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Provenance of the Lower Cretaceous President Beaches Formation, Livingston Island, South Shetland Islands, West Antarctica

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ABSTRACT. Medium to coarse-grained sandstones of the Lower Cretaceous President Beaches Formation in the Byers Peninsula, Livingston Island, were studied to infer the lithology and tectonic settings of the source areas. In terms of major framework constituents (quartz, feldspar and rock fragment), the President Beaches sandstones range from feldspathic litharenite to litharenite. Sandstone detrital mode in various ternary diagrams indicates that the provenance of the President Beaches Formation is a magmatic arc setting. Characteristics of textural modes of monocrystalline quartz and volcanic lithic fragments indicate that the volcanic activity in the source area, probably the Antarctic Peninsula region, was active during or just before the deposition of the President Beaches Formation.

Key Words: President Beaches Formation, Byers Peninsula, sandstone, provenance, magmatic arc

Introduction

Composition of sandstone largely depends on the tectonic setting, lithology of the source rocks, sediment transport process, intensity of weathering, depositional environments and diagenesis (Johnsson and Basu, 1993). Among them, tectonic setting and lithology of the source area are the most important factors to define the composition of sandstone. Many workers have unravelled the relationship between sandstone petrography and tectonic setting using various petrological and geochemical methods (e.g., Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Cox and Lowe, 1996). Especially, provenance studies of active margin sedimentary sequences such as the Antarctic Peninsula region have been used to reconstruct the evolution of the associated magmatic arc (e.g., Garzanti, 1985; Dorsey, 1988; Marsaglia and Ingersoll, 1992).

The aim of this study is to unravel the tectonic setting of the President Beaches Formation distributed in the Livingston Island using petrological natures of sandstones and pebbly sandstones. The Antarctic Peninsula represents the eroded roots of a Mesozoic to Cenozoic magmatic arc developed in response to eastward subduction of proto-Pacific oceanic lithosphere beneath the continental margin of Gondwana (Thomson *et al.*, 1983). Fore-arc basin was developed northwestward of the Antarctic Peninsula where the Livingston Island located (Fig. 1). The President Beaches Formation is a sedimentary sequence developed in fore-arc basin, and mostly composed of parallel laminated, dark gray mudstone. The 15 to 100 cm thick sandstone beds used in this study are mainly confined to lenticular sand-rich packages which form less than 10% of the total outcrop of the President Beaches Formation.

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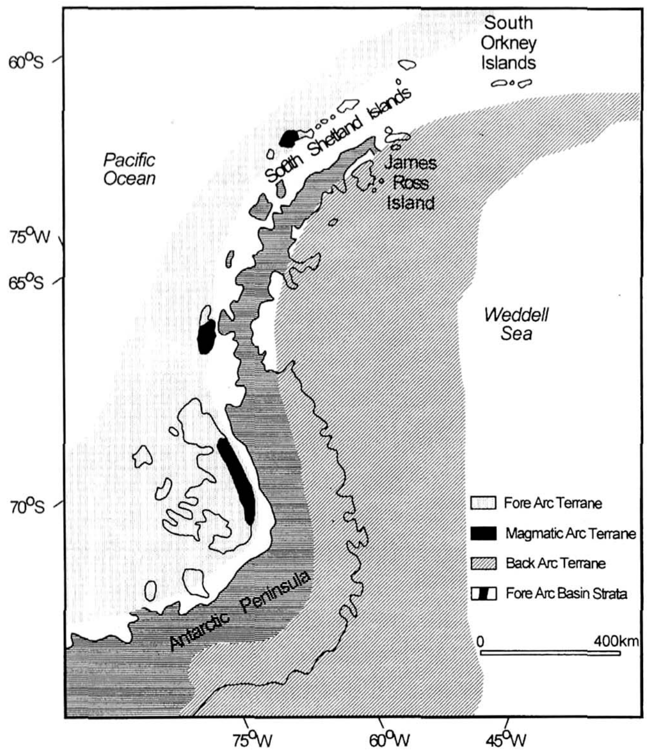

Fig. 1. Paleogeographic map of the Antarctic Peninsula showing lithotectonic units of Middle Jurassic to Early Cretaceous age (adopted from Elliot, 1983).

