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Article

Geomorphology and Volcaniclastic Deposits around Dokdo: Dokdo Caldera

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Abstract : Detailed investigations on both submarine and subaerial volcaniclastic deposits around Dokdo were carried out to identify geomorphologic characteristics, stratigraphy, and associated depositional processes of Dokdo caldera. Dokdo volcano has a gently sloping summit (about 11 km in diameter) and relatively steep slope (basal diameter is about 20-25 km) rising above sea level at about 2,270 m. We found ragged, elliptical-form of Dokdo caldera with a diameter of about 2 km estimated by Chirp (3-11 kHz) sub-bottom profile data and side scan sonar data for the central summit area of Dokdo volcano. We interpreted that the volcaniclastic deposits of Dokdo unconformably consist of the Seodo (west islet) and the Dongdo (east islet) formations based on internal structure, constituent mineral composition, and bedding morphology. The Seodo Formation mainly consisted of massive or inversely graded trachytic breccias (Unit S-I), overlain by fine-grained tuff (Unit S-II), which is probably supplied by mass-wasting processes resulting from Dokdo caldera collapse. The Dongdo Formation consists of alternated units of stratified lapilli tuff and inversely graded basaltic breccia (Unit D-I, Unit D-III, and Unit D-V), and massive to undulatory-bedded basaltic tuff breccias (Unit D-II and Unit D-IV) formed by a repetitive pyroclastic surge and reworking processes. Although, two islets of Dokdo are geographically near each other, they have different formations reflecting their different depositional processes and eruptive stages.

Key words : Dokdo, Dokdo caldera, mass-wasting processes, pyroclastic surge.

1. Introduction

Dok Island or Dokdo is one of the alkaline volcanoes such as Ulleungdo, Chejudo, Mt. Paekdu, Chugaryong Rift valley, Kilju-Myoncheong Graben, and some northeastern volcanoes in China (Min *et al.*, 1988; Won and Lee, 1988; Kim *et al.*, 1998), but until recently little is known about its geomorphologic characteristics and associated depositional processes. Geochemical characteristics of volcanic rocks (Kim *et al.*, 1987; Min *et al.*, 1988; Won and Kim, 1988; Kim, 2000), eruption ages (Sohn and Park, 1994; Kim, 2000), stratigraphy (Kim *et al.*, 1987; Sohn and Park, 1994), and gravity as well as magnetic data (Han *et al.*, 1997; Kim *et al.*, 2000) have been obtained from Dokdo studies. However the caldera formation and associated depositional processes are still poorly known. Sohn and Park (1994) have suggested that Dokdo was described to be remnants of the crater rim, but actual evidences did not confirm the suggest. In 1999, a research group from the Korea Ocean Research and Development Institute (KORDI) investigated the depositional processes of volcaniclastic deposits, and carried out deep and shallow seismic explorations, multibeam data acquisition (SeaBeam 2000), and gravity and magnetic surveys around Dokdo. Paleomagnetism and geochemical characteristics of volcanic rocks on and around Dokdo were also studied to get more synthetic information about the Dokdo volcano and adjacent two seamounts (Kim, 2000). The work has focused on the existence of Dokdo caldera and associated depositional processes.

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In this paper, we present the detailed stratigraphy and depositional processes of submarine and subaerial volcaniclastic deposits on and around Dokdo. We also identify the caldera of Dokdo volcano on the basis of submarine observations of the Chirp subbottom profile data and side scan sonar data.

2. Methods and data

Data for this study were obtained from the submarine summit of Dokdo volcano and subaerial outcrops on Dokdo. We described the texture, sedimentary structure, mineral composition, thickness, and lateral stratigraphic continuity of volcaniclastic deposits on Dokdo in 2000. The Seodo Formation has been recognized in west islet, which consists of two sedimentary units (Unit S-I and Unit S-II), and the Dongdo Formation in the east islet is divided into five sedimentary units (Unit D-I, Unit D-II, Unit D-III, Unit D-IV, and Unit D-V) reflecting their different depositional processes and eruptive ages.

Seafloor morphology and subbottom profile data were acquired with a Chirp subbottom profile system (CAP6000W; DataSonics Co.) and side scan sonar system (SMS260; EG&G Co.) of the R/V Eardo in 1999. Side scan sonar data from the northeastern part of Dokdo which were used to prove lateral continuity of volcanic successions (Fig. 1B). Chirp subbottom profile data were obtained following a NE-SW trending survey track to interpret the morphology of summit area of the Dokdo volcano (Fig. 1B). We have also observed more than 100 photographs of the volcaniclastic deposits around Dokdo.

