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The Irosin co-ignimbrite ash-fall deposit: A widespread tephra marker in the Bicol arc, south Luzon, Philippines

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ABSTRACT

The Irosin caldera, which is located in the province of Sorsogon, southern Luzon, Philippines, represents the largest extrusion of highly silicic magmas in the Bicol arc at ca. 41 cal ka BP. The 41 cal ka BP rhyolitic eruption led to a collapse and formation of the 11 km–wide Irosin caldera. This paper presents the results of the stratigraphy, grain assemblage, morphology, and geochemistry of the recently discovered rhyolitic fine ash which is exposed in the crater of Inascan scoria cone, 80 km from Irosin caldera.

The morphology of glass shards obtained at Inascan cone is not only pumice-type but also bubble-wall-type glass shards which are typical of a co-ignimbrite ash. The mineral assemblage of the fine ash is quite similar to those of Irosin pumice. The refractive index, measured using the thermal immersion method, together with geochemical analyses of glass shards from the fine rhyolitic ash deposits and ignimbrite deposits from Irosin caldera, both indicate a strong geochemical similarity between the ignimbrite and fine ash deposits. Thus, the tephra sequence at Inascan scoria cone is interpreted as co-ignimbrite ash falls sourced from the 41 cal ka BP catastrophic eruption that formed the Irosin caldera. The Irosin co-ignimbrite ash-fall deposit, which measures 1.3 m thick and 80 km away from its source volcano, represents the most explosive eruption in the Bicol arc. The identification of the Irosin co-ignimbrite ash-fall deposit is a valuable contribution to the establishment of a chronological framework of widespread tephra in the Philippines as well as a potential regional tephra marker.

1. Introduction

Widespread tephras generated from large-scale pyroclastic flows such as co-ignimbrite ash falls, provide useful time-marker beds (Machida and Arai, 1976, 2003; Sparks and Walker, 1977). The identification and establishment of widespread tephra is very important not only in understanding volcanic processes but also in its application to related fields of geology. In tectonically active regions such as the Philippines (Fig. 1), tephra deposits as marker beds have a potentially wide application to other fields of earth science. Since the discovery of two widespread tephras, the Kikai-Akahoya (K-Ah) and Aira-Tn (AT) tephras, the catalogue of tephras in Japan has significantly been refined (e.g., Machida and Arai, 1983, 2003).

Previous tephra studies in the Philippines (e.g., Catane et al., 2003, 2005), particularly in the Bicol arc, recognized proximal tephras, which were useful in establishing the stratigraphy of a particular eruptive event. This study, for the first time, recognized a widespread tephra marker in the Bicol arc and in the Philippines. This paper presents a correlation between a vitric ash fall 80 km from the caldera to the Irosin ignimbrite, which was erupted during a caldera-forming event (Delfin et al., 1993), in terms of mineralogy, chemistry and physical characteristics. This widespread tephra is important not only in understanding the eruptive history of the Irosin caldera and the active Bulusan volcano (Fig. 1), but also in providing a chronological framework of the volcanism of the Bicol Arc.

