INTRODUCTION

The majority of the world’s explosive volcanic eruptions and earthquakes occur near convergent plate boundaries where two or more tectonic plates move towards one another. Although the volcanic and seismic events occur in the same regions in close succession, the causal relation between them began to be investigated rather recently after the global datasets of earthquakes and volcanic eruptions became available (Linde & Sacks, 1998; Manga & Brodsky, 2006; Walter & Amelung, 2007; Watt et al., 2009). These studies show that an earthquake can increase the activity of a volcano hundreds of kilometres from the epicentre within days to years either by shaking the magma chamber or by rupturing the crust. As for ancient volcanic eruptions and earthquakes, temporal linkages between them could hardly be established because the timescales of paired seismic–volcanic events are beyond the resolution limits of current dating techniques. However, a close relationship between regional tectonics, which would certainly accompany seismicity, and volcanism has been inferred by a number of studies in ancient volcanic fields (e.g., Aguirre-Diaz & Labarthe-Hernandez, 2003; Brogi et al., 2010; Nairn et al., 1998). Although most of these studies discuss the relationship on a timescale of $10^5$–$10^6$ years, a recent study has shown that a paired tectonic–volcanic event, which occurred on a human timescale (days to months), can be deciphered from the field relationship of eruption sequences (Gravley et al., 2007).

In this paper, we introduce a thin (2–4 m thick) but laterally extensive ignimbrite, named the Southern Kusandong Tuff (SKT), from a Cretaceous continental backarc basin of Korea (Figure 1). The tuff is a single, physically continuous unit but is characterised by lateral compositional variations and variable palaeoflow patterns, suggesting that the tuff originated from two volcanic sources. Here we shows that the tuff resulted from two pyroclastic density currents (PDCs), which were generated by synchronous eruptions of two volcanoes in the nearby volcanic arc, most likely triggered by a regional seismic event, and then collided with each other in the backarc region within minutes. The paired seismic–volcanic event raises concerns for intensified volcanic hazards over large areas in regions of clustered volcanoes.

Geological record of a Cretaceous seismic event paired with multiple volcanic eruptions

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Abstract

Explosive volcanic eruptions can occur within days to years after an earthquake, suggesting a causal relation between them. Such paired seismic–volcanic events in the past, which occurred on a human timescale, can only be confirmed by field relationship of eruptive products. The Southern Kusandong Tuff (SKT) is an ignimbrite in a Cretaceous backarc basin of Korea, which shows north-to-south variations in grain componentry, chemical composition, magnetic properties and palaeoflow patterns, suggesting that the tuff originated from two volcanic sources. Here we shows that the tuff resulted from two pyroclastic density currents (PDCs), which were generated by synchronous eruptions of two volcanoes in the nearby volcanic arc, most likely triggered by a regional seismic event, and then collided with each other in the backarc region within minutes. The paired seismic–volcanic event raises concerns for intensified volcanic hazards over large areas in regions of clustered volcanoes.
significant implications regarding the emplacement processes of PDCs and volcanic hazard assessment in arc regions because the tuff provides the first field evidence for collision and mixing of PDCs, from which the physical properties of PDCs can be inferred, and raises the possibility of intensified volcanic hazards in arc regions due to multiple-vent eruptions over wide areas within a short period of time.