3. Geological setting and stratigraphy

Alkaline volcanic islands of the East Sea (Sea of Japan), Dokdo and Ulleungdo, are located at boundaries between the Ulleung Basin and topographic highs such as the Oki Bank and the Korea Plateau (Fig. 1A). Interpretation of ocean bottom seismometer data (Kim *et al.*, 1998) and gravity data (Han *et al.*, 1997; Kim *et al.*, 2000) has suggested that Dokdo and Ulleungdo are resulted from uprising mantle plume (S'edin and Sato, 1996) at a border between oceanic and continental crusts.

Dokdo is a part of seamount chain which consists of three seamounts trending NW-SE and lies at the northernmost seamount (Kim *et al.*, 2000). Previous studies during the past decade have been carried out on the stratigraphy and classification of volcanic rocks (Kim *et al.*, 1987; Sohn and Park, 1994). Little is fully known of their stratigraphy and eruption age due to limited data (Kim *et al.*, 1987; Sohn and Park, 1994; Kim, 2000).

Kim *et al.* (1987) revealed that Dokdo was simply composed of lower trachybasaltic agglomerates and upper trachyandesites or trachyte lava flows, and pyroclastic air fall layers. Detailed stratigraphic descriptions of Dokdo have been reported by Sohn and Park (1994). They suggested that stratigraphic records from Dokdo indicate that the islands are comprised of subaqueous stage (Trachyte I), Surtseyan eruptive stage (Unit P-I), Taalian eruptive stage (Unit P-II) and subaerial stage (Unit P-III,

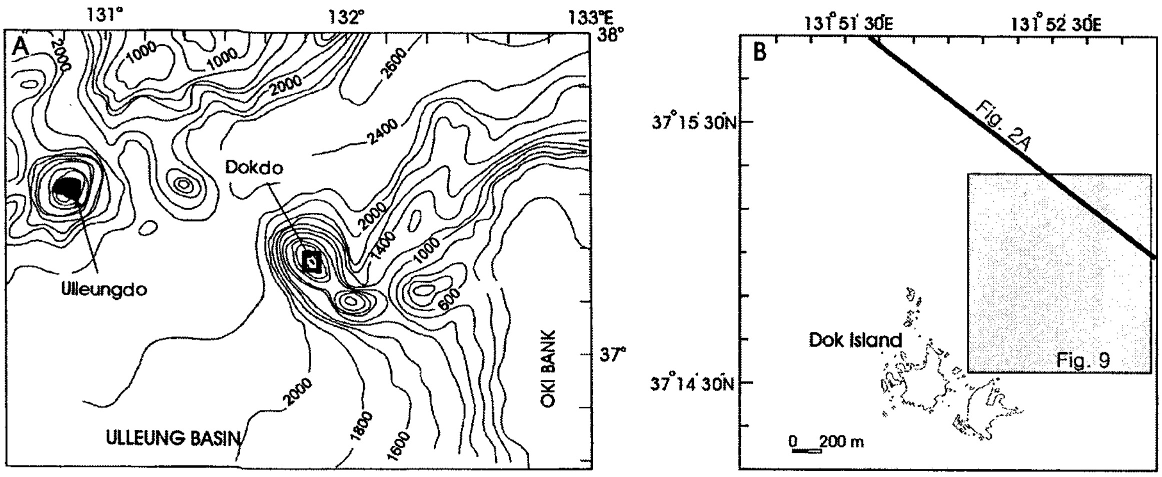

Fig. 1. (A) Location map of Dokdo nearby eastern margin of the Ulleung Basin. Contours in meters. (B) Shade box indicates the area of side scan sonar survey. The thick line represents the track of Chirp (3-11 kHz) subbottom profile data.

Table 1. Stratigraphy and eruption ages of volcanic rocks from Dokdo and Ulleungdo.