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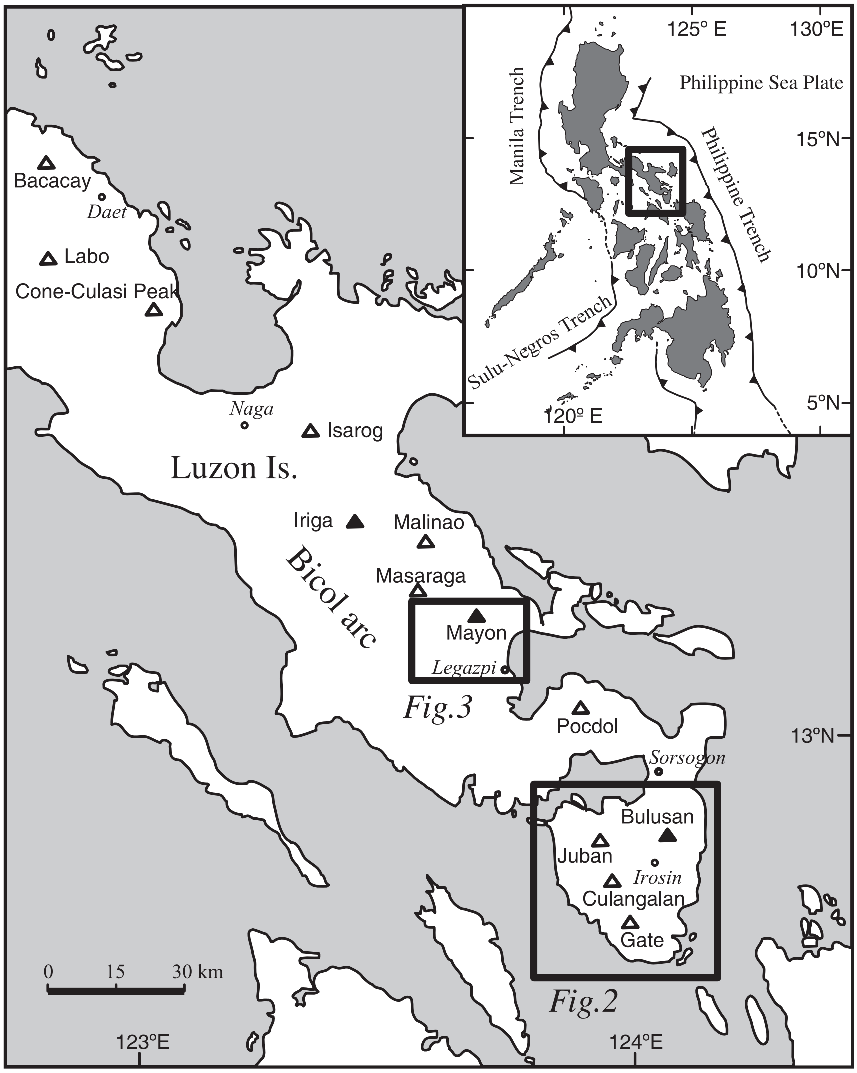

Fig. 1. Index maps. (A) Map showing the Philippines Islands. Rectangle indicates approximate area of the Bicol arc. (B) Distribution of the major volcanoes in the Bicol arc (modified from PHIVOLCS, 2002). Filled triangles denote active volcanoes. Open triangles denote inactive and potentially active volcanoes. Bulusan volcano is the only active post-caldera volcano in the Bulusan Volcanic Complex (BVC). Rectangles indicate the areas for Figs. 2 and 3, respectively. Open circles indicate major city or town.

2. Geological outline of Irosin caldera

2.1. Geological setting

Irosin caldera is part of the Bulusan Volcanic Complex (BVC) which lies in the southern part of the Bicol arc (Fig. 1). The arc is associated with the westward subduction of the Philippine Sea Plate along the Philippine Trench (Aurelio et al., 1997; Castillo and Newhall, 2004), and consists of northwesterly aligned andesitic volcanic centers in southern Luzon (Newhall, 1979; Knittel-Weber and Knittel, 1990) (Fig. 1). Three of these volcanoes are classified as active namely, Iriga, Mayon and Bulusan (Fig. 1). Domes and cones occur in association with a large stratovolcano such as Mayon, and the others are associated with a more complex volcanic system such as the BVC.

2.2. Irosin ignimbrite and caldera

The BVC in the southern tip of the Bicol arc consists of the Bulusan volcano, Irosin caldera and older volcanic centers (Fig. 2). The formation of the 11-km wide Irosin caldera represents the largest single extrusion of dacite to rhyolite magmas in the Bicol arc (Delfin et al., 1993). The Irosin ignimbrite is widely distributed around the caldera (Fig. 2). It was formed by the eruption of the Irosin ignimbrite, which is mostly structureless, poorly to moderately sorted, dacitic to rhyolitic pyroclastic flows (Delfin et al., 1993; McDermott et al., 2005). The ignimbrite was divided into two units: lower fine and upper coarse (Mirabueno et al., 2007), but the Irosin ignimbrite consisted mostly of the latter (Kobayashi et al., in preparation). Apart from clast size, both units are distinguished by stratification. The upper coarse unit is commonly structureless, whereas the lower fine unit commonly exhibits stratification. The total volume of the Irosin ignimbrite was estimated to be 60 km^3 in DRE (Delfin et al., 1993), corresponding to a VEI of 7. The caldera formation represents the second stage of the three-stage eruptive history of the BVC. Previous studies such as Delfin et al. (1993) and McDermott et al. (2005) did not describe a plinian eruption that preceded the ignimbrite-forming eruption, but a sub-plinian pumice fall deposit is present around the caldera at three localities (Kobayashi et al., in preparation). The actual distribution is difficult to establish due to very few pumice fall outcrops, but the main distribution pattern is likely to the north. The glass chemistry