Geologic Setting

The Byers Peninsula, Livingston Island comprises thick Mesozoic sedimentary sequence (Byers Group) and volumetrically important intrusive igneous materials (Fig. 2). The Byers Group is composed of 1 to 1.5 km of marine sedimentary rocks unconformably overlain by a similar thickness of nonmarine volcaniclastic strata (Hathway and Lomas, 1998; Lomas, 1999; Fig. 3). The Byers Group is divided into five formations and their vertical alignment represents regressive megasequence. Emergence and expansion of the arc in the Antarctic Peninsula region was accompanied on its outboard margin (essentially 'fore-arc') by a discontinuous transition from deep water pelagic/hemipelagic sedimentation (Anchorage Formation) through deep slope apron (President Beaches Formation) and shallow marine systems (Start Hill and Chester Cone formations) into alluvial and lacustrine volcaniclastic deposition (Cerro Negro Formation) (Hathway and Lomas, 1998; Hathway, 1997).

The President Beaches Formation conformably overlies the lower Anchorage Formation and is unconformably overlain by the Start Hill and Chester Cone formations (Fig. 3). The formation is at least 600 m thick, but poor exposure and widespread deformation make it difficult to estimate its precise thickness. The President Beaches Formation mostly comprises parallel laminated, dark gray mudstone with subordinate sandstone bodies mantled surrounding mudstones. The President Beaches Formation is generally interpreted to be deposited in the Early Cretaceous (Berriasian) (Smellie *et al.*, 1980; Crame *et al.*, 1993; Askin, 1983; Duane, 1994), and restricted to mid-Berriasian to latest Berriasian by detailed study of dinoflagellate cyst assemblage (Duane, 1996). Predominance of mudstone indicates that the President Beaches Formation is deposited on a marine slope apron (Hathway and Lomas, 1998). The limited infauna in the mudstone suggests a relatively inhospitable (generally dysaerobic) seafloor environment. Subordinate sandstones were deposited from low- and high-concentration turbidity currents, mainly confined to submarine channels (Hathway and Lomas, 1998; Lomas, 1999). Choe and Rhee (1999) divided these sandstone bodies into two groups, typical turbidite and reworked turbidite. The former is interpreted as fills of shallow chute or channel, whereas the latter was deposited more basinward and reworked in its upper unit (Choe and Rhee, 1999).

Materials and Methods

39 sandstone and mudstone samples were collected from six areas where sandstone bodies are well developed (Fig. 2), and thin sections were made perpendicular to bedding. Among them, 18 medium- to coarse-grained sandstone samples were analyzed to minimize the effect of grain size on sandstone compositon. Average over five hundred points were counted in each thin section where the spacing between points was set larger than the maximum grain size in modal analysis. Gazzi-Dickinson method was adopted. For lithic fragment identifica-

