Geosciences Journal
Vol. 12, No. 4, p. 317 − 329, December 2008
DOI 10.1007/s12303-008-0032-7

Tephra-filled volcanic neck (diatreme) of a mafic tuff ring at Maegok, Miocene Eoil Basin, SE Korea

Chang Woo Kwon
Young Kwan Sohn*
Department of Earth and Environmental Sciences and Research Institute of Natural Science, Gyeongsang National University, Jinju 660-701, Korea

ABSTRACT: The Eoil Basin is one of the Miocene sedimentary basins in SE Korea, containing abundant volcanic deposits in addition to sedimentary deposits. Origin of a mafic volcaniclastic deposit at Maegok in the southeastern basin margin has remained enigmatic although it was interpreted as peperite by some workers. New features of the deposit were revealed by recent re-exposure of the outcrop, including 1) the occurrence of the deposit as an isolated vertical cylinder, 2) an abundance of hydroclastically fragmented sideromelane shards within the matrix, 3) tilting, faulting, and ductile deformation of the surrounding sedimentary strata, indicating synvolcanic vent-ward collapse of the strata, 4) dike-like structures composed of fine-grained tephra, some of which intruded into the surrounding sedimentary deposits, and 5) some clasts arranged in a jigsaw fashion, indicating *in situ* fragmentation by shock waves. These features suggest that the deposit represents a tuff pipe or the diatreme (tephra-filled volcanic neck) of a phreatomagmatic volcano. Plastically deformed mafic clasts, formerly regarded as evidence for peperitic interaction between magma and wet sediment, show neither the features of simultaneous intrusion and mingling of magma with wet sediments nor the features of in situ fragmentation, which are essential characteristics of peperite. An abundance of sideromelane ash and the lack of juvenile lapilli in the deposit suggest that the diatreme belongs to a phreatomagmatic volcano that was produced by contact-surface steam explosivity, and that the volcano had probably the morphology of a tuff ring. The Maegok exposure is inferred to belong to the deeper part of the diatreme in spite of its occurrence at a shallow level, about 100 m below the pre-eruption surface. The conduit of the tuff ring is therefore interpreted to have had a shallow (a few hundred meters deep) and flared-up geometry.

Key words: Eoil Basin, diatreme, volcanic neck, tuff ring, phreatomagmatism

1. INTRODUCTION

Volcanism was active together with sedimentary basin formation in SE Korea from the Paleogene to the early Middle Miocene because of crustal extension associated with the back-arc opening of the East Sea (Sea of Japan) (Shimazu et al., 1990; Yoon, 1997; Lee et al., 1999). Tertiary sedimentary basins in SE Korea therefore contain abundant volcanic and volcaniclastic deposits in addition to epiclastic (non-volcaniclastic) sedimentary deposits (e.g., Bahk and Chough, 1996; Yoon, 1997; Son, 1998; Son et al., 2000; Son et al., 2005). The Eoil Basin (Fig. 1) is one of the Miocene, volcanics-rich sedimentary basins in SE Korea, of which the basinfill consists of the fluviolacustrine Gampo Conglomerate, the mafic volcanic-volcaniclastic Eoil Formation, and the alluvial to fluviomarine Songjeon Formation in ascending order (Chwae et al., 1988; Son et al., 2000). The lower two formations occur almost exclusively in the northeastern subbasin of the basin (Fig. 1B), which has the geometry of a northwest-dipping half graben (Fig. 1C). Therefore, the Gampo Conglomerate crops out mainly in the southeastern margin of the basin whereas the Eoil Formation crops out in the rest of the basin. However, a small and isolated body of mafic volcaniclastic deposit, which apparently belongs to the Eoil Formation in lithology, occurs at Maegok area close to the southeastern basin margin (Fig. 2). Occurrence of the mafic volcaniclastic deposit at that location is rather unusual because the lowermost part of the Gampo Conglomerate is supposed to occur in that area given the overall attitude of the basinfill strata. There have been two hypotheses for the origin of the deposit. Yoon et al. (1990) argued that the deposit is a peperite (see White et al., 2000 for definition) that was produced by mingling of ascending basaltic magma with unconsolidated sediments of the Gampo Conglomerate. On the other hand, some researchers regarded the deposit as part of the Eoil Formation that was downthrown by later normal faulting (Son et al., 2000).

Recently, the authors had an opportunity to examine in detail the mafic volcaniclastic deposit at Maegok when the deposit was re-exposed during road construction (Fig. 3). Fresh exposure of the deposit together with the surrounding sedimentary deposits of the Gampo Conglomerate enabled us to draw an alternative interpretation that the mafic volcaniclastic deposit represents a diatreme, which is a 'tuff pipe' or the tephra-filled volcanic neck of a phreatomagmatic volcano exposed below the eruption surface (Lorenz, 1986; White, 1991). In this paper, we describe and interpret the characteristics of the mafic volcaniclastic deposit at Maegok and then reconsider the peperite hypothesis for the deposit in the light of recent volcanological concepts and

*Corresponding author: yksohn@gnu.ac.kr

processes. The surface and subsurface characteristics of the phreatomagmatic volcano that comprised the diatreme will also be reconstructed on the basis of its lithofacies characteristics and its stratigraphic position within the basinfill.

2. GEOLOGICAL SETTING

A number of small Tertiary sedimentary basins were produced along the southeastern margin of the Korean Peninsula in association with NNW-SSE spreading of the East Sea during the Early to Middle Miocene (Jolivet et al., 1994; Yoon and Chough, 1995; Son, 1998). The majority of these basins were rifted during the Early Miocene and filled by kilometer-thick successions of nonmarine to shallow-marine sediments together with abundant dacitic and basaltic volcanic deposits (Bahk and Chough, 1996; Son et al., 2000; Son et al., 2005; Jeong et al., 2006, 2008), whereas the rest (e.g., the Pohang Basin) were extended further until the Middle Miocene when they were eventually filled by deep-marine sediments (Hwang et al., 1995; Sohn et al., 2001; Sohn and Son, 2004).

The Eoil Basin (Fig. 1) is one of the Early Miocene basins, about 12 km long and 5 km wide, bounded by NE- or ENE-trending normal faults along the northwestern and southeastern margins and by NNW-trending dextral strike-slip faults along the northeastern and southwestern margins (Son et al., 2000). The basin is divided into the northeastern and southwestern subbasins by an intrabasinal strike-slip fault that trends NNW. The lower two formations (the Gampo Conglomerate and the Eoil Formation) occur almost exclusively in the northeastern subbasin whereas the overlying Songjeon Formation occurs mainly in the southwestern subbasin (Fig. 1).

The Gampo Conglomerate at the base, estimated to have a stratigraphic thickness of about 800 m (Chwae et al., 1988), is composed of gravelly alluvial-fan deposits, gravelly to sandy braided-stream deposits, swamp or lacustrine deposits, and minor amounts of volcaniclastic deposits. The overlying Eoil Formation is composed of mainly basaltic volcanic/volcaniclastic deposits, locally containing pillow lavas