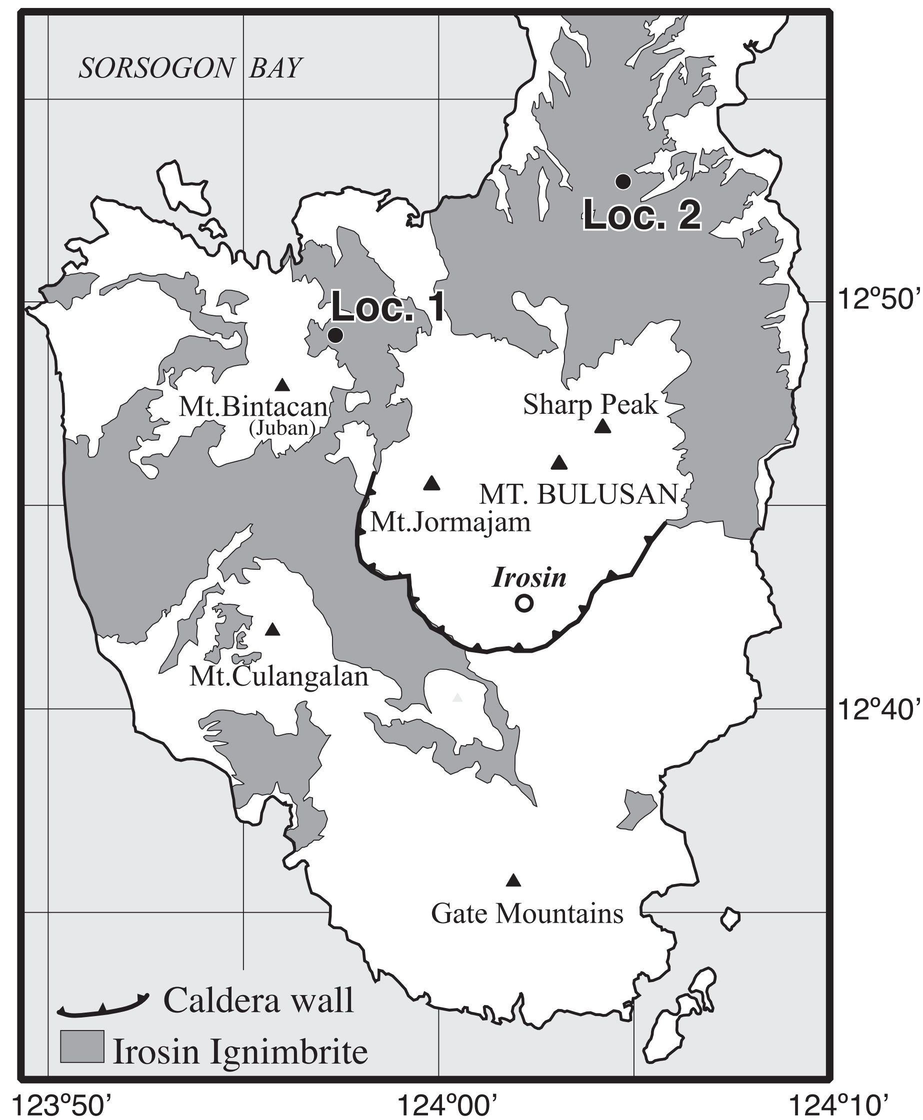

Fig. 2. Map showing the distribution of the Irosin ignimbrite (after Delfin et al., 1993; McDermott et al., 2005). Filled triangles and circles represent volcanoes and sampling sites (Locs. 1 and 2), respectively. Solid line traces the outline of the Irosin caldera rim.

of the pumice sample shows 75.8 wt. % of SiO_2, which is consistent with a rhyolite composition. An eruption age of the ignimbrite have been reported as ca. 41 cal ka BP by radiocarbon dating (Mirabueno et al., 2007), and 0.04 ± 0.06 Ma by K–Ar dating (Ozawa et al., 2004).

Cone-building episode constituted the first stage which commenced at 1.10 Ma, and formed the pre-caldera andesitic volcanoes. Post-caldera volcanism in the latest stage formed domes and stratovolcanoes, including the active volcano, Bulusan (Newhall and Dzurisin, 1988).