2 | SOUTHERN KUSANDONG TUFF

The southeastern part of the Korean Peninsula was part of a continental volcanic arc in the Cretaceous, which was a lateral extension of the Japanese Arc formed by subduction of the proto-Pacific plate under the Eurasian continent (Chough & Sohn, 2010). The backarc basin behind the arc, named the Gyeongsang Basin, was the site of thick (~9 km) accumulation of non-marine, sedimentary and volcanic deposits (Choi, 1986). The SKT is a 2–4 m thick, laterally extensive (c. 100 km), non-welded, pumice-free, rhyolitic tuff, which was emplaced by highly expanded, dilute and turbulent PDCs (Sohn et al., 2005, 2009). The tuff has been used as an excellent key bed in the basin because of its unique lithology and the ease of recognition in the field (Chang et al., 1977; Jeon & Sohn, 2003). The tuff overlies the Haman Formation composed of purple mudstones and thin interbeds of sandstones and siltstones with abundant ripple marks, mudcracks, calcrete nodules and dinosaur tracks, indicating well-drained and oxidising floodplain environment (Choi, 1986). The tuff is overlain by the Jindong Formation dominantly composed of black shales and thin interbeds of sandstones and siltstones with abundant dinosaur tracks, which were deposited in shallow lacustrine environments (Houck & Lockley, 2006).

Statement of significance

Clustering of volcanic eruptions is a well-known phenomenon in many volcanic fields, suggesting the causal relation between volcanic eruptions and earthquakes. This paper provides an extreme endmember example of a paired seismic–volcanic event that has never been reported so far, i.e., synchronous eruptions of two volcanoes in a volcanic arc triggered by a regional seismic event and the collision of two pyroclastic density currents in the backarc region. This finding has significant implications regarding volcanic hazard assessment because synchronised eruptions of multiple volcanoes paired with a seismic event can result in intensified geological hazards over large areas.

FIGURE 1 Location and geology of the study area. (a) Distribution of Cretaceous sedimentary basins in Korea. (b) Simplified geologic map of the southern part of the Gyeongsang Basin. The sedimentary rocks are filling a backarc basin behind a volcanic arc platform, which is composed of volcanic/volcaniclastic rocks and later granitic plutons (Chough & Sohn, 2010). The locations and boundaries of the calderas are after Cha and Yun (1988). The Southern Kusan Dong Tuff (SKT), intercalated in the middle of the basinfill, is Cenomanian in age (Jwa et al., 2009) and predates the volcanic/volcaniclastic rocks and calderas in the arc platform, which are Campanian to Palaeocene in age. Therefore, the SKT is not related to any of the currently known calderas. The palaeoflow data are from Sohn et al. (2005), Sohn et al. (2009) [Colour figure can be viewed at wileyonlinelibrary.com]
The SKT shows the identical sequence of deposit structures throughout the c. 100 km long outcrop trace, composed of a thin (4–33 cm thick) but remarkably continuous, parallel- to low-angle inclined-stratified division at the base (basal layered division, BLD) and an overlying, thicker (1.3–3.8 m thick) and massive division (Sohn et al., 2005, 2009). Modal grain componentry, grain fabrics, anisotropy of magnetic susceptibility (AMS) and bulk magnetic susceptibility were analysed together with conventional petrographic observations under microscope to characterise the SKT. These analyses show that the SKT has subtly to contrastingly different characteristics between the northern and the southern parts. They are therefore referred to as SKT$_{north}$ and SKT$_{south}$, respectively, hereafter, although they constitute a single, physically continuous ignimbrite unit.

The massive division of the SKT$_{north}$ between localities 1 and 18 consists of 43.7 vol.% crystals (mostly feldspar and quartz), 0.9 vol.% accidental lithics (mostly mudstone fragments) and 54.9 vol.% matrix (vitric ash and crystal fragments smaller than 0.1 mm in the long axis in thin section; Jeong et al., 2005). K-feldspar crystals are about twice more abundant than quartz crystals. The palaeoflow vectors inferred from an analysis of grain fabrics and AMS generally radiate away from a source several tens of kilometres east of the present exposures, which we named the Masan source, and are directed towards the southwest at the southernmost locality 1 (Sohn et al., 2005, 2009; Figure 1b). The bulk magnetic susceptibility is very high, generally in excess of $10^{-5}$ emu (Figure 2).