Age	Ma	Dokdo		Ulleungdo
		Sohn and Park (1974)	This study	Kim *et al.* (1999)
H				
0.01				Stage 5 Stage 4
	0.5			Stage 3
Pleistocene				Stage 2
	1.0			
				Stage 1
	1.5			
1.64				
	2.0			
		Trachyte dyke	Trachyte dyke	
Piiocene	2.5	Trachyte III --Intrusion--	Trachyte III --Intrusion--	
		Trachyte II Unit P-III Trachyandesite	Trachyte II Trachyandesity	
		Unit P-II(basalt clast: ca.4.6 Ma) Unit P-I ~~Unconformity~~ Trachyte I	Dongdo Formation ~~Unconformity~~ Seodo Formation ~~Unconformity~~ Trachyte I	

Trachyandesite, Trachyte II, Trachyte III and dikes). The basal part of Dokdo is supposed to consist of Trachyte I which has its only exposure along southeastern coastal cliffs on the west islet (Sohn and Park, 1994). K-Ar dating of Trachyte II and Trachyandesite gives an age of ca. 2.7 Ma and that of Trachyte III is ca. 2.5 Ma (Sohn and Park, 1994). Kim (2000) recently reported that K-Ar ages of Trachyte II range from 2.28 to 2.42 Ma. These results suggest that the basal volcanic rocks of Ulleungdo (1.37-0.97 Ma; Kim *et al.*, 1999) are younger than those of Dokdo by about 1 Ma (Table 1). In this study, we considered that eruptive units (Units S-I, S-II, D-I, D-II, D-III, D-IV, D-V) to be the deposits of different eruptive ages and depositional processes on the basis of bedding morphology, internal structure, and constituent mineral compositions. The results showed that two islets are geographically near each other, but eruptive units (Unit S and Unit D) are quite different reflecting their different depositional processes and eruptive ages.

4. Results

Geomorphologic characteristics of submarine topography

Detailed analyses of high frequency Chirp (3-11 kHz) subbottom profiling data from the summit of Dokdo

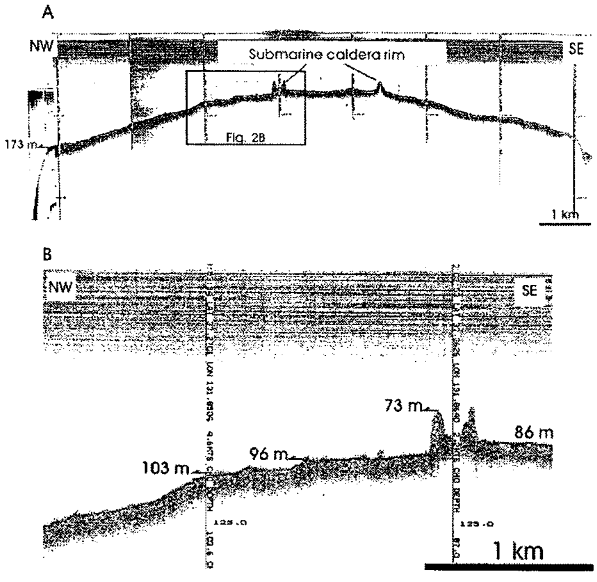

Fig. 2. Chirp subbottom profile data of summit area in Dokdo volcano showing broad, gently sloping, and convex-formed submarine geomorphology. (A) The several submarine volcanic successions observed on the central summit. (B) The submarine topography between two subaqueous volcanic successions is higher about 10 m than that of outside (for location see Fig. 1B).

volcano identified submarine volcanic successions and seafloor morphology around Dokdo. The summit of Dokdo volcano showed a strong reflector, and the internal structures below the reflector are not discernible (Fig. 2). The summit is broad and gently sloping, and is about 11 km in diameter and extends to about 173 m in depth below sea level (Fig. 2A). The summit has the steep flanks (Fig. 2B). Subaqueous volcanic successions occur at about 86-96 m depth (Fig. 2B). The submarine topography between two subaqueous volcanic successions is higher (about 10 m deep) than that of outside. A relatively flat seafloor, similar to a wave-cut-platform, lies 96 m and 103 m in depth.