2.3. Fine ash falls on Inascan scoria cone

A sequence of rhyolitic and basaltic tephra layers was discovered at a former crater of Inascan scoria cone, one of the basaltic cones at the western slope of Mayon volcano (Fig. 3). The crater was mostly dissected, and the eroded morphology of the basaltic cones indicates that they are older than Mayon volcano. Based on AMS radiocarbon dates, the oldest eruptive event at Mayon volcano occurred shortly after 20 cal ka BP (Mirabueno et al., 2006). The tephra sequence at Inascan (Loc. 3 in Fig. 3) consists of a lower, white to beige rhyolitic ash and an upper, indurated and stratified basaltic lapilli and ash (Fig. 4). The rhyolitic tephras which measure a total of 1.3 m in thickness consist mostly of pumice-type and bubble-wall-type glass shards, with small amount of pumice fragments indicating a volcanic source far from the location of Inascan scoria cone. They are composed of at least 12 units of mainly fine sand to silt size ashes. The maximum diameter of grain is 4 mm. The upper basaltic tephra units have thickness of more than 2 m. They are composed of coarse sand and fine to medium gravel-sized lapilli clasts, which were probably derived from an unnamed cone 1 km northwest of Inascan. Soil was absent at the contact of the basaltic and rhyolitic tephras, but wavy and soft sediment deformation structures were present (Fig. 4).

3. Experimental procedures

3.1. Sampling sites

Sampling locations are shown in Figs. 2 and 3. Seven samples were analyzed for their petrographic and/or major chemical compositions. Iro 1, 2 and 3 are samples from Irosin ignimbrites

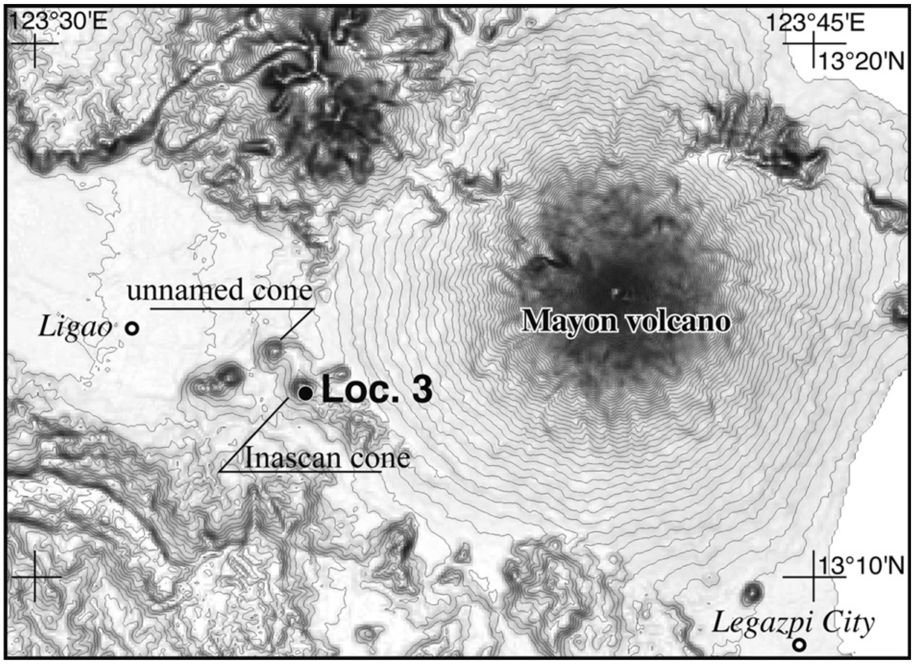

Fig. 3. Geomorphological map of Mayon volcano, Inascan scoria cone and unnamed scoria cone, the likely source of the basaltic tephra overlying the co-ignimbrite ash fall. Filled circle indicates Loc. 3, the former crater of Inascan scoria cone. Slope gradation map (Sasaki et al., 2008) made by H. Sasaki was used as base map. Contour interval is 20 m.