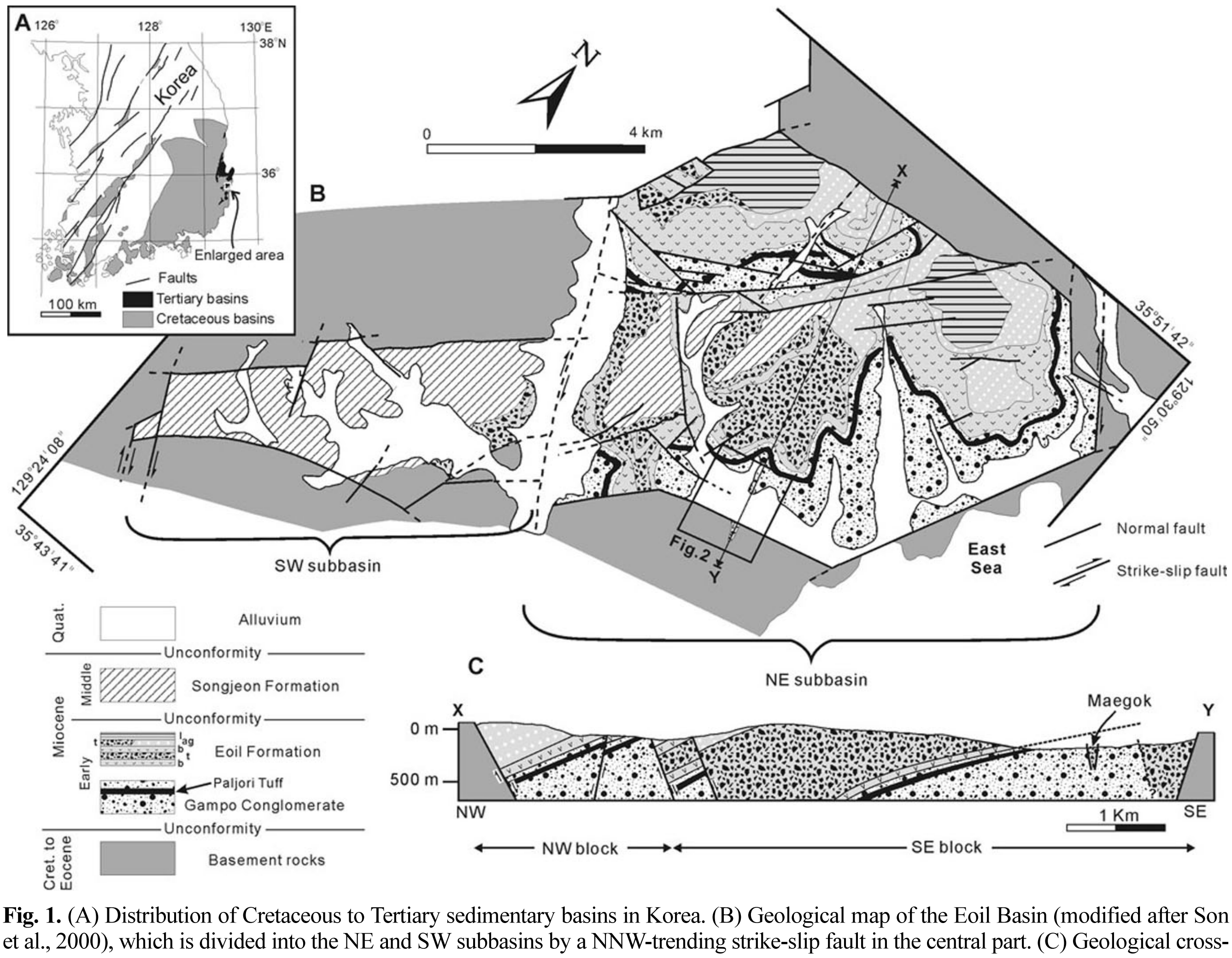

Fig. 1. (A) Distribution of Cretaceous to Tertiary sedimentary basins in Korea. (B) Geological map of the Eoil Basin (modified after Son et al., 2000), which is divided into the NE and SW subbasins by a NNW-trending strike-slip fault in the central part. (C) Geological cross-section of the NE subbasin, showing the bed attitude of the basinfill strata dipping progressively steeper toward the northwest.

and breccias and well-bedded rim deposits of phreatomagmatic volcanoes in addition to subaerial lavas, dikes or sills, resedimented volcaniclastic deposits, and rare non-volcaniclastic fluviolacustrine deposits (Chwae et al., 1988; Son et al., 2000 and authors' own observations). The overall lithofacies characteristics suggest that the Eoil Formation resulted from the effusion and explosive hydrovolcanic eruption of basaltic magma through the unconsolidated and wet sediments of the Gampo Conglomerate followed by resedimentation of volcaniclasts by fluviolacustrine processes. Basaltic lavas in the formation are dated to be between 18 and 20 Ma old (Lee et al., 1992).

3. CHARACTERISTICS OF THE MAEGOK EXPOSURE

A recent road-cut at Maegok area (Fig. 2) reveals clearly the contact characteristics between a mafic volcaniclastic deposit and the surrounding sedimentary deposits. The contact is conspicuous because of the distinct color contrast between the dark-colored volcaniclastic deposit and the light-colored sedimentary deposits (Fig. 3). The contact surface is highly irregular and uneven (Fig. 4A), but its overall geometry is of a subvertical curved plane, encircling the mafic volcaniclastic deposit in the eastern, northern, and western parts. The southern limit of the mafic volcaniclastic deposit couldn't be constrained because of a thick alluvial cover. The mafic volcaniclastic deposit is, however, presumed to have the geometry of a vertical cylinder, less than about fifty meters in diameter, cross-cutting the surrounding sedimentary deposits of the Gampo Conglomerate.

The mafic volcaniclastic deposit is composed of a very poorly sorted mixture of mafic volcaniclasts and epiclasts that are supported in a dark gray to dark brown, fine-grained tuffaceous matrix. The mafic volcaniclasts can be divided into two types based on clast shape, vesicularity, and phenocryst content: 1) blocky and angular, non-vesicular and aphanitic clasts (Fig. 4B) and 2) irregularly shaped, poorly vesicular and porphyritic clasts (Fig. 4C). The former constitute the majority of the volcaniclasts and range in size

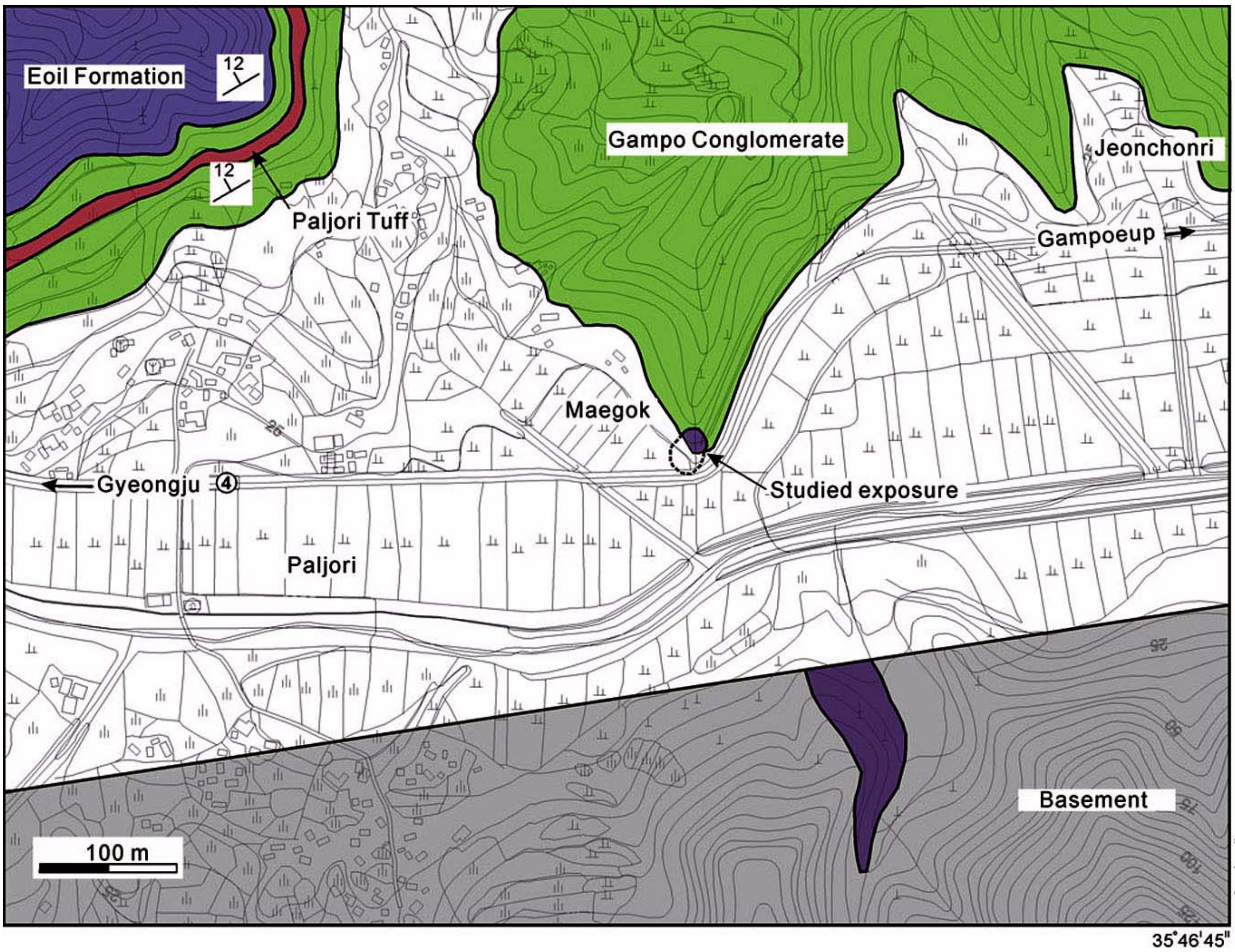

Fig. 2. Enlarged geological and topographic map of the study area, showing the location of the studied exposure at Maegok.