On the other hand, the massive division of the SKT$_{south}$ at the southernmost localities 2-1 and 2-2 comprises smaller amounts of crystals (26.5 vol.%) and much more abundant (72.5 vol.%) matrices with subequal amounts of quartz and K-feldspar crystals. Palaeoflow vectors are towards the northeast, indicating a southwestern source, which we named the Namhae source (Figure 1b). Bulk magnetic susceptibility is markedly smaller than that of the SKT$_{north}$, having values far below $10^{-5}$ emu (Figure 2). The difference in the bulk magnetic susceptibility was confirmed by petrographic observations, which show that the SKT$_{north}$ contains 0.44 vol.% opaque minerals (magnetite) whereas the SKT$_{south}$ is devoid of opaque minerals.

These differences in particle componentry, magnetic properties and palaeoflow vectors have led to some confusion regarding the origin of the tuff. For example, Kim et al. (2013) suggested that the SKT$_{north}$ and the SKT$_{south}$ are different ignimbrite units based on different U-Pb zircon ages, which are $104.1 \pm 1.3$ and $103.4 \pm 2.1$ to $95.79 \pm 0.98$ Ma, respectively. However, we found new exposures between the SKT$_{north}$ and the SKT$_{south}$, which clearly indicate that they have an intertonguing relationship with each other, constituting a composite but single ignimbrite unit. At locality 3-2, the SKT shows distinctive structures, such as multiple internal layering of decimetre-thick units with different grain sizes, loaded or eroded internal layer boundaries (Figure 3a) and cross-stratification produced by megaripple migration at the top (Figure 3b). At locality 3-1, the SKT is overall massive and does not show any distinguishing structures. However, the palaeoflow vectors obtained at various levels of the tuff are highly variable and commonly opposing (Figure 4); the bulk magnetic susceptibility has the values of either the SKT$_{north}$ or the SKT$_{south}$ at the same localities, depending on the level of the measurement (Figure 5); and the ratio of quartz to K-feldspar crystals also shows similar variations (Table 1; Figure 5). All these features suggest that the SKT at these localities is a mixture of the SKT$_{north}$ and the SKT$_{south}$.