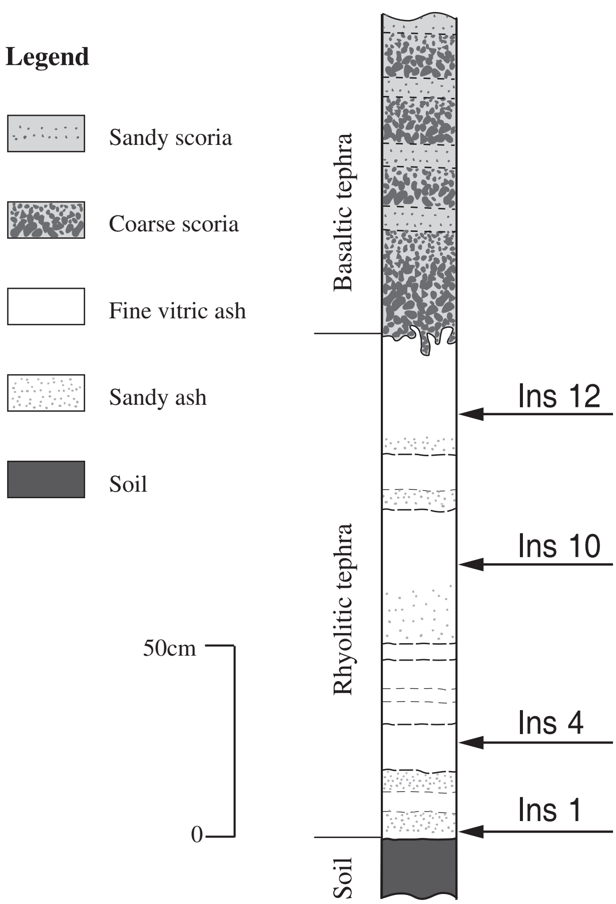

Fig. 4. Stratigraphy of rhyolitic and basaltic tephra layers at Inascan scoria cone and sampling horizons for Ins 1, 4, 10 and 12. Note the lack of soil horizon and presence of soft sediment structures at the contact of upper basaltic and lower silicic tephra deposits. Location of Inascan scoria cone is shown in Fig. 3.

outcropping around the Irosin caldera (Fig. 2). Samples Iro 1 (Loc. 1: N 12° 49′ 17″, E 123° 57′ 30″) and Iro 2 and 3 (Loc. 2: N 12° 52′ 08″, E 124° 04′ 52″) are pumice clasts from the lower fine and upper coarse units of the ignimbrite, respectively. Iro 3 is a representative matrix sample from the upper coarse unit of the ignimbrite at Loc. 2. Samples Ins 1, 4, 10 and 12, were collected from the 1.3-m thick fine white ash covered by scoria falls near the top of Inascan scoria cone (Loc. 3: N 13° 13′ 34″, E 123° 35′ 10″). To determine systematic changes in chemical composition during eruptive sequence, representative samples were collected from multiple horizons shown in Fig. 4.

3.2. Grain assemblages and refractive index measurement

Each tephra sample was washed on 63-, 125- and 250-μm mesh sieves, and residual grains from between the 63- and 125-μm meshes were mounted on glass slides. The bulk grain composition, heavy mineral composition, and morphological types of volcanic glass shards were examined under the microscope. The refractive indices of volcanic glass shards and heavy mineral phenocrysts were measured using a RIMS 2000, an improved refractive index measuring system using thermal immersion method (Danhara et al., 1992). Refractive indices of more than 30 grains were determined for glass shards (n), plagioclase (n_1), and amphibole (n_2). Measurement errors are estimated to be ±0.0002 for glass shards and ±0.0005 for minerals (Danhara, 1993).

3.3. Major element composition of glass shards with EPMA

EPMA analyses were done on the ignimbrite and co-ignimbrite representative samples to determine the major element composition of the glass shards from Iro 1 and 2, and Ins 1, 4, 10 and 12. Each sample was washed by an ultrasonic cleaner and wet-sieved on a 63-μm mesh sieve. The residual grains were dried at less than 40 °C and embedded into mounts made of polyester resin. Surfaces of the mounts were polished with diamond paste (1 μm) until the internal surfaces of the glass particles were exposed, and coated with carbon. The major oxide compositions of volcanic glass shards of nine major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, and K), were analysed using a scanning electron microscope (SEM, JEOL JSM-7001F) equipped with an energy dispersive X-ray spectrometer (EDS, Oxford INCA X-Max) at the Faculty of Science, Kumamoto University, Japan. The accelerating voltage of EDS was 15 kV, the specimen current was 1 nA, and live time was 50 s. The beam scanning area was 10 μm wide. The ZAF correcting method was adopted to calculate the abundance of the oxides. One point was measured per volcanic glass shard and 16–20 points for each sample. The accuracy and precision of these analyses were checked using an obsidian standard (No. 33 obsidian, Astimex Scientific Ltd.). The AT tephra collected from Shintomi-town (N 32° 05′ 21″, E 131° 27′ 39″) in Kyushu Island, Japan was also analyzed because the glass shards of AT ash are homogeneous (Machida and Arai, 2003) enough to use as in-house standard for checking analytical reproducibility in major element analysis.

4. Results

4.1. Grain assemblages and refractive index of glass shards

The results of the RIMS analyses and mineral assemblage measurement are presented in Fig. 5 and Table 1, respectively. Clast samples (Iro 1 and Iro 2) contained abundant pumice-type glass shards with refractive index of 1.4975–1.4984 with a mode of 1.498 (Fig. 5). Light minerals in the clast samples consisted of plagioclase and rare quartz (Table 1). Plagioclase crystals were commonly euhedral and tabular with a main refractive index ranging from 1.541–1.555 (andesine) with a mode of 1.549. Heavy minerals were cummingtonite, biotite, opaque minerals and zircon. Cummingtonite crystals were euhedral with an index of 1.657–1.662 and a mode of 1.659. Lithic fragments were found in trace amounts.