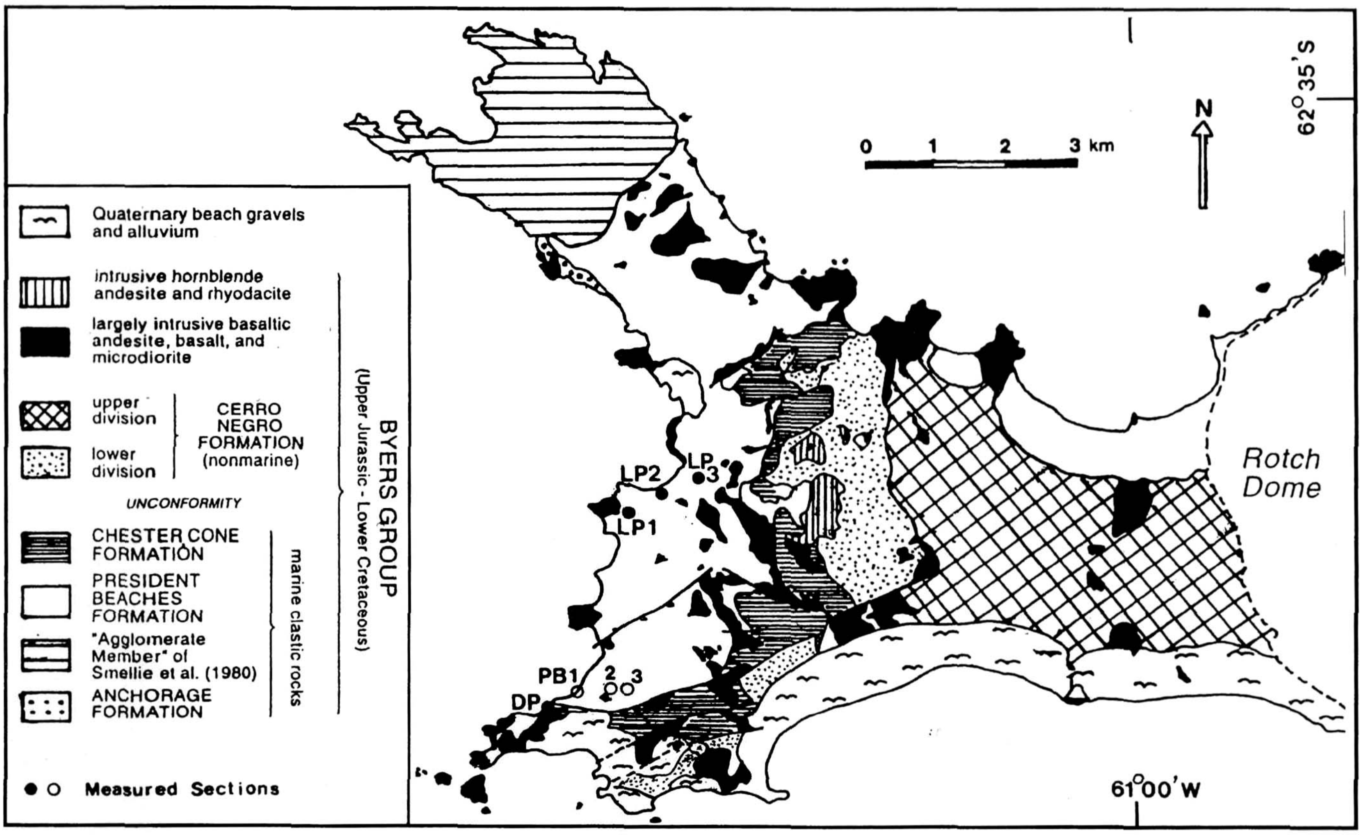

Fig. 2. Geologic map of the Byers Group distributed in the Byers Peninsula. Sampling sites of the President Beaches Formation are also shown.

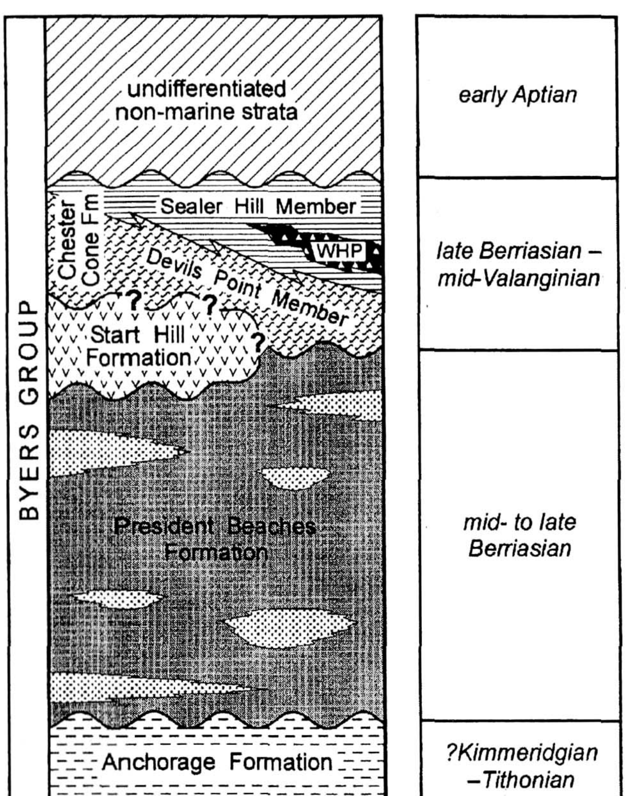

Fig. 3. Lithostratigraphy of the Byers Group (adopted from Lomas, 1999).

tion, the objective criteria of Dorsey (1988) were applied in this study. Feldspars were stained according to the method of Houghton (1988).