### 3 INTERPRETATIONS

Ignimbrites commonly show lateral variations in lithic contents and other lithological properties, not because of the proximal-to-distal changes in the transport capacity of PDCs, but because of their sequential eruptions through propagating fractures that developed across different lithologies (Hildreth & Mahood, 1986; Wilson & Hildreth, 2003). The lateral variations of the SKT cannot, however, be explained by multiple-vent eruptions along a fracture of a volcano because a number of data suggest that the SKT originated...
from compositionally different magmas that evolved under different volcanoes. This interpretation is based on (1) the absence of magnetite crystals and the very low magnetic susceptibility in the SKT_{south}, (2) the difference in the ratio of quartz to K-feldspar crystals, (3) the difference in major element composition of the ash matrices, particularly in Na_{2}O (~1.36 wt.% in SKT_{south} and ~7.37 wt.% in SKT_{north}), K_{2}O (~2.93 wt.% in SKT_{south} and ~0.18 wt.% in SKT_{north}), and MgO (~2.66 wt.% in SKT_{south} and ~0.41 wt.% in SKT_{north}; Jeong et al., 2005), and (4) the opposing (southwestward for SKT_{north} vs. northeastward for SKT_{south}) palaeoflow directions. We therefore conclude that the SKT originated from two volcanic sources, one in the east (Masan source) and the other in the southwest (Namhae source) of the present exposures. The inferred source vent areas of the SKT are covered by later, several kilometre-thick arc volcanics, and there are no known volcanoes or calderas in these areas that can be linked with the SKT.
| Location | North Orientation | Imbrication | Bedding plane |
|----------|------------------|-------------|---------------|
| 15       | N=62 V.M.=89-269 C.I.=±17 | S89W | N=26 V.M.=24 C.I.=±37 |
| 35       | N=111 V.M.=78-258 C.I.=±54 | S78W | N=46 V.M.=13 C.I.=±43 |
| 55       | N=25 V.M.=143-323 C.I.=±90 | N37W | N=35 V.M.=7 C.I.=±34 |
| 75       | N=417 V.M.=150-330 C.I.=±3 | N30W | N=79 V.M.=16 C.I.=±21 |
| 105      | N=22 V.M.=114-294 C.I.=±90 | N66W | N=30 V.M.=40 C.I.=±51 |
| 115      | N=26 V.M.=104-284 C.I.=±70 | N76W | N=13 V.M.=68 C.I.=±90 |
| 135      | N=42 V.M.=86-266 C.I.=±90 | S86W | N=42 V.M.=12 C.I.=±49 |
| 150      | N=37 V.M.=63-243 C.I.=±90 | S63W | N=34 V.M.=37 C.I.=±24 |
| 180      | N=34 V.M.=73-253 C.I.=±24 | S73W | N=30 V.M.=16 C.I.=±15 |
| Unit I   | N=17 V.M.=119-299 C.I.=±45 | N61W | N=30 V.M.=16 C.I.=±25 |
| Unit II  | N=22 V.M.=159-339 C.I.=±63 | N21W | N=45 V.M.=4 C.I.=±20 |
| Unit III | N=24 V.M.=54-234 C.I.=±90 | S54W | N=31 V.M.=40 C.I.=±49 |
| Unit IV  | N=17 V.M.=176-356 C.I.=±40 | N4W | N=14 V.M.=2 C.I.=±48 |
| Unit VI  | N=16 V.M.=23-203 C.I.=±64 | S23W | N=23 V.M.=12 C.I.=±26 |
In the mid-zone between the SKT\textsubscript{north} and the SKT\textsubscript{south}, the SKT shows complicated characteristics (Figure 5). At locality 3-2, the middle part of the tuff has the characteristics of the SKT\textsubscript{south}, whereas the topmost and bottommost parts have the characteristics of the SKT\textsubscript{north}. At locality 3-1, the lower part of the tuff has the characteristics of the SKT\textsubscript{north}, whereas the rest shows mixed characteristics of the SKT\textsubscript{north} and the SKT\textsubscript{south}. Highly variable palaeoflow vectors at the same localities are also notable. The complicated componentry, magnetic properties and palaeoflow patterns in these localities are interpreted to be due to collision and mixing of two PDCs derived from two opposite sources. Given the duration of ignimbrite-forming eruptions, which commonly lasts hours (Cioni et al., 2015), and the time required for ignimbrite deposition from turbulent suspension currents, which can be as short as minutes (Dade, 2003), these PDCs are inferred to have been generated almost at the same time by synchronous eruptions of two volcanoes in the arc and collided with each other on an alluvial plain in the backarc region within minutes after eruptions. The volcanoes are presumed to have been more than a hundred kilometres apart, considering the average spacing (\textasciitilde50 km) of volcanoes in Andean-type subduction zone (Shimozuru & Kubo, 1983) and the opposing palaeoflow directions of the SKT at the collision zone, which suggest that the PDCs...

**TABLE 1** Modal composition (in vol.%) of the massive division of the Southern Kusandong Tuff at localities 3-1 and 3-2. Modal analysis of particle componentry was carried by counting one thousand points on each thin-section under polarising microscope. Accidental crystals include metamorphic quartz, muscovite and microcline, which were derived from the basement rocks or basinfill sediments. Particles smaller than 0.1 mm in diameter were counted as matrix.

