature of strong explosion, generally producing pyroclastic rocks, such as fine breccias and tuffs, and in the case of introduction of terrigenous detritus, pyroclastic rocks and pyroclastic-sedimentary rocks of the Fossil Hill Member were formed. Afterwards, what were erupted were basalt-andesitic and andesitic magmas of the Block Hill Member, which had a slightly higher SiO_2 content than magmas in the first phase owing to a high degree of magmatic differentiation and had a relatively high viscosity as well owing to a high degree of crystallization in the magma chamber and conduits, so breccia lavas increased in the Block Hill Member. Basic lavas of the Long Hill Member might be derived from the border zone or transition zone at the eastern tip of the magma chamber, so their composition is more basic. But by that time the magma chamber had already shrunk greatly and the volume of erupted magmas had also been very small; then magmatic activity approached an end.

During the last phase of magmatic activity, the volume of the magma chamber was reduced continuously with eruption of voluminous magmas and residual magmas became too limited to produce an additional eruption. Under regional tectonic stresses, magmas in different zones of liquid immiscibility were injected into fissure system of the covers to form subvolcanic bodies, such as dykes and apophyses.

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