Detrital Mode of the President Beaches Sandstone

Table 1 displays recalculated point-counting parameters and Table 2 shows the recalculated point-counting data of the President Beaches sandstone. The main framework grains of the President Beaches sandstone are volcanic lithic fragments, feldspar and quartz with subordinate mica, chlorite and heavy minerals. Calcite and chlorite cements and clay matrix fill the interstices between the framework grains (Fig. 4). Framework grains are poorly sorted. The amount of cement ranges 0 to 15.8%, with an average of 7.5%. Matrix is 0 to 27.8%, with an average of 7.9%.

Table 1. Definitions of grain parameters (adopted from Dorsey, 1988)

Qt-F-L	Qt = Qm + Qp, where: Qt = total quartz grain Qm = monocrystalline quartz Qp = polycrystalline quartz
	F = P + K, where: F = total feldspar grains P = plagioclase K = potassium feldspar
	L = Lv + Ls + Lm, where: L = total litic fragments Lv = total volcanic lithic fragments Ls = total sedimentary lithic fragments Lm = total metamorphic lithic fragments
Qm-F-Lt	Qm = monocrystalline quartz F = total feldspar grains Lt = total lithic fragments + polycrystalline quartz
Qp-Lvm-Lsm	Qp = polycrystalline quartz Lvm = total volcanic and metavolcanic lithic fragments Lsm = total sedimentary and metasedimentary lithic fragments
Qm-P-K	Qm = monocrystalline quartz P = plagioclase K = potassium feldspar

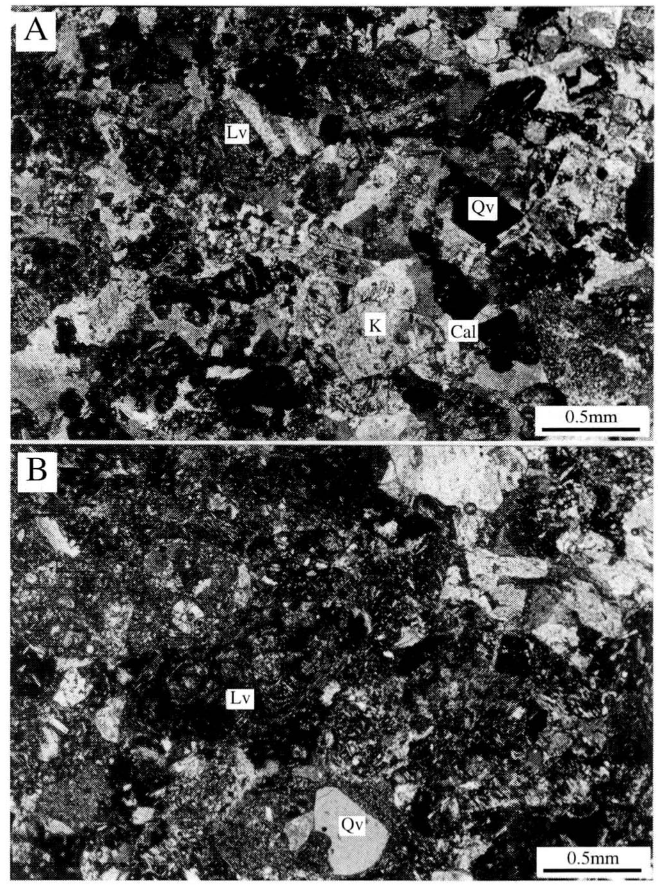

Fig. 4. Photomicrographs of the President Beaches sandstones. Crossed nicol. Volcanic lithic fragments (Lv) are dominant and calcite cement (Cal) occupied the spaces between detrital grains. (A) Euhedral volcanogenic quartz (Qv) shows straight crystal boundary and K-feldspar (K) is partially replaced by calcite. (B) Euhedral volcanogenic quartz (Qv) represents embayed texture and volcanic lithic fragments (Lv) shows perlitic fractures.

Quartz

Quartz comprises between 2 and 12.4% (average 5.6%) of the framework composition (Table 2). In quartz population, the ratio of monocrystalline quartz is larger than that of polycrystalline quartz. Polycrystalline quartz displays better rounded feature than monocrystalline quartz and is categorized as fragment that contains more than two crystals per unit. Quartz grains commonly display straight boundaries with curved edge and clear under microscope without inclusions (Fig. 4A). Some quartz grains show embayed features (Fig. 4B).

