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Lithofacies of volcanic rocks in the central Coastal Range, eastern Taiwan: implications for island arc evolution

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Abstract

The Miocene igneous rocks in the central Coastal Range, eastern Taiwan, consists of intrusive diabase, andesitic lavas, andesitic to dacitic volcaniclastic rocks, ignimbrites and basaltic lavas. Based on rock characteristics, they can be grouped into ten lithofacies. Furthermore, these lithofacies can be appropriately linked to form five lithofacies associations according to paleoenvironments and type of volcanism. The volcanic eruptions may have commenced on a deep ocean floor in the early Miocene, poured out in a shallowing environment in the middle to late Miocene and, finally, taken place in a subaerial condition at the end of the Miocene. Subaqueous eruptions produced voluminous pillow lavas and breccias, hyaloclastites, massive lavas and thick volcaniclastic deposits. Subaerial eruptions yielded only limited amounts of ignimbrites and basaltic lavas. After the cessation of volcanism due to the arc-continent collision, the volcanoes rapidly subsided and were later overlain by thick terrigenous sediments.

Keywords: Volcanic lithofacies; Coastal range of eastern taiwan; Luzon arc; Arc-continent collision

1. Introduction

Lithofacies analysis is a useful approach to unravel the eruption history and the evolution of volcanism in old terranes, where the volcanic deposits have undergone post-emplacement deformation that overprinted the original stratigraphic and structural features. In the past, this tool has been applied to unravel the paleoenvironment, paleoenvironmental conditions and the evolution of volcanic activity (e.g. Busby-Spera, 1988; White and Busby-Spera, 1987; Hackett and Houghton, 1989; Orth et al., 1989; Ricketts et al., 1989; Aitchison and Landis, 1990; Riggs and Busby-Spera, 1991; Kano et al., 1993).

A lithofacies is a rock body or interval having a unique definable character, which may be compositional, textural or structural, that has genetic significance, such as the conditions of eruption or deposition (Selley, 1978; Walker, 1984; Cas and Wright, 1987).

Volcanoes in the Coastal Range of eastern Taiwan form the northern extension of the Luzon Arc, which formed in response to the subduction of the South China Sea crust beneath the Philippine Sea plate (Fig. 1). Subduction was terminated by the collision of the arc with the Eurasian continental plate at about 5 Ma (Teng, 1990). Volcanic stratigraphy and primary features were destroyed and became ambiguous due to the arc-continent collision (Yen, 1967). Thus, the study of volcanic characteristics and evolution were scarce up to now, although abundant data of tectonic features and post-collision processes have been published. In this paper, the occurrences of volcanic and volcaniclastic rocks that are well exposed in the core of the central Coastal Range (Fig. 2) are described in detail using the lithofacies analysis method. Furthermore, the lithofacies associations are organized to reconstruct the paleotopography and evaluate the eruptive conditions and the evolution of volcanism.

2. Geological background

The Neogene volcanic and volcaniclastic rocks of the Taiwan Coastal Range, more than 4000 m in thickness, form an igneous complex dominated by andesitic rocks. It constitutes the northern segment of the Luzon Arc and might have formed in response to the subduction of the South China Sea beneath the Philippine Sea plate. Finally it was thrust onto the continental margin through arc-continent collision (Fig. 1) (Teng, 1990).

The Coastal Range volcanic and related rocks mainly accumulated in an oceanic environment (Song and Lo,