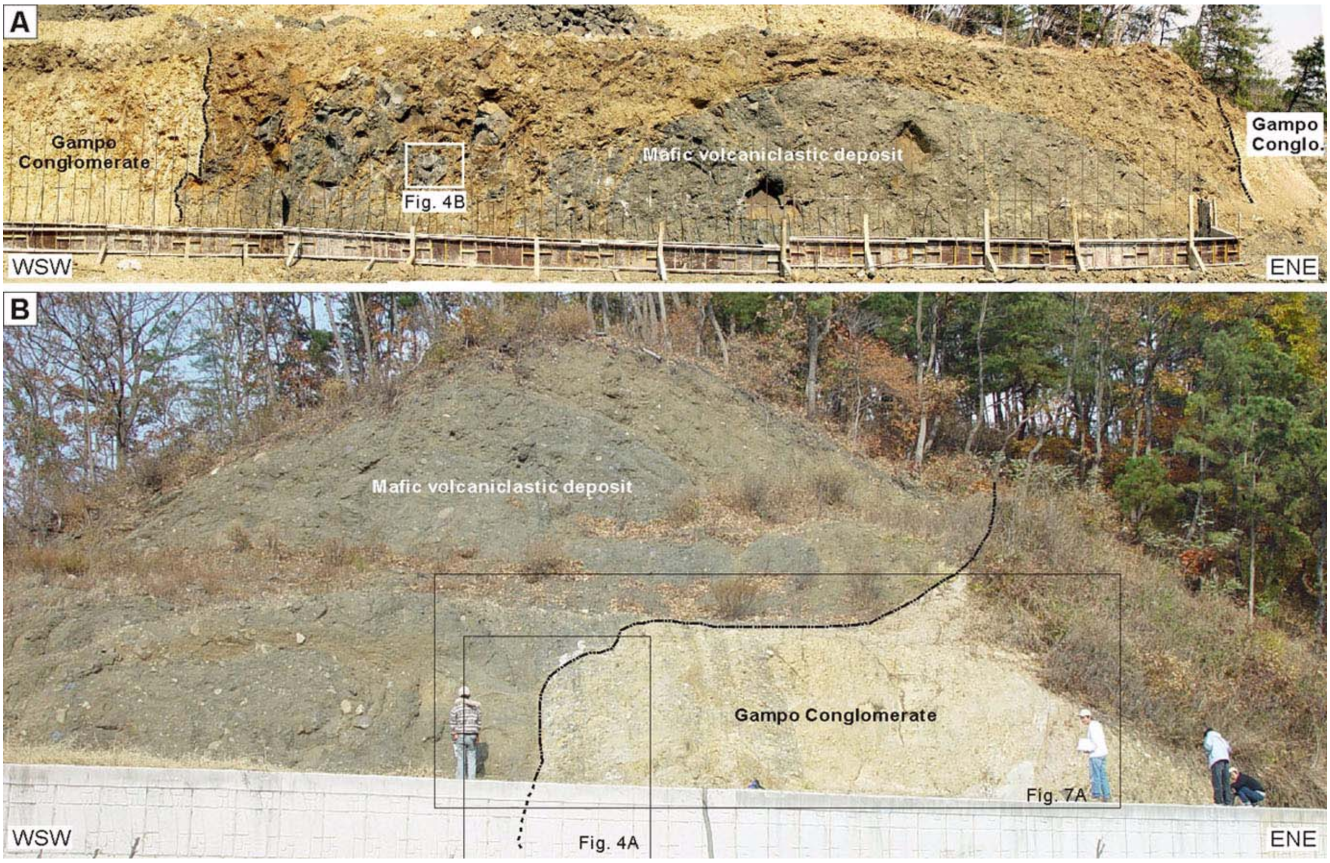

Fig. 3. Recent roadcut exposures at Maegok. (A) The outcrop shows the irregular and subvertical contacts between the mafic volcaniclastic deposit and the surrounding Gampo Conglomerate on both sides. The pedogenically altered part of the mafic volcaniclastic deposit is reddish brown whereas the freshly exposed, unaltered part of the deposit is dark gray in color. Dark gray parts in the left one fourth of the mafic volcaniclastic deposit are large volcaniclasts of non-vesicular and aphanitic basalt. The mafic volcaniclastic deposit has a width of about 26 m. The deposit disappears northward (into the page) very abruptly within less than about 10 m and is not found on another outcrop surface in the background. (B) Re-exposed outcrop of the mafic volcaniclastic deposit along the motorway a few tens of meters southward from the exposure in (A). Subvertical and curved contact is conspicuous between the mafic volcaniclastic deposit and the enclosing Gampo Conglomerate.

from fine pebble to large boulder (up to 1.3 m in diameter). They are generally devoid of phenocrysts and vesicles and have sharp edges and corners (Fig. 4B). On the other hand, the latter are subordinate in amount and mostly pebble to cobble in size. Large cobble-size clasts have highly irregular reentrant margins (Fig. 4C) whereas smaller ones have more blocky and angular shapes. Under microscope, the blocky and non-vesicular clasts consist mainly of plagioclase microlites (Fig. 5A) whereas the irregular and vesicular clasts contain abundant phenocrysts of plagioclase and pyroxene in a fine-grained groundmass (Fig. 5B).

The epiclasts consist mostly of the gravel clasts that were derived from the Gampo Conglomerate. They are subangular to well rounded and generally pebble to cobble in size (yellow arrows in Fig. 4B). Their lithologies are identical to those of the gravel clasts in the Gampo Conglomerate, composed of dacitic volcanic rocks and granites. Gravel clasts derived from the adjacent basement rocks haven't been found. Sandstone fragments are also present in minor amounts, especially near the contact with the enclosing sedimentary deposits (Fig. 4A). They have elongated to rounded shapes commonly with diffuse margins. Carbonized or silicified plant debris was also found.

The matrix of the volcaniclastic deposit is composed of fine-grained and poorly sorted, basaltic tuffaceous materials. Under microscope, the matrix consists mostly of yellow to light brown sideromelane and opaque tachylite grains with subordinate amounts of plagioclase crystals, detrital quartz grains, and rock fragments (Fig. 5C). The sideromelane and tachylite shards are non-vesicular and palagonitized. Second electron micrography reveals that the shards have blocky and equant morphology with scarce vesicle-wall margins (Fig. 5D).

The mafic volcaniclastic deposit is disorganized and lacks internal layering and preferred clast fabrics. However, the clasts are not uniformly distributed in the deposit but are concentrated in irregular patches with very indistinct and diffuse margins (Fig. 6A). The deposit is therefore rich in

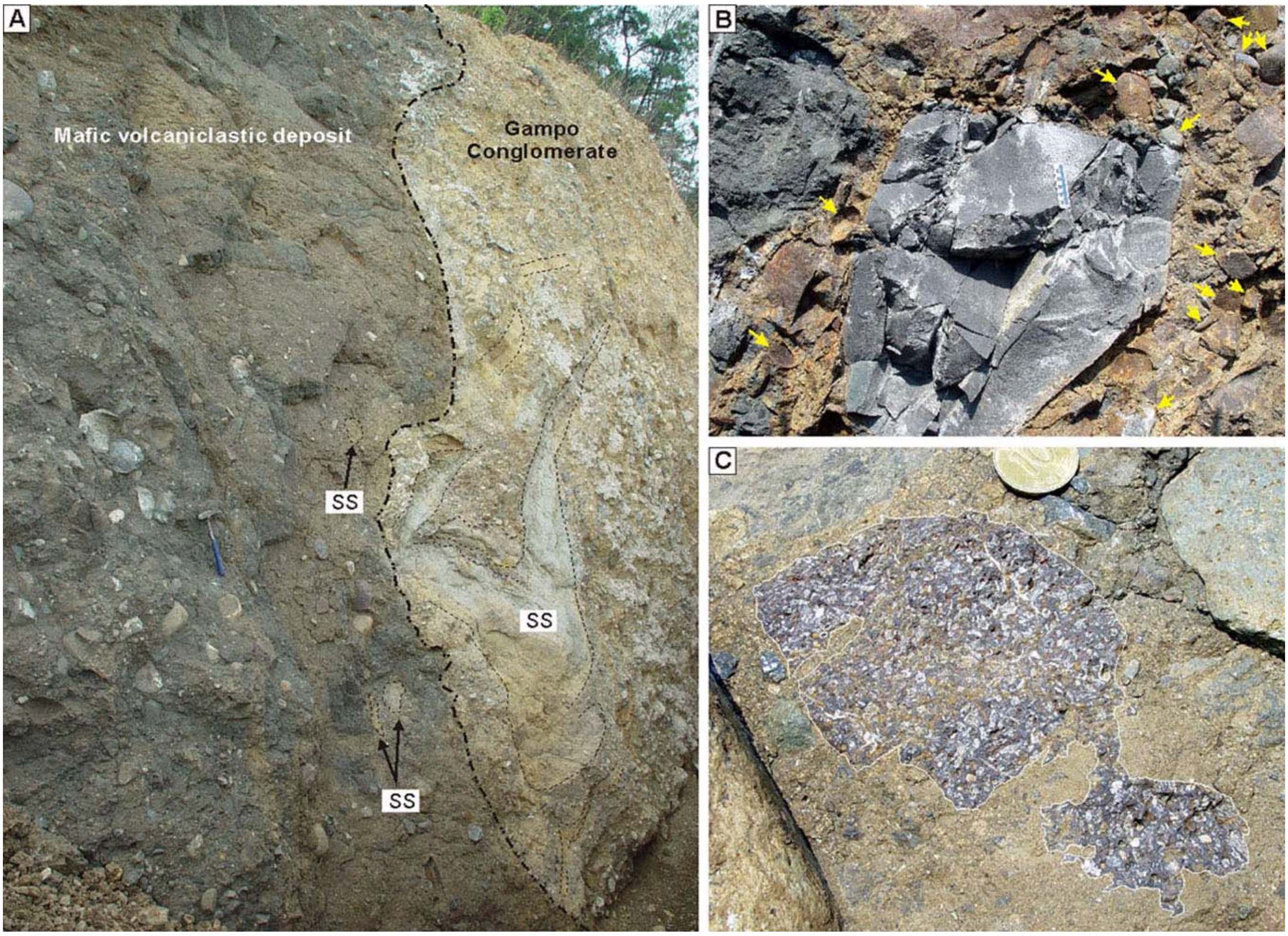

Fig. 4. Characteristics of the contact and mafic volcaniclasts. (A) Close-up of the irregular and partly overhanging contact between the mafic volcaniclastic deposit and the Gampo Conglomerate. Note the folded and dismembered sandstone (ss) layers in the Gampo Conglomerate and the sandstone clots near the contact within the mafic volcaniclastic deposit (black arrows). (B) A meter-long, angular and blocky, non-vesicular and aphanitic, mafic volcaniclast surrounded by rounded pebble-to-cobble gravel (yellow arrows) with epiclastic sand matrix. The scale bar is 10 cm long. (C) An irregularly shaped, vesicular and porphyritic mafic volcaniclast with delicate reentrant margins. The coin is 2.3 cm in diameter.

coarse pebble-size clasts in some parts (Fig. 6B) and rich in granule- to fine pebble-size clasts in the other parts (Fig. 6C). The deposit locally contains vertical dike-like structures, several centimeters thick and less than a meter long, that are composed of sand- to silt-size grains (Fig. 6D). They have very diffuse, gradational, and irregular boundaries with the surrounding clast-rich parts, bifurcating or coalescing vertically. They locally show faint internal lamination along the contact with the clast-rich parts. A few cobble- to boulder-size clasts, either volcaniclastic or epiclastic, are arranged in a jigsaw fashion (Fig. 6E).