Feldspar

Feldspar content of the President Beaches sandstone range from 5.2 to 23.6%, with an average of 16.7%. Plagioclase is predominant (average 91.6%) over potassium feldspar (less than 10%). Plagioclase grains are largely replaced by calcite and chlorite (Fig. 5). Some plagioclase grains are completely replaced by secondary minerals and the primary component can be deduced by its shape. Some plagioclase grains have albite overgrowth which is also replaced by calcite or chlorite in various amounts (Fig. 5). This feature indicates that replacement of secondary minerals prolonged during entire diagenesis of the President Beaches Formation.

Lithic Fragment

Lithic fragment is a predominant component of the President Beaches sandstone, which ranges from 53 to 80.8% with an average of 62.3%. It is largely composed of volcanic lithic fragments with small amount (less than 2%) of sedimentary lithic frag-

Table 2. Modal point-count data for the President Beaches Formation sandstones

Sample No.	Quartz			Feldspar			Rock fragment			Cement			Matrix
	Qm	Qp	Qt	K	P	F	Lv	Ls	L	chlorite	calcite	total	
PB 29	1.2	0.8	2.0	0.0	5.2	5.2	80.8	0.0	80.8	0.0	12.0	12.0	0.0
PB 01-1	2.4	0.6	3.0	1.2	12.4	13.6	74.4	0.8	75.2	0.0	8.2	8.2	0.0
PB 01-2	3.2	0.0	3.2	0.6	11.4	12.0	65.4	1.6	67.0	0.0	1.6	1.6	16.2
PB 01-4	1.8	1.2	3.0	0.0	15.8	15.8	63.2	0.0	63.2	0.0	15.8	15.8	2.2
PB 02-1	3.4	0.8	4.2	4.2	13.8	18.0	64.2	0.0	64.2	2.6	7.6	10.2	3.4
PB 02-2	6.8	1.6	8.4	0.8	18.6	19.4	60.8	0.0	60.8	0.4	4.8	5.2	6.2
PB 02-3	2.4	1.0	3.4	1.0	14.8	15.8	53.0	0.0	53.0	0.0	0.0	0.0	27.8
PB 02-4	3.6	2.4	6.0	2.4	13.4	15.8	57.4	0.8	58.2	0.0	9.2	9.2	10.8
PB 02-5	4.8	1.4	6.2	1.0	22.6	23.6	53.8	0.0	53.8	3.6	0.0	3.6	12.8
PB 02-7	2.2	0.8	3.0	1.6	17.2	18.8	62.2	0.0	62.2	2.2	7.4	9.6	6.4
PB 02-8	4.2	0.6	4.8	0.8	16.8	17.6	57.0	0.0	57.0	0.4	9.2	9.6	11.0
PB 02-10	8.2	4.2	12.4	2.2	14.4	16.6	66.6	0.6	67.2	0.0	3.6	3.6	0.2
PB 02-12	5.6	1.6	7.2	1.4	20.0	21.4	58.8	0.0	58.8	0.0	10.4	10.4	2.2
PB 02-13	4.4	0.6	5.0	0.6	12.8	13.4	59.6	0.0	59.6	0.6	6.8	7.4	14.6
PB 02-15	4.0	0.8	4.8	1.6	19.4	21.0	62.4	0.0	62.4	1.6	0.0	1.6	10.2
DS 01-1	5.4	2.8	8.2	2.2	16.4	18.6	60.0	0.8	60.8	1.2	4.8	6.0	6.4
DS 01-2	8.2	3.2	11.4	0.8	18.2	19.0	53.4	1.2	54.6	0.0	12.2	12.2	2.8
DS 01-3	2.6	1.4	4.0	1.6	12.8	14.4	62.8	0.4	63.2	0.6	8.8	9.4	9.0