| Locality number | 3-1 | 3-2 |
|-----------------|-----|-----|
| Vertical levels and units | 15 cm | 75 cm | 105 cm | 135 cm | 180 cm | Unit I | Unit II | Unit III | Unit IV | Unit VI |
| Juvenile crystals | | | | | | | | | | |
| Quartz | 4.8 | 6.1 | 3.0 | 3.6 | 5.7 | 5.2 | 4.1 | 4.0 | 6.1 | 4.9 |
| K-Feldspar | 8.8 | 3.6 | 6.6 | 6.9 | 6.4 | 8.5 | 3.6 | 4.4 | 5.0 | 8.2 |
| Plagioclase | 14.7 | 18.5 | 14.1 | 15.7 | 19.0 | 12.6 | 17.8 | 19.1 | 21.0 | 37.2 |
| Biotite | 0.9 | 0.8 | 1.1 | 0.5 | 0.8 | 0.7 | 0.4 | 1.4 | 0.3 | 2.9 |
| Opaque | 0.6 | 0.3 | 0 | 0.1 | 0.2 | 0 | 0.3 | 0 | 0.2 | 0.7 |
| Zircon | 0 | 0.2 | 0.2 | 0 | 0.1 | 0 | 0 | 0 | 0.2 | 0.2 |
| Matrix | 70.1 | 70.2 | 74.9 | 73.0 | 67.7 | 72.9 | 73.7 | 71.7 | 67.2 | 45.2 |
| Accidental lithics and crystals | 0.1 | 0.3 | 0.1 | 0.2 | 0.1 | 0.1 | 0.1 | 0 | 0 | 0.7 |
did not originate from two adjacent volcanoes in the arc. The most likely trigger of the eruptions that can affect two widely spaced volcanoes at the same time is a regional seismic event that can shake magma chambers hundreds of kilometres from the epicentre (Linde & Sacks, 1998; Manga & Brodsky, 2006; Walter & Amelung, 2007; Watt et al., 2009). This seismic event was possibly paired with or accompanied by tectonic subsidence, or ‘collateral subsidence’ in the sense of Gravley et al. (2007), in the basin, as represented by the abrupt facies transition of the basinfill from the fluvial redbeds of the Haman Formation into the dark gray lacustrine deposits of the Jindong Formation after the eruption of the SKT (Sohn et al., 2009).

4 | IMPLICATIONS

The deposit features of the SKT in the collision zone of two PDCs provide important implications regarding the physical properties and depositional processes of PDCs, which have been a contentious issue since the birth of volcaniclastic sedimentology (Fisher, 1966; Sparks, 1976). The overall poor sorting and structureless nature of most ignimbrites have been attributed either to continuous and simultaneous deposition of both coarse and fine particles from a boundary zone that was developed beneath a turbulent flow (Branney & Kokelaar, 2002; Fisher, 1966) or to en masse deposition of high-concentration, poorly expanded, laminar flows (Sparks, 1976). The deposit features of the SKT in the collision zone suggest that the deposition occurred more likely in a progressive layer-by-layer fashion from turbulent flows that comprised multiple pulses with different grain sizes and variable palaeoflow vectors. The variable palaeoflow vectors are attributed in part to inherently random motion of turbulence structures in the PDCs and in part to enhanced turbulence and flow diversion due to PDC collision. Dense and laminar flows colliding with each other can possibly produce intertonguing deposition relationship because their deposits can be produced by stacking of multiple surges or rollwaves (Davies, 1986; Major, 1997). However, the componentry of the SKT, including the magnetic minerals in addition to the quartz and K-feldspar crystals, suggests that the PDCs that formed the SKT could be thoroughly mixed with each other at the particle level, thereby resulting in the componentry intermediate between the SKT north and the SKTsouth at locality 3-1. Such a mixing process is unlikely in dense and laminar flows, providing strong evidence for emplacement of the SKT from turbulent suspension currents.

Many examples of ‘clustered’ eruptions on a timescale of $10^2$–$10^5$ years have been reported from volcanic fields with active volcanotectonism (Charlier et al., 2003; Gravley et al., 2007; Nairn et al., 1998). The synchronous multiple-vent eruptions of the SKT probably represent an endmember in the closeness of eruption clustering hitherto documented. This finding therefore has significant implications regarding volcanic hazard assessment in arc regions or in regions of clustered volcanoes, because such synchronised eruptions are sure to cause disasters over much larger areas within a short period of time. This study also shows that the volcaniclastic deposits in volcanic arcs or in areas of clustered volcanoes can preserve the records of palaeoearthquakes, suggesting the potential significance of volcaniclastic deposits in the study of palaeoseismology.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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