The morphological feature of the Ulleungdo (Chun, 2000) and Dokdo volcanoes are very similar below sea-level. Ulleungdo and Dokdo volcanoes have nearly a basal diameter of 20 to 25 km and height of about 2,100 m below sea level. However subaerial sections of the two islands are quite different (Fig. 3). The subaerial part of Dokdo volcano (Dokdo) is rising 168 m above sea level on the west islet (National Geographic Institute, 1981) whereas that of Ulleungdo is rising 983 m above sea level (Chun, 2000). Subaerial sections of Ulleungdo mainly consist of trachytic domes like a major volcanic mass such

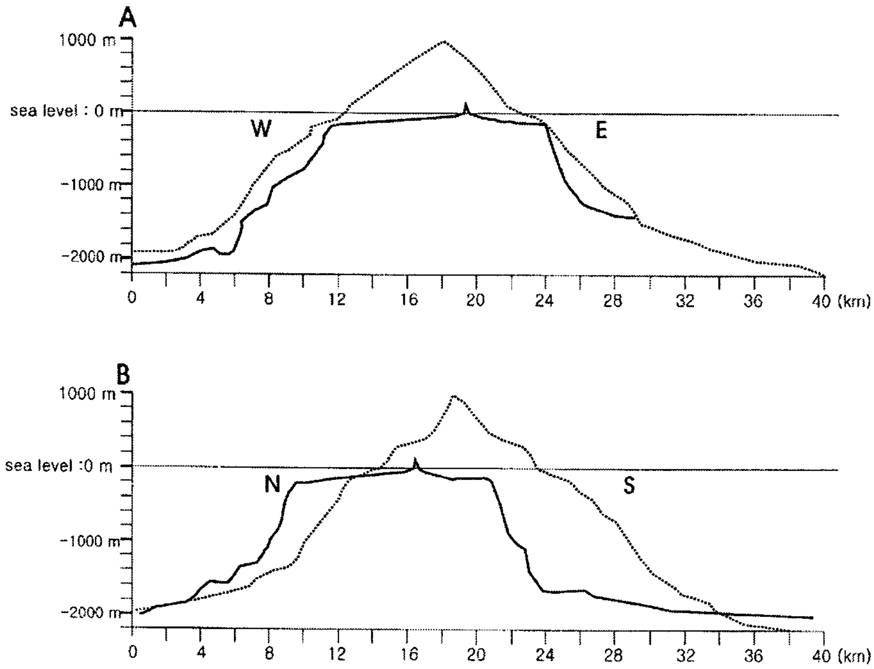

Fig. 3. The cross-sections showing topography in Dokdo and Ulleung volcanoes with the E-W (A) and N-S (B) trends. Dokdo volcano represents thick solid line, which has broad and gently sloping summit. The subaerial part of summit, as Dokdo consists of a very small volume, whereas that of Ulleung Island (dot line) relatively forms a lot of volume.

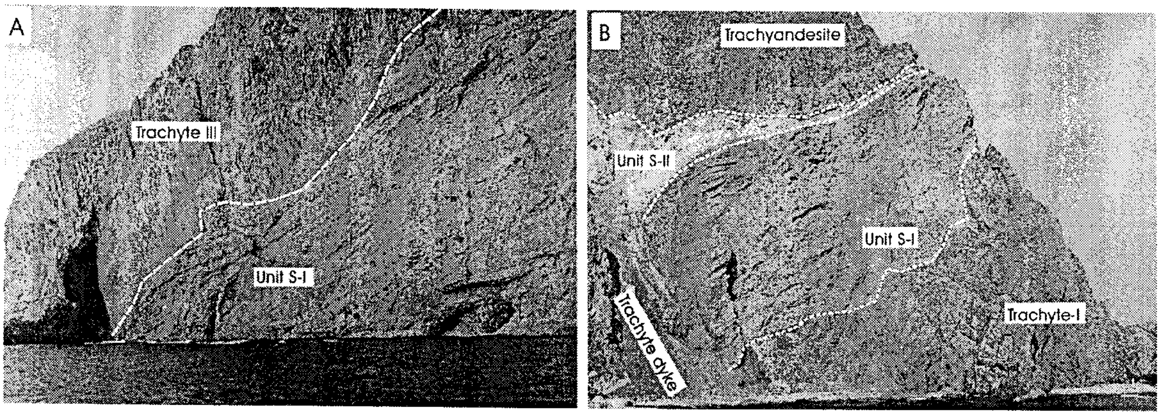

Fig. 4. The Seodo Formation was deposited between the Trachyte I (A) and Trachyte III or Trachyandesite (B) on west islet. This is divided into two units: Unit S-I consists of inclined massive or inversely graded trachytic breccias, which unconformably overlay parallel to inclined and irregular Trachyte I paleosurface; Unit S-II is composed of light gray colored stratified lapilli tuff.