The sedimentary deposits surrounding the mafic volcaniclastic deposit are composed of pebble-cobble conglomerates with intervening sandstone lenses. They show a number of features due to deformation. The bedding is overall undulatory as if the strata were gently open-folded (Fig. 7A). The strata near the contact with the mafic volcaniclastic deposit are either steeply inclined (Fig. 7B) or severely deformed, resulting in tight folding, stretching, and dismemberment of sandstone layers (Fig. 4A). Steep and deformed bedding also occurs in the right margin of the exposure, several meters away from the mafic volcaniclastic deposit, where a syndepositional fault (or a shear zone) was developed (Fig. 7A). Offset of bedding and stretching of layers indicate normal slip of the hangingwall strata. Another noticeable feature of the sedimentary deposits is the presence of irregular patches or dike-like structures that are rich in mafic tuffaceous materials (Fig. 7C, D). They are not as dark as the mafic volcaniclastic deposit but are darker-colored than the surrounding sedimentary deposits. They have very diffuse and gradational boundaries but are apparently cross-cutting the bedding of the sedimentary strata.

4. EMPLACEMENT PROCESSES

Absence of the features that can be produced by fault slip,

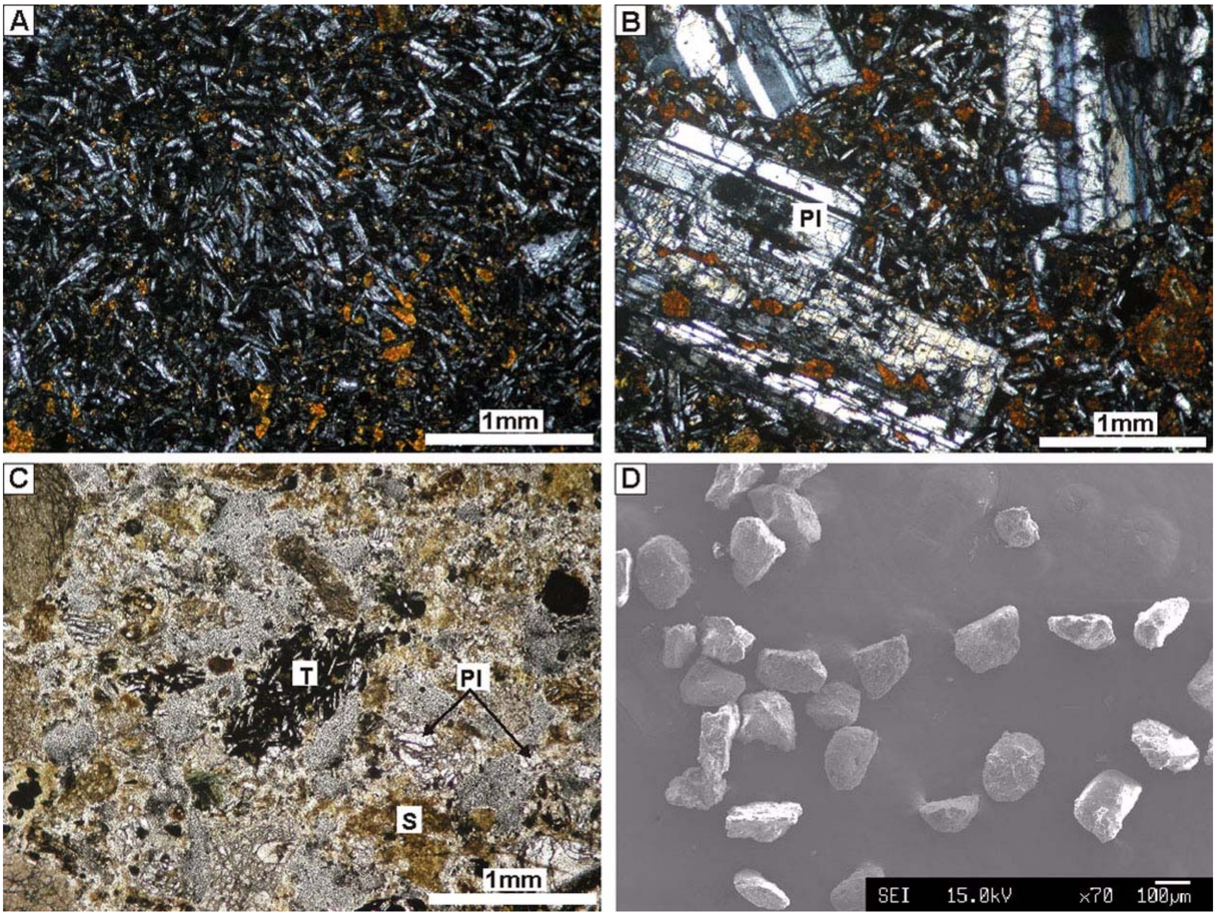

Fig. 5. Petrographic characteristics of the mafic volcaniclastic deposit. (A) Thin-section photomicrograph of non-vesicular and aphanitic mafic volcaniclast under crossed nicols. (B) Thin-section photomicrograph of vesicular and porphyritic mafic volcaniclast under crossed nicols with large plagioclase (Pl) phenocrysts. (C) Thin-section photomicrograph of fine-grained tuff matrix under open nicols, consisting of yellowish brown sideromelane (S) and opaque tachylite (T) grains as well as tiny fragments of plagioclase crystals. (D) Second electron micrographic image of sideromelane shards that were sieved and picked up from the fine-grained tuff matrix of the mafic volcaniclastic deposit. The shards are blocky and equant and have scarce vesicle-wall margins.

such as slickensides and slickenlines, along the contact between the mafic volcaniclastic deposit and the surrounding sedimentary deposits negates the possibility of juxtaposition of the two deposits via faulting, which necessitates downthrow of the Eoil Formation by more than one hundred meters. The contact is neither thought to be sedimentary in origin because the still fragile, unconsolidated deposits of the Gampo Conglomerate are not likely to maintain the subvertical to partly overhanging erosion surface (Fig. 4A), upon which the deposition of the mafic volcaniclastic deposit can take place. Instead, the occurrence of the mafic volcaniclastic deposit as an isolated body presumably with the geometry of a vertical cylinder is in favor of an intrusive origin. At the same time, petrographic characteristics indicate that the deposit has a pyroclastic ('hydroclastic' to be more specific) origin, consisting mainly of finely fragmented, non-vesicular, blocky and equant sideromelane shards (Fig. 5C, D) that can be classified as type 1 pyroclasts of Heiken and Wohletz (1985). The mafic volcaniclastic deposit at Maegok thus has the attributes of both intrusive and pyroclastic (hydroclastic) deposits and can be interpreted as a tuff pipe or a diatreme, i.e., the tephra-filled volcanic neck of a phreatomagmatic volcano (Lorenz, 1986; White, 1991).

A number of features in the Maegok exposure can be interpreted in terms of the volcanological processes related to the diatreme formation. The steeply inclined bedding (Fig. 7B) and chaotic deformation (Fig. 4A) of the sedimentary strata together with the syndepositional fault (Fig. 7A) suggest subsidence and collapse of the sedimentary strata down into the adjacent volcanic conduit, involving tilting and ductile deformation. The syndepositional fault may be one of a series of ring faults, which commonly develop around a diatreme because of subsidence of the country rocks into the root zone of the diatreme (Lorenz and Kurszlaukis, 2007). The irregular and subvertical to overhanging contact surface (Fig. 4A) suggests that the collapse of the sedimentary strata occurred in the presence of lateral support from the conduit-filling materials rather than