Iro 3, a sample of the matrix, contained similar mineral assemblage to the clast samples except for the presence of green hornblende, apatite and orthopyroxene and higher concentrations of light minerals and bubble-wall glass shards (Danhara et al., in preparation).

The rhyolitic tephra sample from Inascan cone (Ins 4 in Fig. 4) contained abundant pumice-type and bubble-wall-type glass shards with index and mode of 1.4966–1.4998 and 1.498, respectively (Fig. 5). Light minerals consisted of plagioclase and rare quartz. Plagioclase crystals were euhedral with an index of 1.543–1.555 (andesine) and 1.557–1.559 (labradorite), and the mode is 1.549. Cummingtonite, biotite and opaque minerals were present in the sample (Fig. 5). Euhedral cummingtonite crystals had an index of 1.657–1.662 and a mode of 1.659. Green hornblende was also present.

4.2. Major element compositions of glass shards

Table 2 shows the mean values and standard deviations of major chemical compositions of volcanic glass shards in each sample. All analyzed shards were vitreous and isotropic, and showed no sign of alteration in transmitted or reflected light.

The major chemical compositions of obsidian standard and AT glasses show good agreement with recommended values. The major chemical compositions of glass shards of AT showed homogeneous chemical characteristics (Table 2) that were highly consistent with those reported by previous studies (e.g., Machida and Arai, 2003).

The glass shards from both the ignimbrite and co-ignimbrite deposits showed similar chemical composition as characterized by a narrow range of all major element compositions such as SiO_2 = 77–78 wt.% (Fig. 6). No systematic changes in major chemical compositions were recognized throughout the rhyolitic tephra sequence.

5. Discussion

5.1. Correlation of the Irosin ignimbrite and the rhyolitic tephra at Inascan

Field occurrence of the rhyolitic fine tephra deposits at Inascan cone (Loc. 3) strongly suggests that they are all co-ignimbrite ash falls, as indicated by their glass shard type and particle size. There is

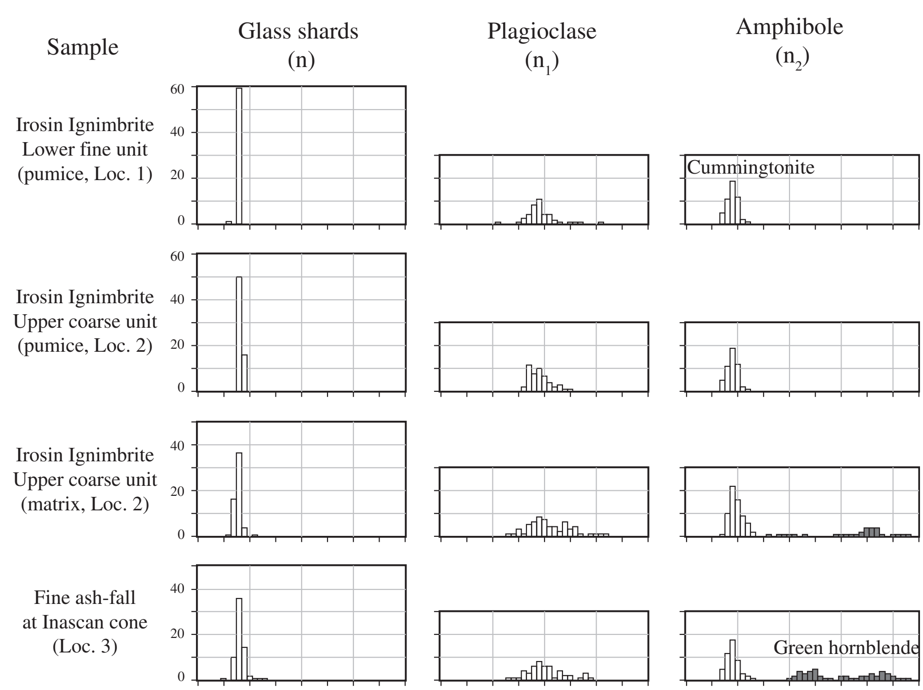

Fig. 5. Refractive indices of analyzed samples. Sampling locations are shown in Figs. 2 and 3.

Table 1
Grain assemblages of analyzed samples.