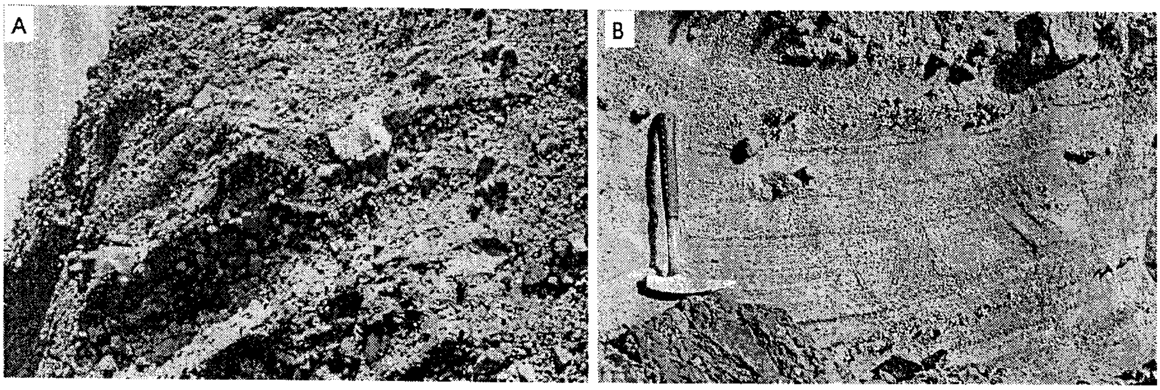

Fig. 5. Unit S-I is well exposed along the coastaline of the southwestern west islet. Where Unit S-I are several ten meters thick, it consist of a two-component sequence of: (A) lower massive trachytic breccia; and (B) upper inversely graded or stratified breccia.

as the main phase (Yoon, 1986) whereas that of Dokdo does not contain trachytic domes.

West Islet

The Seodo Formation of the west islet only consists of several ten-m-thick Unit S-I and several m-thick Unit S-II, in which basal Trachyte I and Trachyte III or Trachyandesite are unconformably contacted (Fig. 4). Bedding plane of Unit S-I are parallel to inclined rugged surface of trachyte I (Fig. 4B). Unit S-II is exposed at several locations throughout the west islet (Fig. 4). The bedding thickness abruptly increased at the fault zone near trachyte dyke (Fig. 4).

The lower section of Unit S-I mainly consists of massive breccia including boulder-sized trachytic clasts (Fig. 5A). The upper part of Unit S-I is commonly composed of alternating stratified tuff and inversely graded breccia which mainly consist of cobble-sized trachytic clasts (Fig. 5B). Unit S-II consists of fine-grained tuff, which clearly reveals mantle bedding according to previous topography (Fig. 4B).

East Islet

The Dongdo Formation consists of five units which show alternating stratified lapilli tuff and inversely graded basaltic tuff breccia (Unit D-I, Unit D-III, and Unit D-V) and massive to undulatory-bedded basaltic tuff breccias (Unit D-II and Unit D-IV). Units D-I, D-III, and D-V commonly consist of pebble to cobble-sized basaltic clasts in tuff breccia layers and pebble-sized white tuff clasts in

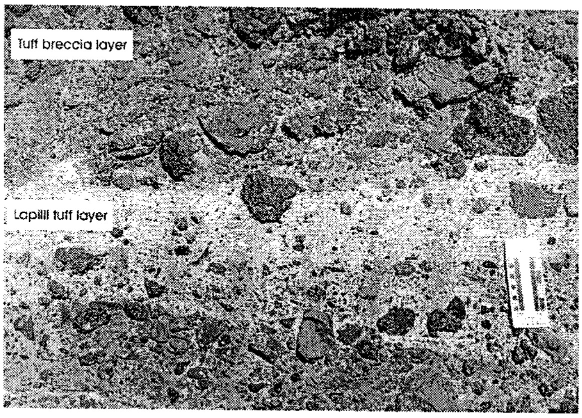

Fig. 6. Photograph of stratified lapilli tuff and inversely basaltic tuff breccia. Three units (Unit D-I, Unit D-III, and Unit D-V) consist of alteration with stratified lapilli tuff and inversely basaltic tuff breccia.

lapilli tuff layers (Fig. 6). The Dongdo Formation and basal Trachyte I are not discernible in the east islet, and they are overlain by Trachyandesite (Fig. 7A). The bedding planes are subhorizontal (Unit D-I) to horizontal (Unit D-III and V). Unit D-II shows both lateral and vertical changes in grain size and internal structures such as the amount of boulder to cobble-sized basaltic clasts or bed morphology (Fig. 7). Boundary of the D-II and D-III is sharp and flat, and interpreted as an erosional surface (Fig. 7B). The stratified lapilli tuff and inversely graded basaltic tuff breccias laterally pinch out and show concave-convex geometry in northern coast of the east islet. The east islet was affected by a large number of faulting, and formations of several depressions (Fig. 8A). In the central part of the east islet, it was observed fault breccia unconformably covering a fault plane (Fig. 8B).