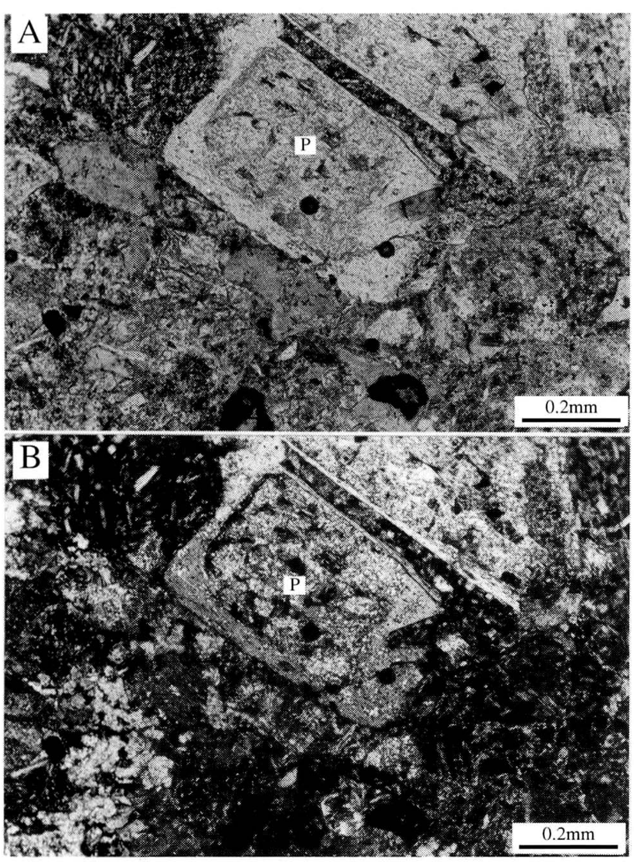

Fig. 5. Photomicrographs of the President Beaches sandstone showing plagioclase. Detrital plagioclase (P) was partially replaced by chlorite and authigenic albite overgrowth developed around detrital plagioclase grain. All other grains are volcanic lithic fragments. (A) Opened nicol (B) Crossed nicol

ments. Volcanic lithic fragment comprises ferromagnesian minerals, feldspar laths and volcanic glass matrix (Fig. 6A). Most of the volcanic lithic fragments are fresh but some are replaced by chlorite, zeolite and calcite. Some volcanic lithic fragments display perlitic and amygdale textures. Perlitic cracks develop in response to hydration of the glass and show arcuate and gently curved shapes (Fig. 6B). The amygdales are infilled with chlorite and calcite.

Provenance analysis

Among the main framework components, lithic fragment is a predominant component in all sandstones (Table 2). All sandstones, except one sample, are arenite and belong to feldspathic litharenite to litharenite field in the Folk' s sandstone classification scheme (Fig. 7).

For identifying the tectonic setting of source area of the President Beaches Formation, recalculated point-counting data of sandstone are plotted on various ternary diagrams defined by Dickinson et al. (1983) and Dickinson (1985) (Fig. 8). The results of

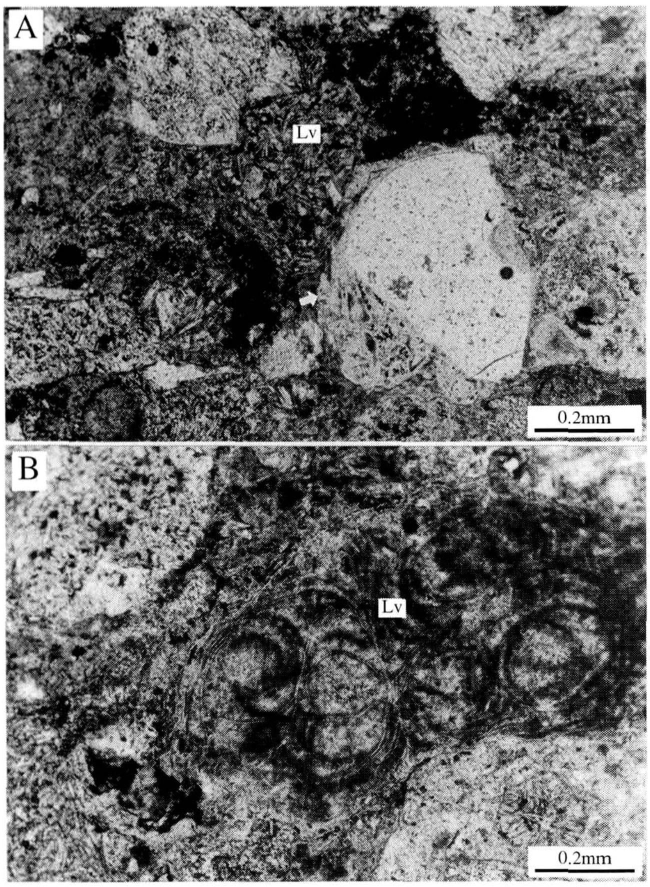

Fig. 6. Photomicrographs of the President Beaches sandstone represent characteristic volcanic lithic fragments. Opened nicol. (A) Volcanic lithic fragment (Lv) consists of plagioclase laths set in an altered groundmass. Large monocrystalline quartz is included in volcanic lithic fragment (arrow). (B) Volcanic lithic fragment (Lv) showing typical perlitic fractures commonly developed in volcanic rocks.