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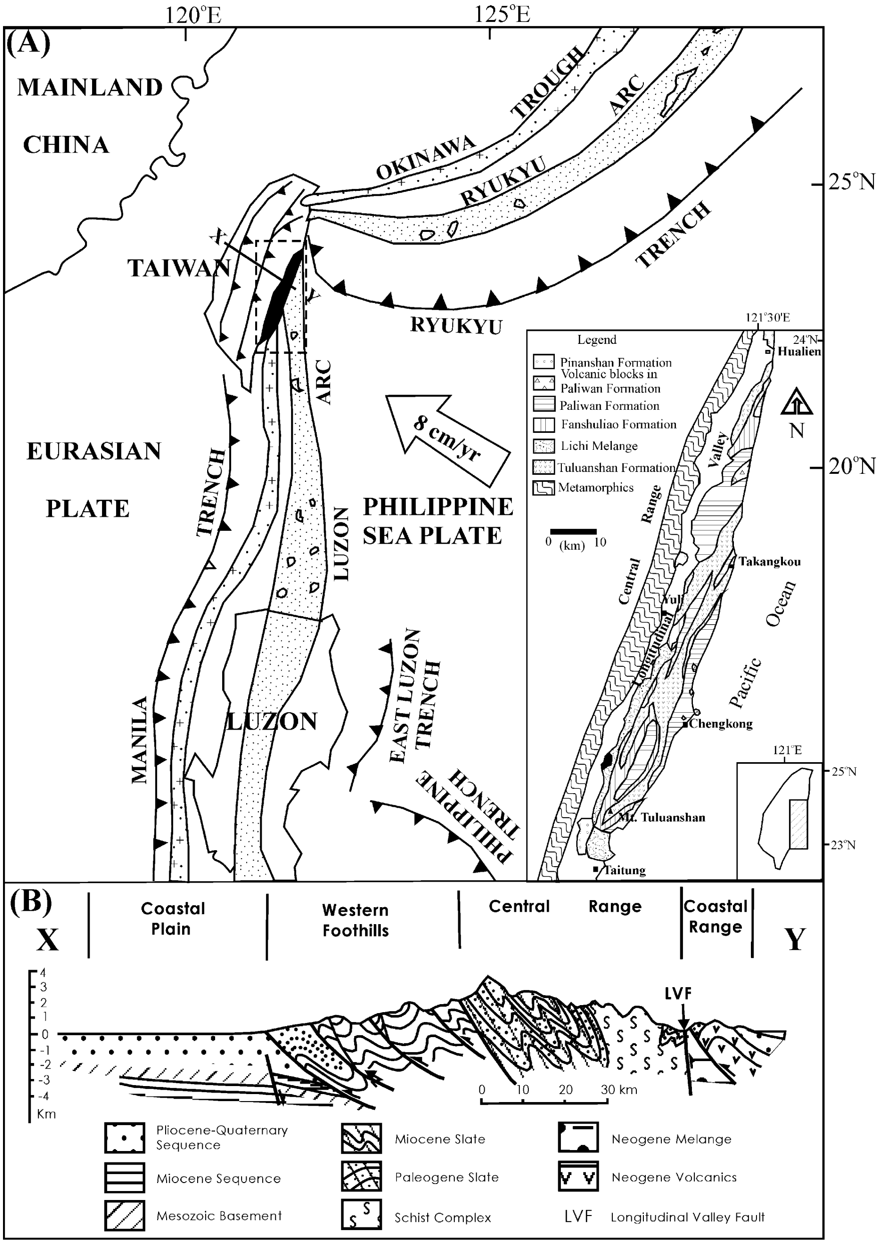

Fig. 1. (A) Tectonics in the vicinity of Taiwan (modified from Ho, 1986). Insert map shows the geologic map of the Coastal Range, eastern Taiwan (modified from Chen, 1988). (B) Schematic cross section of Taiwan collision zone. Location shown in (A). Modified from Teng (1990).

1987, 1988). They comprise basaltic to andesitic pyroclastic rocks, lava flows, shallow intrusive and volcaniclastic rocks. In addition, exposed limestones regarded as reef deposits may have formed on the fringes of volcanic islands (Huang et al., 1988). All of these rocks are traditionally grouped into two units, the Chimei Igneous Complex and the Tuluanshan Formation (Fig. 2) (Ho, 1986; Song and Lo, 1990).

The Chimei Igneous Complex is composed mainly of intrusive diabase, dikes, lava flows and pyroclastic rocks, which are divided into two members, namely, the Tienkangshan Diabase and Wantian Andesite (Song and Lo, 1990). These rocks suffered at least three stages of hydrothermal alteration (Lan, 1982). Fission-track and potassium–argon dating constrain the age of the Chimei Igneous Complex as older than 15.4 Ma (Table 1) (Richard et al., 1986; Yang et al., 1988).

The Tuluanshan Formation includes a variety of volcanic and volcaniclastic rocks such as lava flows, volcanic breccias, lapillistones, tuffs, tuffaceous conglomerates and sandstones and associated limestones. These rocks have been divided into three members, the Shihmen Breccia, the Shihtiping Tuff and the Kangkou Limestone (Fig. 2) (Song and Lo, 1990). The age of the Tuluanshan Formation in the central Coastal Range is between 16.6 and 5 Ma (Tables 1 and 2) as dated by potassium–argon and fossil ages (Juang and Bellon, 1984; Huang et al., 1988).