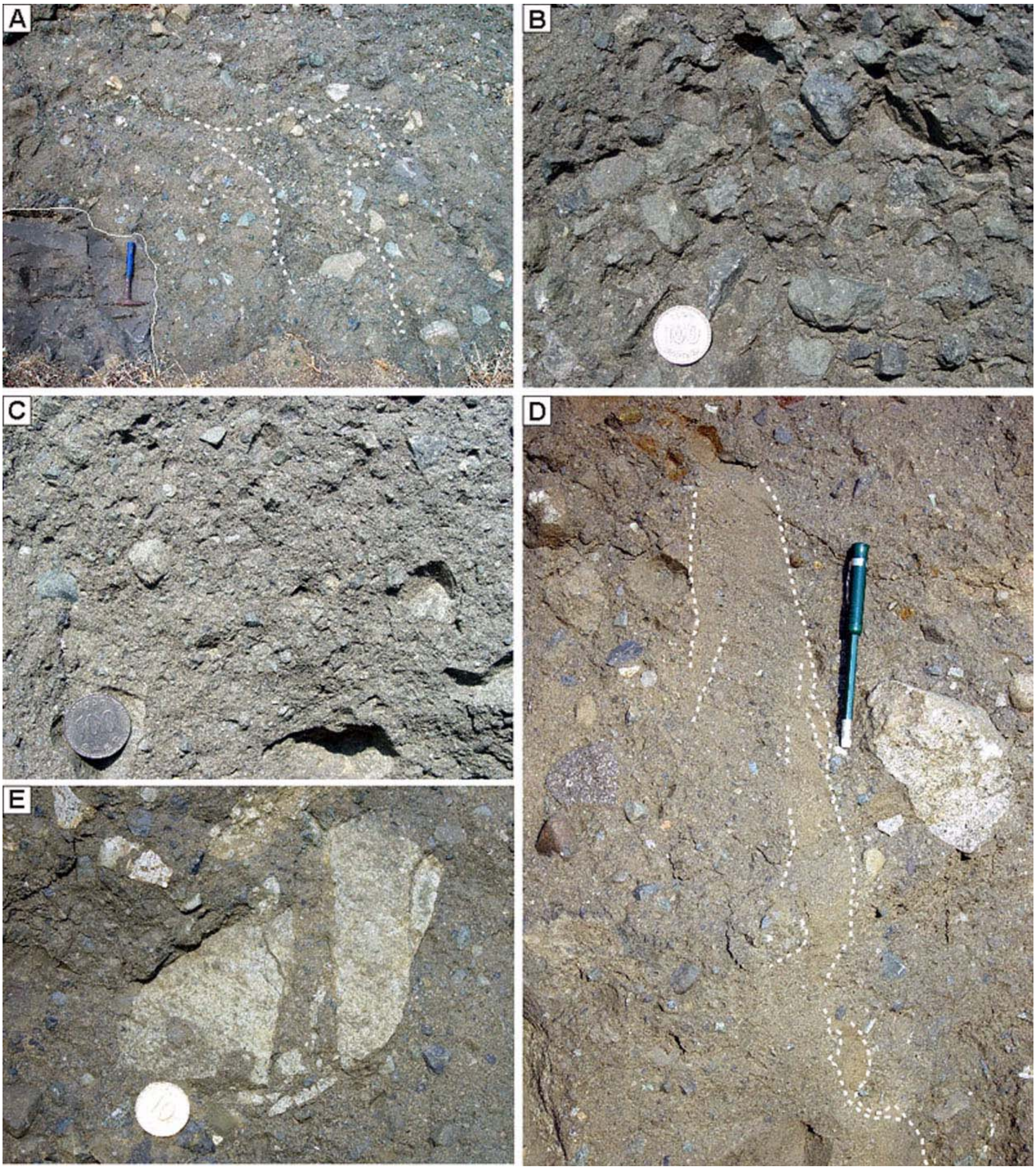

Fig. 6. Outcrop characteristics of the mafic volcaniclastic deposit. (A) An exposure showing non-uniform distribution of clasts within the mafic volcaniclastic deposit. An irregular patch, rich in fine pebble clasts and clast-supported, is outlined with broken lines. (B) Close-up of clast-supported and pebble clast-rich part within the mafic volcaniclastic deposit. (C) Close-up of relatively fine-grained part of the mafic volcaniclastic deposit, consisting mainly of granule- to fine pebble-size clasts. (D) Vertical, anastomosing, dike-like structure composed of sand- to silt-size grains within the mafic volcaniclastic deposit. (E) A granitic clast that was fractured in situ in a jigsaw fashion. The coin in (B) and (C) is 2.4 cm in diameter; the coin in (E) is 2.3 cm in diameter; the pencil in (D) is 15.5 cm long.

into an open space. The slid or collapsed sedimentary strata could be thus subject to local compressional deformation, resulting in tight folding of sandstone layers (Fig. 4A).

The disorganized nature of the mafic volcaniclastic deposit is interpreted to be due to episodic circulatory mixing of the materials that were brought into the volcanic conduit by various processes, including forceful upward injection of finely fragmented hydroclastic tephra from below, falling-back of debris that was explosively ejected by phreatomagmatic explosions, and collapse of the conduit wall deposits

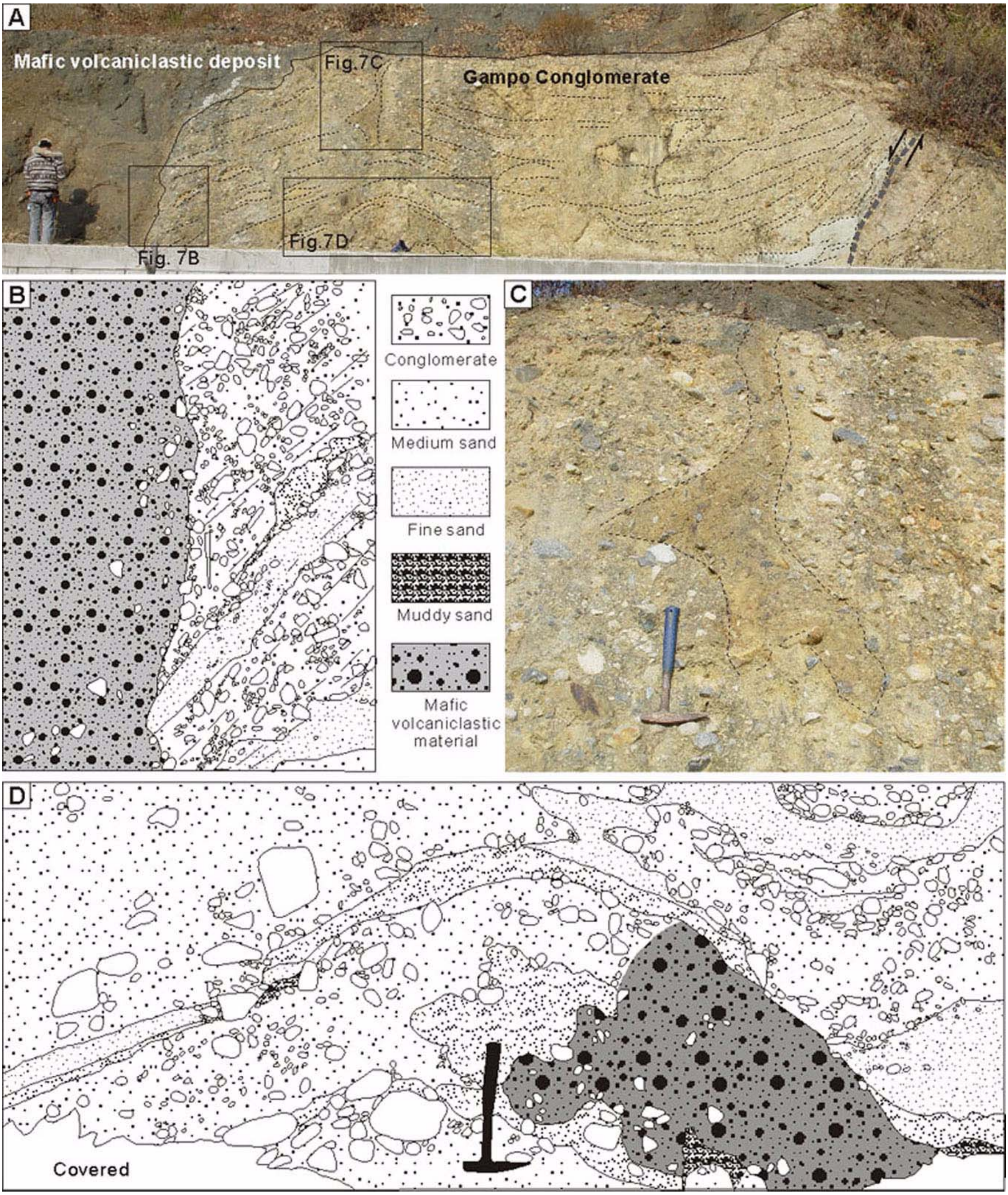

Fig. 7. Characteristics of the Gampo Conglomerate adjacent to the mafic volcaniclastic deposit. (A) Overall undulatory bedding of the Gampo Conglomerate composed of pebble-cobble conglomerates and intervening sandstone lenses. Note the steep bedding near the contact with the mafic volcaniclastic deposit and the syndepositional fault to the right. (B) Sketch of steeply inclined strata of the Gampo Conglomerate at the contact with the mafic volcaniclastic deposit. (C) An irregular patch or dike-like structure within the Gampo Conglomerate, rich in mafic tuffaceous materials and darker-colored than the surrounding gravelly deposit. (D) Sketch of the folded or updomed part of the Gampo Conglomerate, in which the bedding is deformed and truncated by an irregular pod or apophysis of mafic tuffaceous materials.

and the rim deposits that accumulated around the vent of the phreatomagmatic volcano (White, 1991). Fossil wood fragments, unless they were derived from the Gampo Conglomerate, suggest that near-surface deposits and the overlying vegetation participated in the collapse processes (Lorenz, 1986). The absence of bedding, grading, and any directional clast fabrics and the presence of large unconsolidated intraformational clasts from the Gampo Conglomerate suggests that the materials from different sources were almost thoroughly remolded and mixed up because of repeated cycles of explosive upward ejection and falling-back of debris into the vent. The poor sorting of the deposit is interpreted to be due to en masse emplacement of debris that fell back into the vent from the eruption column (White, 1991). Local heterogeneity in clast concentration (Fig. 6A) is probably due to incomplete homogenization of debris that entered the conduit by different backfall or collapse episodes.