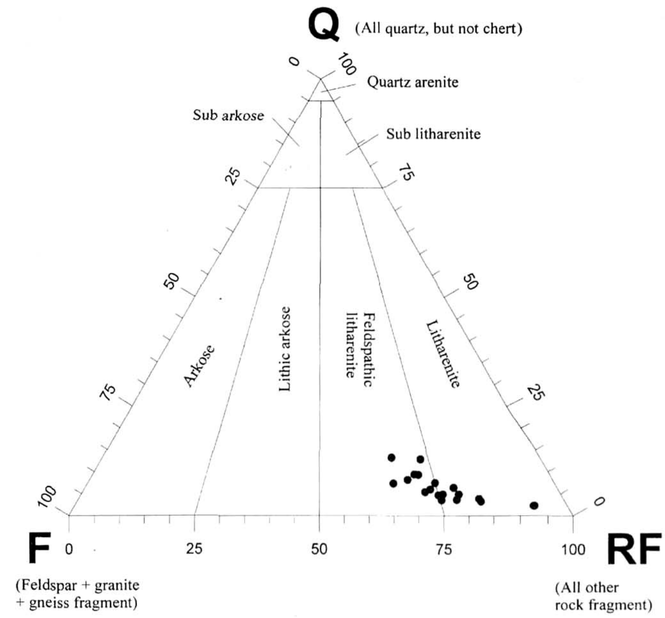

Fig. 7. Classification of the President Beaches sandstones after Folk (1974). Classification involves the removal of matrix, cement, micas etc., and recalculation of components to 100%.

plotting on Qt-F-L and Qm-F-Lt diagrams indicate that the President Beaches sandstone was derived from magmatic arc region (Figs. 8A and B). The main characteristics of sedimentary sequence derived from magmatic arc developed parallel to subduction zone is existence of significant amount of volcanic lithic fragments. Prolonged weathering of magmatic arc leads to exposure of plutonic basement to the surface and causes increasing of feldspar and quartz in sedimentary sequence. Predominance of volcanic lithic fragments and small amount of feldspar in the President Beaches sandstone represent that volcanic event in the source area was active during or just before the deposition of the President Beaches Formation. Petrographic natures of monocrystalline quartz and well preserved volcanic textures in volcanic lithic fragments also support this interpretation. On the Qp-Lvm-Lsm diagram (Fig. 8C), the President Beaches sandstone also plotted on the arc orogen field. The Qm-P-K diagram (Fig. 8D) shows only partial grain populations, but reveals the character of the monocrystalline components of the framework which mainly reflects degree of weathering in source area. Using Qm-P-K parameters, Dickinson and Suczek (1979) defined a curve becoming more quartz-rich with increasing ratio of plutonic to volcanic components in magmatic arc provenance. Point-counting data of the President Beaches sandstone plotted on the field where plagioclase is dominant over other components (Fig. 8D). This feature indicates the President Beaches Formation has been deposited before the plutonic basement was exposed in magmatic arc region.

Other sedimentological studies of the President Beaches Formation represent the sedimentary sequence has been derived from the source south- to southeastward of the Livingston Island (Lomas, 1999). Age data from the magmatic arc distributed in the Antarctic Peninsula, southeast of the Livingston Island, display that there were Late Triassic-Early Jurassic (236-199 Ma), Mid-Jurassic (180-160 Ma), and Early and Late Cretaceous mag-