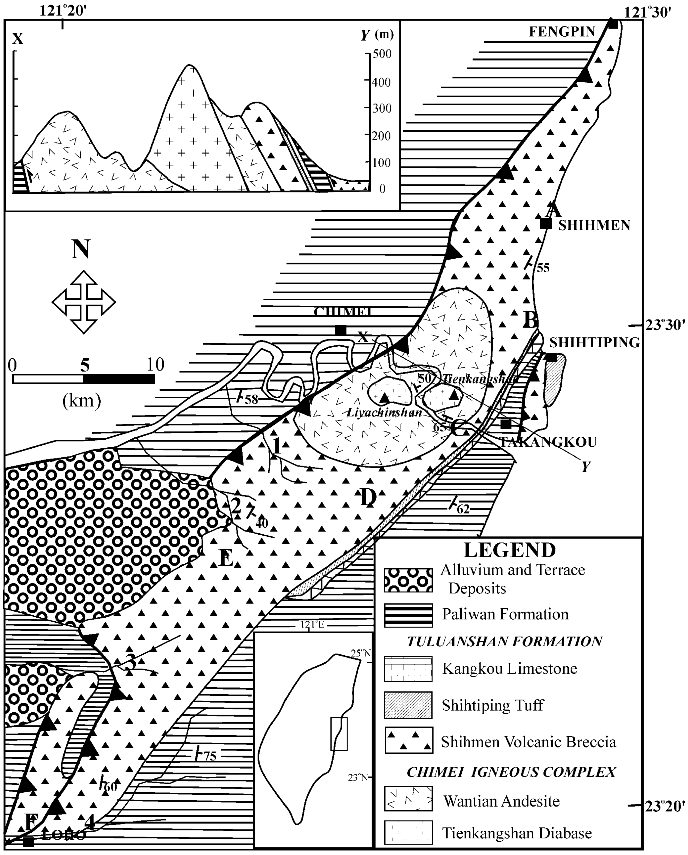

Fig. 2. The geologic map of the central Coastal Range, eastern Taiwan. Insert shows schematic NE–SW cross section of Chimei Volcano. Vertical exaggeration 15 times. Letters A to F show locations of lithologic columns depicted in Fig. 3. Letters 1 to 4 show locations of measurements of block-size distribution in Table 4.

3. Descriptions of lithofacies

Volcanic terranes can be expected to contain a greater diversity of lithologies than any other sedimentary environment (Fisher and Schmincke, 1984; Cas and Wright, 1987). Hence, it is not surprising that within the period of volcanic activity, few events are recognized that can be correlated over large areas to provide benchmarks for a detailed stratigraphy.

Based on the results of detailed fieldwork, ten lithofacies can be identified in the central Coastal Range, eastern Taiwan.

3.1. Intrusives

The Tienkangshan Diabase forms a stock which outcrops on both banks of the River Hsiukuluanchi, downstream of the Chimei area (Fig. 2). It is a dark greenish gray rock, massive in structure and pervasively altered by closely spaced zeolite veinlets (Wang and Yang, 1974). The major constituent minerals of the diabase are common augite and calcic labradorite with distinct diabasic textures (ophitic, subophitic, or intersertal). Dike swarms of pyroxene andesite with extremely fine and hyalopilitic groundmass extensively intrude the diabase body. It has suffered

Table 1
Ages of volcanic rocks in the central Coastal Range, eastern Taiwan

Locality	Age	Method	References
Chimei Igneous Complex	9.0–22.2	K–Ar dating	Ho, 1969
	9.2–29.7	K–Ar dating	Juang and Bellon, 1984; Richard et al., 1986
	15.4–16.4	Fission-track dating	Yang et al., 1988
Shihmen Volcanic Breccia	16.6	K–Ar dating	Juang and Bellon, 1984
	5.5–8.1	K–Ar dating	This study
Shihtiping Tuff	5.1–5.2	Foraminifera	Huang et al., 1988
Kangkou Limestone	3.5–5.2	Foraminifera	Huang et al., 1988

Table 2
The K–Ar isotopic ages of Shihmen volcanic breccias in the central Coastal Range, eastern Taiwan. (The samples were analyzed by the K–Ar Laboratory, Teledyne Isotopes at New Jersey, USA)

Sample number	Sample locality	Rock type	Age (Ma)	^{40}Ar* (scc/gm $\times 10^{-5}$)	% Ar	% K
L83-004	Lohochi	Whole rock	5.1 ± 1.3	0.013	10.5	0.65
L84-251	Lintzechi	Whole rock	8.1 ± 1.4	0.011	4.3	0.36
L85-180	Shihmen	Whole rock	5.5 ± 1.5	0.013	13.9	0.58
Shih-B1	Shihtikang	Whole rock	6.1 ± 1.1	0.011	6.5	0.44

from at least three stages of hydrothermal alteration (Lan, 1982).