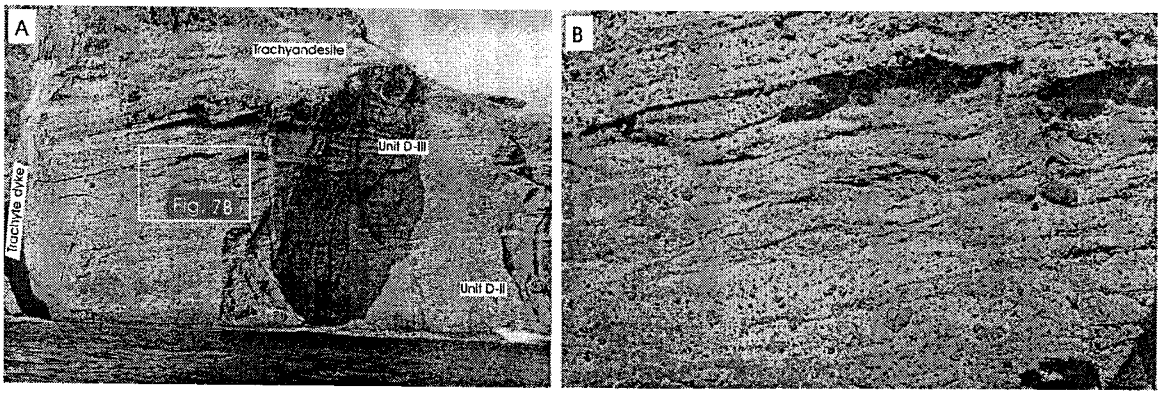

Fig. 7. The Dongdo Formation consists of five units which show alternation of (A) stratified lapilli tuff and inversely graded basaltic tuff breccia, and (B) massive to undulatory-bedded basaltic tuff breccias.

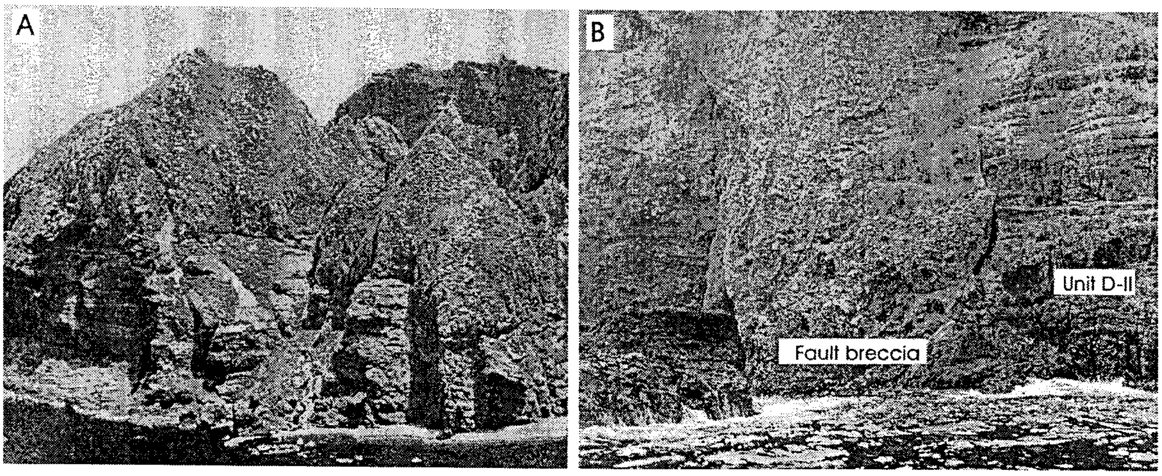

Fig. 8. The central part of east islet develops elliptical depression (A) associated with the fault breccia on the walls (B).