Sample code	Loc.	Glass type	Grain composition (%)					Heavy minerals composition (%)						
			Gl	Lm	Hm	Rf	Others	Opx	Cpx	GHb	Cum	Opq	Bt	Ap
Iro 1	1	pm	94	4	2	0	0	0	0	0	41	23	36	0
Iro 2	2	pm	93.5	4	2	0.5	0	0	0	1	47	10	41	0
Iro 3	2	pm > bw	83.5	7	2.5	7	0	9	2	9	14.5	26.5	31	4.5
Ins 4	3	pm > bw	94	2.5	1	2	0.5	0	0	8	3.5	5	83.5	0

Notes: pm: pumiceous glass, bw: bubble wall glass, Gl: glass shards, Lm: light minerals, Hm: heavy minerals, Rf: rock fragments. Opx: orthopyroxene, Cpx: clinopyroxene, GHb: green hornblende, Cum: cummigtonite, Opq: opaque minerals, Bt: biotite, Ap: Apatite.

Table 2
Results of EPMA analyses of the major chemical compositions of volcanic glass shards.

Sample		SiO_2	TiO_2	Al_2O_3	FeO[a]	MnO	MgO	CaO	Na_2O	K_2O	Cl	Total	*n*
Ins12	AV.	77.52	0.18	12.70	0.76	0.09	0.17	0.97	4.03	3.58		93.41	20
	S.D.	0.20	0.07	0.10	0.12	0.07	0.04	0.09	0.14	0.17		0.68	
Ins10	AV.	77.66	0.16	12.65	0.74	0.09	0.17	0.97	3.98	3.57		93.11	19
	S.D.	0.21	0.07	0.10	0.11	0.08	0.05	0.07	0.22	0.16		0.74	
Ins4	AV.	77.68	0.18	12.60	0.75	0.08	0.19	1.00	3.97	3.54		93.19	19
	S.D.	0.19	0.06	0.12	0.12	0.06	0.04	0.05	0.13	0.13		0.62	
Ins1	AV.	77.54	0.18	12.66	0.75	0.06	0.16	1.02	3.98	3.64		94.07	18
	S.D.	0.28	0.07	0.16	0.14	0.07	0.04	0.08	0.15	0.22		0.83	
Iro2	AV.	77.45	0.19	12.65	0.75	0.09	0.18	0.97	4.03	3.68		94.62	17
	S.D.	0.14	0.05	0.09	0.09	0.07	0.05	0.05	0.08	0.09		0.48	
Iro1	AV.	77.52	0.17	12.70	0.74	0.10	0.16	0.95	4.05	3.63		95.04	16
	S.D.	0.17	0.05	0.10	0.09	0.07	0.04	0.05	0.08	0.06		0.94	
AT	AV.	77.64	0.16	12.26	1.31	0.05	0.11	1.15	3.78	3.54		94.47	20
	S.D.	0.24	0.07	0.12	0.15	0.07	0.04	0.09	0.12	0.16		0.99	
Obsidian[b]	AV.	74.55	0.07	13.05	1.57	0.10	0.03	0.81	4.05	5.42	0.35	97.62	17
	S.D.	0.16	0.07	0.09	0.11	0.06	0.04	0.05	0.08	0.08	0.03	0.62	

Notes: Data are normalized to 100% on a water-free basis and presented as a mean and standard deviation. *n*: number of analyses.
[a] Total iron oxide as FeO.
[b] Astimex Scientific Ltd.

a possibility that the lowermost coarse layer at Inascan cone may be related to the pumice fall deposit, however there is no evidence to suggest that it can be correlated to the sub-plinian pumice fall deposit observed around the caldera.

Mineral assemblages from the Irosin ignimbrite clasts and matrix are also highly consistent with the rhyolitic fine ash at Inascan cone (Loc. 3). Both biotite and cummingtonite were abundantly present in the rhyolitic tephras at Inascan. The coexistence of biotite and cummingtonite in the pumice is quite a unique characteristic only found in the Irosin ignimbrite in the province of Sorsogon. Green hornblende in the matrix of the Irosin ignimbrite and in the Inascan tephras are accessory minerals. EPMA analyses also show that all samples plot in the same field in the Harker diagrams (Fig. 6). The obvious similarities in the mineral assemblage and geochemistry strongly indicate the same origin for the Irosin ignimbrite and the fine rhyolitic ash at Inascan cone.