The dike-like structures with anastomosing geometry (Fig. 6D) are interpreted to have formed by some sort of current moving within the conduit associated with fluidization, which has long been assigned a dominant role in diatreme development (White, 1991; Gernon et al., 2008). The fine constituent grains suggest that the structures were produced by a local upward flow of fine-grained steamy tephra after the bulk of the diatreme has been formed. The irregular patches or dike-like features of tuffaceous materials that cross-cut the bedding of the surrounding sedimentary deposits (Fig. 7C, D) are also interpreted to be structures formed by forceful injection of mafic volcaniclastic debris into the unconsolidated sediments around the volcanic conduit associated with fluidization or degassing of the diatreme deposit.

The clasts arranged in a jigsaw fashion (Fig. 6E) are interpreted to have been fragmented by the shock waves that were released during explosive thermohydraulic interaction of hot magma and water (Zimanowski et al., 1997). The shock waves are known to be energetic enough to shatter large amounts of brittle country rocks (Grady and Kipp, 1987) and destabilize unconsolidated sediment masses around the root zone of a diatreme (Lorenz et al., 2002). It is not impossible but less likely that the clasts were fragmented by the impact of a falling-back clast upon hitting the wall or the floor of the conduit. In either case, the jigsaw-fit clasts suggest that the mafic volcaniclastic deposit was emplaced during an explosive phreatomagmatic eruption and underwent minimal transport after fragmentation.

5. DIATREME VS. PEPERITE

Diverse volcaniclastic deposits can be generated by disintegration of magmas and lavas mingling with unconsolidated and wet sediments in many volcanic and sub-volcanic environments (McPhie et al., 1993). Peperite is one of the deposit types that can be generated by this process. It is defined as a rock or deposit generated by *in situ* disintegration of magma intruding and mingling with unconsolidated or poorly consolidated, typically wet sediments (White et al., 2000). The term also refers to similar mixtures generated by the same processes operating at the contacts of lavas and other hot volcaniclastic deposits with such sediments. The peperite-forming processes are therefore an integral part of the diatreme-forming processes because phreatomagmatic explosions commonly result from the interaction of ascending magma with unconsolidated and wet sediments (White, 1991, 1996). Lorenz et al. (2002), for example, reports fragments of peperite-like magma-sediment mixtures, which are interpreted to have formed within the root zone of diatremes by ingestion of soft sediments into coherent melt (magma) that is later fragmented by an explosive process. It is therefore worth discussing the distinction between peperite and diatreme and the validity of the interpretation of Yoon et al. (1990), who regarded the mafic volcaniclastic deposit at Maegok as peperite.

Yoon et al. (1990) interpreted the angular, non-vesicular, and aphanitic clasts and the irregularly shaped, vesicular, and porphyritic clasts as representing the solidified crust and fluidal interior of an intrusion, respectively, which was subsequently fragmented due to explosive fluidization. One of the main bases for this interpretation was the presence of irregularly shaped or plastically deformed mafic clasts with delicate reentrant margins (e.g., Fig. 4C) in the deposit. We agree that these clasts can provide good evidence for 'primary' emplacement of the mafic volcaniclastic deposit because such clasts would not survive prolonged transport or reworking processes. The plastically deformed clasts cannot, however, be evidence for 'in situ fragmentation', which is one of the essential criteria for the definition of peperite (White et al., 2000). We think that these clasts may have been produced by transient magmatic activity during an overall phreatomagmatic eruption and then admixed with the conduit-filling materials without significant modification of the clast shape. Even when we accept the hypothesis of Yoon et al. (1990), the volcaniclastic deposit at Maegok cannot be interpreted as peperite using the definition of White et al. (2000) because the mafic volcaniclasts were interpreted by Yoon et al. (1990) to have been fragmented 'after' intrusion and partial solidification of magma but not 'simultaneously' with intrusion and mingling of magma with wet sediments (see Lorenz et al., 2002 for more discussion on this topic).

It is also doubtful whether the angular and non-vesicular clasts and the irregularly shaped and vesicular clasts originated contemporaneously from in situ fragmentation of a single basaltic intrusion, as postulated by Yoon et al. (1990). If this was the case, some transitional types of clasts with intermediate angularity, vesicularity, and crystalinity should have been produced possibly together with the fragments of a magma-sediment mixture or xenolith-rich or xenocrystsrich juvenile clasts (Lorenz et al., 2002). However, only two kinds of mafic volcaniclasts with distinctly different characteristics are found in the deposit, suggesting that they were derived from two different source rocks. Most probably, the irregularly shaped and vesicular volcaniclasts were derived from lava spatters produced during a transient lava-fountaining (or Hawaiian) eruption whereas the angular and non-vesicular volcaniclasts are fragments of coherent lavas or shallow intrusions. Both types of the volcaniclasts at Maegok can therefore be regarded as juvenile or cognate lithic clasts (see Cas and Wright, 1987 for terminology) that are not related with any peperite-forming processes.

The peperite hypothesis also fails to explain the origin of the fine-grained sideromelane shards (Fig. 5C), which constitute the most volumetrically significant part of the Maegok volcaniclastic deposit. It is hardly conceivable that such an abundance of sideromelane shards can be produced by the disruption of a single basaltic intrusion. Probably the only way to produce such abundant fine-grained sideromelane shards seems to be 'sustained' hydroclastic fragmentation of magma. The overall fine grain size of the sideromelane shards in the Maegok deposit, almost totally lacking lapilli-size juvenile fragments, suggests that the magma fragmentation was accomplished mostly by contact-surface steam explosivity (Kokelaar, 1986). It is well known that buoyancy-dominated eruption columns and pyroclastic surges are generated by contact-surface steam explosivity, generally resulting in tuff-ring morphology of the volcanic edifice whereas dense and inertia-dominated eruption columns and jets are generated by bulk-interaction steam explosivity, resulting in tuff-cone morphology (Sohn, 1996). The volcanic edifice at Maegok, which is totally removed by erosion at present, is therefore inferred to have had the morphology of a tuff ring and its rim beds dominated by pyroclastic surge and co-surge fallout deposits.

6. VOLCANO RECONSTRUCTION

The mafic volcaniclastic deposit at Maegok is interpreted to be a diatreme of a phreatomagmatic volcano. The absence of accidental components derived from the Eoil Formation, such as non-vesicular and microcrystalline basalt fragments with large feldspar phenocrysts, mafic scoriaceous fragments, and silicic pumiceous fragments, suggests that the eruption of the volcano commenced before thick accumulation of the Eoil Formation. We interpret therefore that the pre-eruption surface of the volcano coincided roughly with the upper surface of the Gampo Conglomerate. It is also interpreted that the magma ascended through and interacted with hundreds of meter-thick, unconsolidated, porous, permeable, and probably water-logged gravel and sand deposits covered locally by fluvial and shallow lacustrine waters. Such an eruptive setting was probably ideal for explosive phreatomagmatic activity (Ross et al., 2005; Sohn et al., 2008). The magma could be finely fragmented, involving contact-surface steam explosivity (Kokelaar, 1986), and then erupted with great explosivity because much more explosivity results when magma mixes with wet sediment than with pure water (White, 1996). The resultant style of eruption is inferred to have been Taalian (Kokelaar, 1986). During the eruption, part of the ejecta fell inside the crater and some of it made its way down into the conduit floor probably after multiple cycles of ejection and fallback (White, 1991). It is thus interpreted that the magma was injected into this accumulation of wet and unconsolidated tephra and country-rock debris after the initial vent-clearing eruption, and that the erupting materials pierced through the diatreme fill in the conduit.

A low-relief tuff ring is inferred to have formed by the Taalian eruptive activity, which generates mostly ash-rich and buoyancy-dominated eruption columns and dilute pyroclastic density currents (Moore et al., 1966; Waters and Fisher, 1971; Kokelaar, 1986; Sohn, 1996). The tuff ring probably had an unstable, funnel-like conduit within the sedimentary deposits of the Gampo Conglomerate. The absence of basement-derived accidental lithics in the Maegok deposit indicates that the locus of hydroexplosion lay above the basement. Therefore, the vertical dimension of the Maegok diatreme mustn't have exceeded the thickness of the Gampo Conglomerate, of which the maximum stratigraphic thickness is about 800 m (Chwae et al., 1988). The present exposure of the mafic volcaniclastic deposit at Maegok is about 100 m below the pre-eruption surface or the upper surface of the Gampo Conglomerate. It is not quite certain whether the exposure at Maegok represents the shallower part of a relatively deep diatreme or the deeper part of a relatively shallow diatreme. A number of features in the Maegok exposure suggest, however, that the exposure represents the deeper part of a relatively shallow diatreme (Fig. 8).