The fission track ages of diabase are around 15–17 Ma, which indicate the diabase intruded prior to 17 Ma (Yang et al., 1988). The diabase is over 200 m thick at Mt. Tienkangshan and covered by andesitic lavas and pyroclastic rocks as recorded from borehole drilling data. The diabase probably intruded at the subvolcanic level and constitutes the core of the Chimei volcano (Fig. 3) (Wang and Yang, 1974).

3.2. Andesitic lava flows

Andesitic lava flows outcrop in the central Coastal Range, eastern Taiwan, at two different places. Thick layers of lava, ranging from several to tens of meters, outcrop downstream of the Chimei area along the banks of the River Hsiukulanshi and are named the Wantian Andesite (Fig. 2). In these outcrops, some andesitic lava flows contain xenolith fragments of the diabase near the contact, but others show a chilled margin against the diabase. This means that the andesitic lava flows and diabase probably occurred simultaneously. The hydrothermal alteration and dike intrusions also affected the andesitic lava flows. Their fission-track ages are the same as those of the diabase, indicating that the andesitic lava flows may be older than 15–17 Ma.

Thin layers of andesitic lava flows less than several meters thick are intercalated with volcanic breccias, which outcrop near the Chimei area. Far away from Chimei, the andesitic lava flows become thinner and more scarce (Fig. 3).

3.3. Dike swarms

The dikes found within the central Coastal Range, eastern Taiwan, occur in the same localites as the diabase and thick andesitic lava flows (Fig. 4A). Two groups of dikes are found, constituting dike swarms striking N60W and N30W. This indicates that the maximum horizontal compression of the Chimei volcano was northwest–southeast (Ui, 1983; Song and Lo, 1988). The dike is about 30–100 cm in thickness, dark gray, fresher and finer grained than the thick andesitic lava flows and diabase. The main

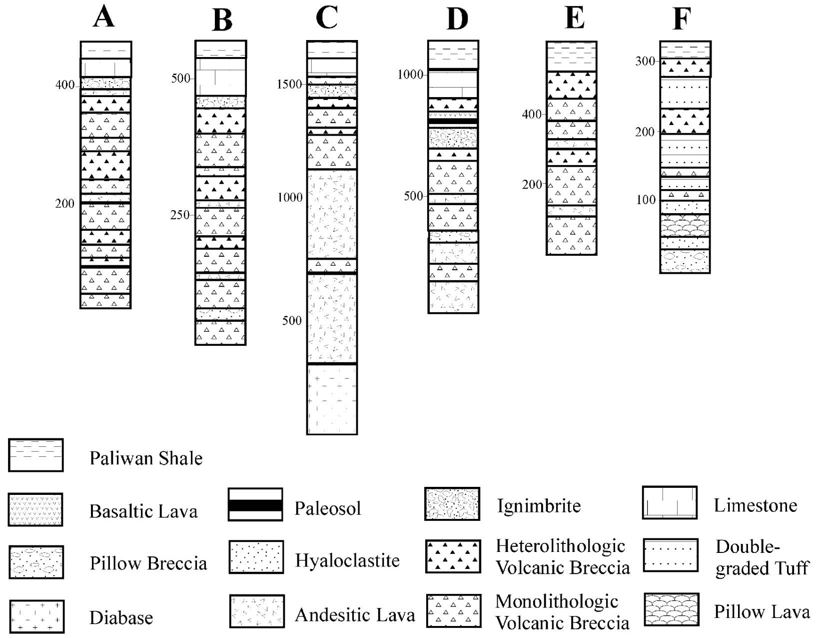

Fig. 3. Lithologic columns of the central Coastal Range, eastern Taiwan. Locations shown in Fig. 2. (A) Shihmen section; (B) Shihtikangchi section; (C) Hsiukuluanchi section; (D) Sanfuchuan section; (E) Lufuanchi section; (F) Lohochi section.