In Luzon Island in the Philippines, Pinatubo volcano generated pumice eruptions during the late Pleistocene (Newhall et al., 1996), and thus it is a candidate source of the rhyolitic tephra. However, it seems to be too distant to be the source based on the thickness of the rhyolitic tephra at Inascan. Another possible source of the rhyolitic tephra is from the Taal caldera, also located in Luzon. However, the ignimbrites associated with the Taal calderagenic eruptions were of andesitic to dacitic composition (Listanco, 1994; Catane et al., 2003, 2005), which are not consistent with the rhyolitic composition of the tephra discovered at Inascan.

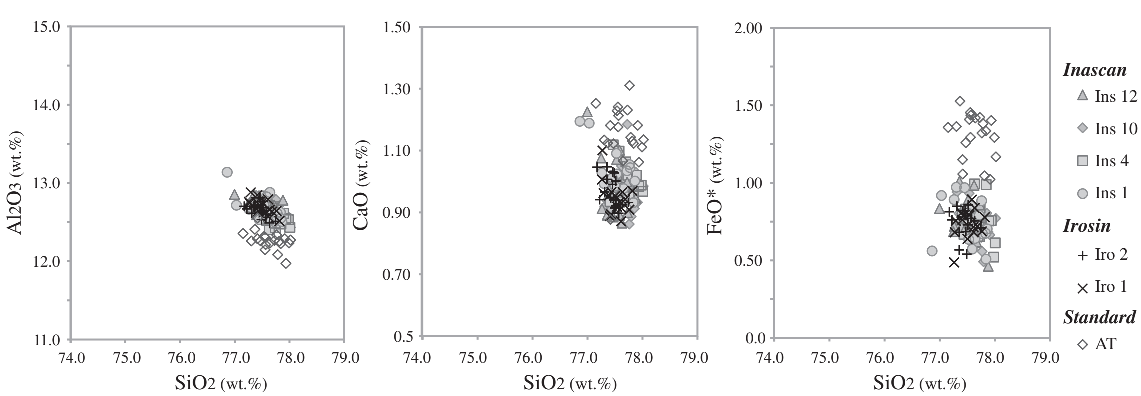

Fig. 6. Harker diagrams showing the chemical composition of representative samples.

5.2. Significance and implication of Irosin co-ignimbrite ash-fall deposit

The tephra at Inascan scoria cone consist of lower fine rhyolitic ash and overlying coarse basaltic ash and lapilli. The absence of soil and presence of wavy structures at the contact of rhyolitic and basaltic tephra layers strongly suggest that the tephras accumulated successively without significant intervening intervals. The thickness and coarse grain size of the overlying basaltic tephra indicate that they originated from the adjacent unnamed scoria cone (Fig. 3). These facts provide a good example of successive eruptions which occurred at two different places, 80 km apart (Fig. 1).

There are many examples of succeeding eruptions which originated from distant volcanoes not only in historical but also in prehistorical times. A famous example in a much larger scale is the Aso-4 ash (Machida et al., 1985). It is a co-ignimbrite ash-fall deposit of the ca. 90 ka Aso-4 ignimbrite from Aso caldera in Kyushu Island, Japan, which is overlain by Kutcharo II/III ignimbrites in Hokkaido Island, Japan. This outcrop is located approximately 1700 km northeast from its source. The good preservation of the fine Aso-4 ash, ca. 15 cm thick is attributed to the rapid deposition of the overlying Kutcharo ignimbrite. This indicates that the two large-scale calderagenic eruptions successively occurred at two distant places. The study of successive eruptions from different volcanoes is important in understanding the mechanisms of volcanic eruptions.

The recognition of a widespread tephra in the Bicol arc provides a first step in establishing the tephrochronological framework in the Philippines. As a regional tephra marker, its potential importance in the identification and correlation of both terrestrial and marine tephras in the surrounding basins of the Bicol arc will be significant. With its unique mineral assemblage, the rhyolitic co-ignimbrite ash-fall deposit will also be valuable to other scientific researches in the Philippines such as marine geology, paleoseismology and climate change studies.

6. Conclusion

The fine rhyolitic ash-fall deposit exposed at Inascan cone is concluded as a co-ignimbrite ash fall associated with the 41 cal ka BP Irosin ignimbrite based on field evidence, similarity of mineral assemblage, refractive indices of volcanic glass, plagioclase and amphibole, and chemical composition of volcanic glass. The discovery of a thick co-ignimbrite ash-fall deposit 80 km from its source is comparable to other widespread tephras documented in Japan such as K-Ah and AT tephras. The sequence of rhyolitic and basaltic tephras at Inascan scoria cone provides a good example of successive eruptions which occurred at two different places, 80 km apart. Further, the first discovery of a widespread tephra can be the first step in establishing the tephrochronological framework in the Philippines.

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