Above all, the absence of bedding within the mafic volcaniclastic deposit suggests thorough mixing of the materials that were brought into the deeper part of a volcanic conduit. On the other hand, faint bedding can be formed during the last backfall episodes within the shallower part of a diatreme (White, 1991). The subvertical to overhanging diatreme surface (Fig. 4A), which suggests maintenance of lateral support from the conduit-filling materials, can be another evidence for the deepness of the deposit within the diatreme. Forceful injection of tuffaceous debris into the surrounding sedimentary deposits (Fig. 7C, D) is also expected to occur around the deeper part of a volcanic conduit. The jigsaw-fit clasts (Fig. 6E), probably fractured by the highly energetic shock waves generated at the bottom of the diatreme, are also suggestive of the proximity of the deposit to the explosion locus or the root zone of a diatreme. The lateral dimension of the deposit, less than 50 m in diameter, is also unusually small to represent the upper part of a

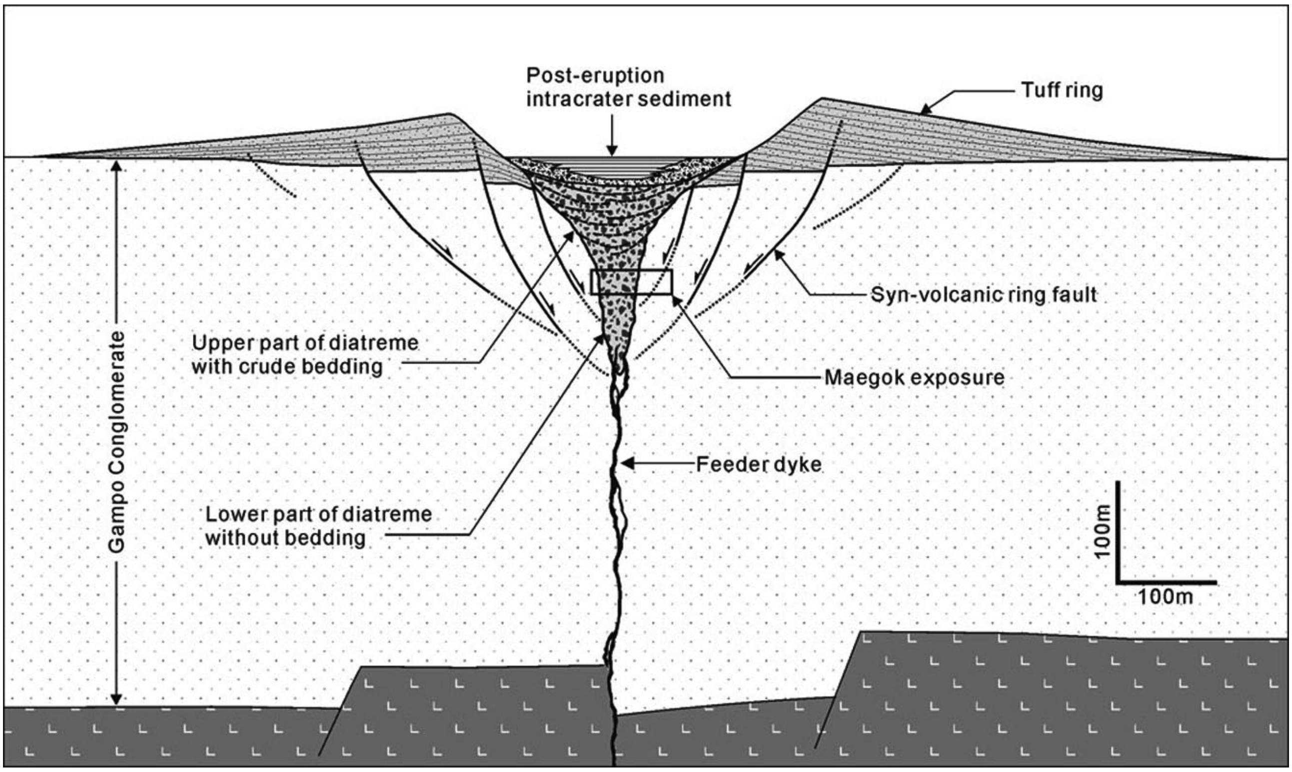

Fig. 8. Reconstruction of the Maegok phreatomagmatic volcano, which is inferred to have had a relatively shallow (a few hundred meters deep) and flared-up conduit and a low-lying rim deposit of a tuff ring.

diatreme, of which the diameter varies between several tens of meters and in excess of 1500 m (Lorenz, 1986).

The Maegok exposure is therefore interpreted to represent the deeper and narrower part of a small and shallow diatreme rather than the shallower part of a deep diatreme (Fig. 8). The small inferred size (especially depth) of the Maegok diatreme is interpreted to be due to maintenance of the diatreme root at a shallow level, about 200-300 m below the pre-eruption surface. This is because hydrostatic pressure of 20 to 30 bars, approximately corresponding to a confining pressure 200-300 m below sea or lake level, is assumed to represent the barrier for most phreatomagmatic explosions (Lorenz, 1986). Probably, groundwater was plentiful in the Gampo Conglomerate and the consumed water for hydroexplosion could be readily replenished in the formation throughout the phreatomagmatic eruption of the Maegok tuff ring (cf., Sohn and Chough, 1992; Sohn, 1996). The friable and unstable nature of the surrounding sedimentary deposits suggests, however, that the narrow conduit in the deeper part may have widened upward greatly as a result of frequent collapse of the upper conduit wall. The lack of lateral support from the diatreme fill together with the differential loading by the ejecta deposits probably facilitated collapse of the substrate adjacent to the upper conduit wall, as suggested for some ‘soft-substrate’ phreatomagmatic volcanoes (Sohn and Park, 2005; Auer et al., 2007). The Maegok tuff ring is therefore inferred to have had a shallow but flaring-upward conduit, having a relatively small diameter in the lower part but with a much larger opening on the surface (Fig. 8). The actual crater diameter or the rim-to-rim width of the tuff ring may have reached more than a few hundred meters.

The conduit of the Maegok tuff ring was mainly filled by fine-grained sideromelane ash as well as abundant accidental components from the Gampo Conglomerate. Temporarily, however, phreatomagmatic activity was replaced by lava fountaining or lava effusion, producing lava spatters and lava flows together with shallow intrusions of dikes and plugs. One possible cause of the change in eruption style from phreatomagmatic to magmatic is the exhaustion of external water for hydroexplosion at the loci of phreatomagmatic explosions (Sheridan and Wohletz, 1983; Wohletz and Sheridan, 1983; Lorenz, 1986). However, the change in the eruption style cannot be accounted for by this explanation if the sedimentary deposits of the Gampo Conglomerate retained plentiful water that could be readily replenished to fuel the hydroexplosions. If this was the case, as implied by the shallowness of the diatreme, the change in the eruption style may have been caused by the fluctuations in the ascent rate of magma, which controls not only the magmatic explosivity (Partitt and Wilson, 1995) but also the migration behavior of nearby groundwater (Delaney, 1982; Kokelaar, 1982), the latter resulting in either efficient mixing of magma and wet sediment and explosions or non-mixing and lava effusion. The lavas and intrusions may therefore have been emplaced within the conduit when consumed external water couldn't be promptly resupplied to the vent or more likely when the rate of magma ascent was greatly reduced. The lavas and intrusions were probably fragmented and mixed up with the diatreme fill by the following phreatomagmatic explosions. They were then incorporated into the mafic volcaniclastic deposit as cognate lithic clasts.

7. CONCLUSIONS

Recent re-exposure of the mafic volcaniclastic deposit at Maegok in the southeastern margin of the Eoil Basin reveals that the deposit has the geometry of a vertical cylinder. A number of features in the deposit and in the surrounding sedimentary deposits can also be interpreted in terms of the processes which operate within and adjacent to the conduit of a phreatomagmatic volcano such as subsidence or collapse and synvolcanic faulting of conduit wall deposits, episodic circulatory mixing of conduit-filling materials, upward flow and lateral intrusion of tephra into the diatreme fill and surrounding sediments, and in situ fragmentation of dense clasts due to shock waves. No convincing evidence for peperitic origin of the deposit, i.e., *in situ* disintegration of magma intruding and mingling with unconsolidated and wet sediments, was found within the deposit. The mafic volcaniclastic deposit at Maegok is therefore interpreted to represent the diatreme or the tephra-filled volcanic neck of a phreatomagmatic volcano, of which the eruption was initiated by the interaction between ascending basaltic magma and unconsolidated, porous, permeable, and probably water-logged gravel and sand deposits of the Gampo Conglomerate. The resultant volcanic edifice is inferred to have had the morphology of a tuff ring, of which the eruption was caused by contact-surface steam explosivity and dominated by Taalian-style activity. The tuff ring is inferred to have had an unstable, shallow (a few hundred meters deep), and funnel-like conduit within the Gampo Conglomerate. A number of features indicate that the Maegok deposit was filling the deeper and narrower part of the conduit. This interpretation has significant implications regarding not only the interpretation of the stratigraphy and structural evolution of the Eoil Basin but also the interpretation of diverse volcanological processes that were prevalent in SE Korea during the Early Miocene.

ACKNOWLEDGMENTS: This work was supported by the Korea Research Foundation Grant (KRF-2006-C00167) funded by the Korean Government (MOEHRD). We thank J.O. Jeong, Y.M. Jeon, and J.S. Kee for assistance and discussions in the field and in the laboratory. The manuscript benefited from careful reviews by Prof. W.H. Ryang and an anonymous reviewer.