5. Discussion

Geochemical and petrological compositions of volcanic rocks on Dokdo are very similar to those of Ulleungdo (Kim *et al.*, 1987; Min *et al.*, 1988; Sohn and Park, 1994). The morphology of the two volcanoes is very similar to each other in the subaqueous part, however the subaerial sections of two islands are quite different in terms of geomorphology, volcaniclastic deposits, and eruption age. Subaerial sections (200-900 m height above sea-level) of Ulleungdo mainly consist of trachytic domes like a major volcanic mass such as main phase (Yoon, 1986). Dokdo does not contain trachytic domes such as Ulleungdo, because of lack or shifting of hot areas resulting from rising of mantle plume in the northeastern Asian region (Kim *et al.*, 1998) or moving off of the plate from a fixed hot spot (Min *et al.*, 1988). A caldera of Dokdo volcano was probably formed by piston-like subsidence resulting from ring-faults (Wright and Gamble, 1999; Marti *et al.*, 2000) when large volumes of lava were removed from the underground magma chamber. The caldera rim of Dokdo volcano is described based on analyses of Chirp subbottom profile data and side scan sonar data (Fig. 9). It indicated that the Dokdo caldera was affected by active subsidence and erosion by sea and wind. Dokdo might be southwestern remnants of Dokdo caldera (Fig. 9). The Seodo Formation is composed of massive breccia including boulder-sized trachytic clasts by subaerial grain flows resulting from mass wasting processes during Dokdo caldera collapse. It was formed by a rapid downslope movement of poorly sorted mass of rock and soil mobilized by gravity at a steep paleosurface of the weathered Trachyte I. The Dongdo Formation is composed of five units which showd alternating of stratified lapilli tuff and inversely graded basaltic tuff breccia and massive to undulatory-bedded basaltic tuff breccias. It was supplied by pyroclastic surge and reworking processes from proximal part near the vent. The basal part of the east islet consists of Unit D-I volcaniclastic deposits, and the basal Trachyte I of west Islet is absent. It suggested that volcaniclastic deposits of the two islets probably have limitation in distribution by geomorphologic and chronological gaps.

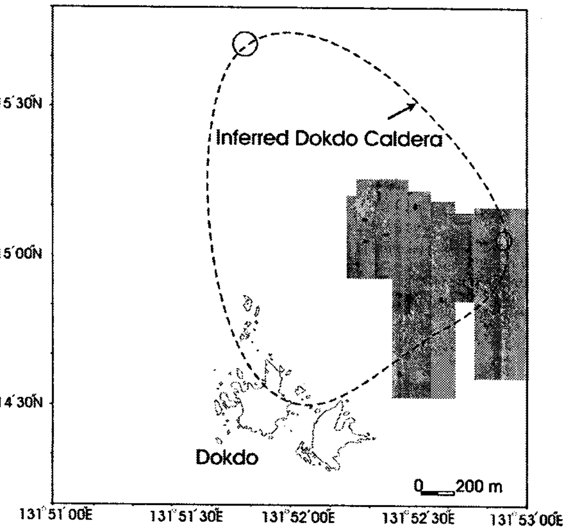

Fig. 9. Location of inferred Dokdo Caldera based on Chirp subbottom profile data and side scan sonar data. Elliptical Dokdo caldera has about 2 km in diameter. Solid circles represent the location of the submarine Dokdo caldera rim identified by chirp subbottom profile data.

6. Conclusions

Submarine geomorphology and volcaniclastic deposits around Dokdo support existence of Dokdo caldera and its associated depositional processes. The Dokdo caldera has about 2 km in diameter, and is elliptical with submarine caldera rim. Volcaniclastic deposits on Dokdo are largely divided into two formations: The Seodo Formation successively consists of massive or inversely graded trachytic breccia, and stratified tuff. It was probably deposited by mass wasting resulting from caldera forming processes; The Dongdo Formation consists of five units which show alternating stratified lapilli tuff and inversely graded basaltic tuff breccia, and massive to undulatory-bedded basaltic tuff breccias. It was supplied by pyroclastic surge and reworking processes at a proximal part near vent. In the Dokdo volcano, supply of trachytic lava probably was getting depleted with vacancy of magma chamber due to moving off or termination of the uprising mantle plume. It might have caused subsidence of the magma chamber by ring-faults, and finally formed the Dokdo caldera such as the Seodo Formation. The last explosive and effusive volcanic activities probably formed the Dongdo Formation and trachytic or trachyandesitic lava and dikes.

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