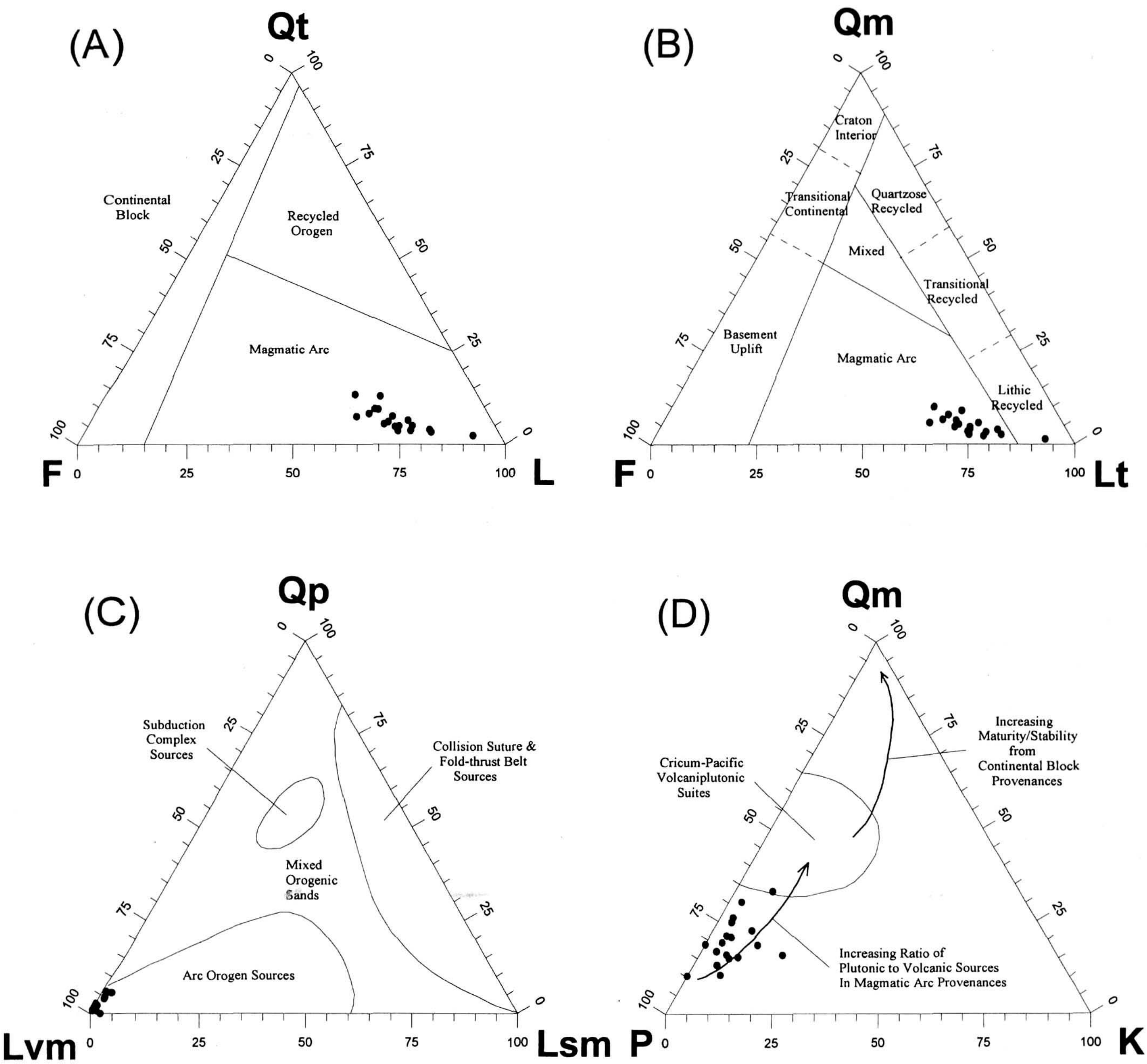

Fig. 8. Detrital modes of the President Beaches sandstones are plotted on various ternary diagrams. (A) Qt-F-L (B) Qm-F-Lt (C) Qp-Lvm-Lsm (D) Qm-P-K. Provenance fields of Qt-F-L plots are after Dickinson et al. (1983) and others are after Dickinson (1985).

matic episodes (Pankhurst, 1982, 1990; Storey *et al.*, 1992). Geochemical evidence of active volcanic episode in the Antarctic Peninsula during the deposition of the President Beaches Formation is consistent with the petrographic natures of sandstone. Existence of relatively thick tuff layers in the President Beaches Formation also indicates active volcanism in the source area.

Summary

1. The President Beaches sandstone is interpreted as submarine channel deposits derived from the Antarctic Peninsula region southeastward of the Livingston Island by turbidity current.

2. The President Beaches sandstones range from feldspathic litharenite to litharenite. Detrital mode of sandstone indicates the source area of the

President Beaches Formation was in a magmatic arc setting.

3. Characteristics of textural modes of monocrystalline quartz and volcanic lithic fragment represent the volcanic activity in source area was active during or just before the deposition of the President Beaches Formation.

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