REFERENCES

Auer, A., Martin, U. and Nemeth, K., 2007, The Fekete-hegy (Balaton Highland Hungary) "soft-substrate" and "hard-substrate" maar volcanoes in an aligned volcanic complex - Implications for vent geometry, subsurface stratigraphy and the palaeoenvironmental setting. Journal of Volcanology and Geothermal Research, 159, 225–245.

Bahk, J.J. and Chough, S.K., 1996, An interplay of syn- and intereruption depositional processes: the lower part of Jangki Group (Miocene), SE Korea. Sedimentology, 43, 421–438.

Cas, R.A.F. and Wright, J.V., 1987, Volcanic Successions: Modern and Ancient. Allen and Unwin, London, 528 p.

Chwae, U.C., Hwang, J.H., Yun, U. and Kim, D.H., 1988, Geological report of the Eoil sheet, 1:25,000, Report, Korea Institute of Energy and Resources, Taejon, 41 p (in Korean with English abstract).

Delaney, P.Y., 1982, Rapid intrusion of magma into wet rock: Groundwater flow due to pore pressure increases. Journal of Geophysical Research, 87, 7739–7756.

Gernon, T.M., Gilbertson, M.A., Sparks, R.S.J. and Field, M., 2008, Gas-fluidisation in an experimental tapered bed: Insights into processes in diverging volcanic conduits. Journal of Volcanology and Geothermal Research: 174, 49–56.

Grady, E.E. and Kipp, M.E., 1987, Dynamic rock fragmentation. In: Atkinson, B.K. (ed.), Fracture Mechanics. Academic Press, London, 429–475.

Heiken, G. and Wohletz, K., 1985, Volcanic Ash. University of California Press, Berkeley, 246 p.

Hwang, I.G., Chough, S.K., Hong, S.W. and Choe, M.Y., 1995, Controls and evolution of fan delta systems in the Miocene Pohang Basin, SE Korea. Sedimentary Geology, 98, 147–179.

Jeong, J.O., Kwon, C.W. and Sohn, Y.K., 2006, The Paljori Tuff in the Miocene Eoil Basin, SE Korea: primary and secondary volcaniclastic sedimentation in a fluvio-lacustrine setting. Journal of the Geological Society of Korea, 42, 175–197.

Jeong, J.O., Kwon, C.W. and Sohn, Y.K., 2008, Lithofacies and architecture of a basin-wide tuff unit in the Miocene Eoil Basin, SE Korea: Modes of pyroclastic sedimentation, changes in eruption style, and implications for basin configuration. Geological Society of America Bulletin, 120, 1263–1279.

Jolivet, L., Tamaki, K. and Fournier, M., 1994, Japan Sea, opening history and mechanism: A synthesis. Journal of Geophysical Research, 99, 22237–22259.

Kokelaar, P., 1982, Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. Journal of the Geological Society, London, 139, 21–33.

Kokelaar, P., 1986, Magma-water interactions in subaqueous and emergent basaltic volcanism. Bulletin of Volcanology, 48, 275–289.

Lee, G.H., Kim, H.J., Suh, M.C. and Hong, J.K., 1999, Crustal structure, volcanism, and opening mode of the Ulleung Basin, East Sea (Sea of Japan). Tectonophysics, 308, 503–525.

Lee, H.K., Moon, H.S., Min, K.D., Kim, I.S., Yun, H. and Itaya, T., 1992, Paleomagnetism, stratigraphy and geologic structure of the Tertiary Pohang and Changgi basins: K-Ar ages for the volcanic rocks. Journal of Korea Institute of Mining Geology, 25, 337–349 (in Korean with English abstract).

Lorenz, V., 1986, On the growth of maars and diatremes and its relevance to the formation of tuff rings. Bulletin of Volcanology, 48, 265–274.

Lorenz, V., Zimanowski, B. and Buettner, R., 2002, On the formation of deep-seated subterranean peperite-like magma-sediment mixtures. Journal of Volcanology and Geothermal Research, 114, 107–118.

Lorenz, V. and Kurszlaukis, S., 2007, Root zone processes in the phreatomagmatic pipe emplacement model and consequences for the evolution of maar-diatreme volcanoes. Journal of Volcanology and Geothermal Research, 159, 4–32.

McPhie, J., Doyle, M. and Allen, R., 1993, Volcanic Textures: a Guide to the Interpretation of Textures in Volcanic Rocks. CODES Key Center, University of Tasmania, Hobart, 198 p.

Moore, J.G., Nakamura, K. and Alcaraz, A., 1966, The 1965 eruption of Taal volcano. Science, 151, 955–960.

Partitt, E.A. and Wilson, L., 1995, Explosive volcanic eruptions - IX. The transition between Hawaiian- style lava fountaining and Strombolian explosive activity. Geophysical Journal International, 121, 226–232.

Ross, P.-S., Peate, I.U., McClintock, M.K., Xu, Y.G., Skilling, I.P., White, J.D.L. and Houghton, B.F., 2005, Mafic volcaniclastic deposits in flood basalt provinces: A review. Journal of Volcanology and Geothermal Research, 145, 281–314.

Sheridan, M. and Wohletz, K., 1983, Hydrovolcanism: Basic considerations and Review. Journal of Volcanology and Geothermal Research, 17, 1–29.

Shimazu, M., Yoon, S. and Tateishi, M., 1990, Tectonics and volcanism in the Sado-Pohang Belt from 20 to 14 Ma and opening of the Yamato Basin of the Japan Sea. Tectonophysics, 181, 321–330.

Sohn, Y.K. and Chough, S.K., 1992, The Ilchulbong tuff cone, Cheju Island, South Korea: depositional processes and evolution of an emergent, Surtseyan-type tuff cone. Sedimentology, 39, 523–544.

Sohn, Y.K., 1996, Hydrovolcanic processes forming basaltic tuff rings and cones on Cheju Island, Korea. Geological Society of America Bulletin, 108, 1199–1211.

Sohn, Y.K., Rhee, C.W. and Shon, H., 2001, Revised stratigraphy and reinterpretation of the Miocene Pohang basinfill, SE Korea: sequence development in response to tectonism and eustasy in a back-arc basin margin. Sedimentary Geology, 143, 265–285.

Sohn, Y.K. and Son, M., 2004, Synrift stratigraphic geometry in a transfer zone coarse-grained delta complex, Miocene Pohang Basin, SE Korea. Sedimentology, 51, 1387–1408.

Sohn, Y.K. and Park, K.H., 2005, Composite tuff ring/cone complexes in Jeju Island, Korea: possible consequences of substrate collapse and vent migration. Journal of Volcanology and Geothermal Research, 141, 157–175.

Sohn, Y.K., Park, K.H. and Yoon, S.H., 2008, Primary versus secondary and subaerial versus submarine hydrovolcanic deposits in the subsurface of Jeju Island, Korea. Sedimentology, 55, 899–924.

Son, M., 1998, Formation and evolution of the Tertiary Miocene basins in southeastern Korea: Structural and paleomagnetic approaches, Ph.D. thesis, Pusan National University, Pusan, 233 p.

Son, M., Seo, H.J. and Kim, I.S., 2000, Geological structures and evolution of the Miocene Eoil Basin, southeastern Korea. Geosciences Journal, 4, 73–88.

Son, M., Kim, I.S. and Sohn, Y.K., 2005, Evolution of the Miocene Waup Basin, SE Korea, in response to dextral shear along the southwestern margin of the East Sea (Sea of Japan). Journal of Asian Earth Sciences, 25, 529–544.

Waters, A.C. and Fisher, R.V., 1971, Base surges and their deposits: Capelinhos and Taal volcanoes. Journal of Geophysical Research, 76, 5596–5614.

White, J.D.L., 1991, Maar-diatreme phreatomagmatism at Hopi Buttes, Navajo Nation (Arizona), USA. Bulletin of Volcanology, 53, 239–258.

White, J.D.L., 1996, Impure coolants and interaction dynamics of phreatomagmatic eruptions. Journal of Volcanology and Geothermal Research, 74, 155–170.

White, J.D.L., McPhie, J. and Skilling, I., 2000, Peperite: a useful genetic term. Bulletin of Volcanology, 62, 65–66.

Wohletz, K. and Sheridan, M., 1983, Hydrovolcanic eruptions II. Evolution of basaltic tuff rings and tuff cones. American Journal of Science, 283, 385–413.

Yoon, S., Hwang, J.Y. and Jung, C.Y., 1990, Peperite in the Tertiary Yangnam Basin, Korea: 1. Peperite at Maegog. Journal of Geological Society of Korea, 26, 187–194.

Yoon, S., 1997, Miocene-Pleistocene volcanism and tectonics in southern Korea and their relationship to the opening of the Japan Sea. Tectonophysics, 281, 53–70.

Yoon, S.H. and Chough, S.K., 1995, Regional strike slip in the eastern continental margin of Korea and its tectonic implications for the evolution of Ulleung Basin, East Sea (Sea of Japan). Geological Society of America Bulletin, 107, 83–97.

Zimanowski, B., Buettner, R., Lorenz, V. and Haefele, H.-G., 1997, Fragmentation of basaltic melt in the course of explosive volcanism. Journal of Geophysical Research, 102, 803–814.

Manuscript received May 15, 2008
Manuscript accepted September 17, 2008