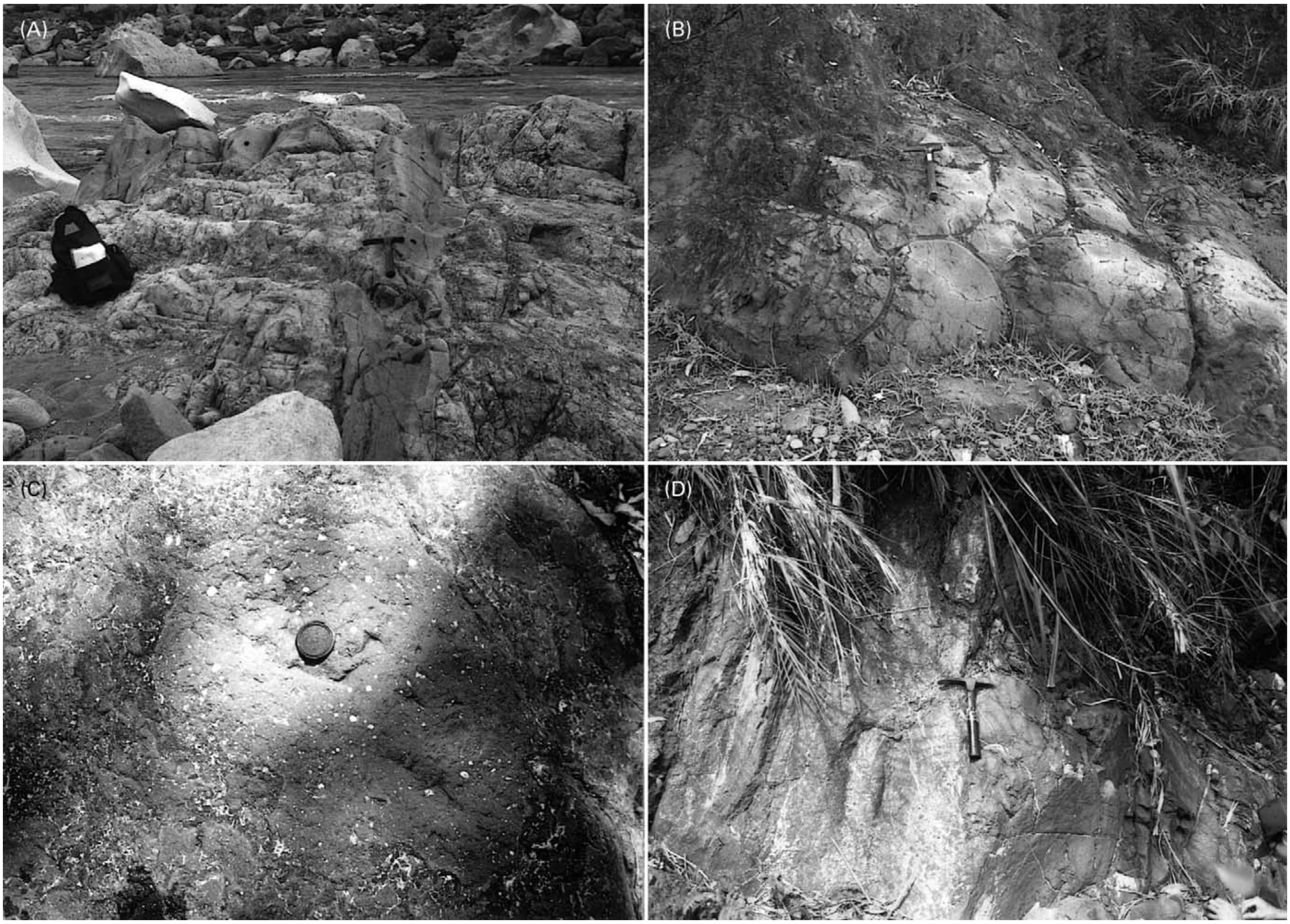

Fig. 4. (A) Dike swarms which intruded into the diabase and thick andesitic lava flows crop out in the Chimei area. The thickness of dikes is about a half meter. (B) Pillow lava crops out in the lower section of Lohochi. The diameter of each pillow is a half to 1 m. (C) Pillow breccia rich in vesicles crops out in the Shihmen Volcanic Breccia. (D) Basaltic lava overlying paleosols crops out in the topmost section of Sanfuchuan. Basal contacts are irregular and sharp. The thickness of paleosol is about 2 m.

constituent minerals are common augite and calcic plagioclase with minor olivine and magnetite that are replaced by epidote, chlorite, zeolite and calcite as a result of hydrothermal alteration.

3.4. Pillow lava

Pillow lavas of the Coastal Range are known from several localities. They are basaltic in composition and considered to be part of the Kuanshan Ophiolite. However, the pillow lavas found in the lower parts of Loho section are basaltic andesites and are products of submarine arc volcanism (Fig. 4B) (Song and Lo, 1987). Each pillow is usually a half to 1 m in diameter and the whole sequence is about 20 m thick, overlain by, or intercalated with hyaloclastites and pillow breccias (Fig. 3). The pillows have a dark gray, chilled margin that contrasts with their pale gray interiors. Vesicles are uncommon (less than 5%) (Fig. 4B) in the pillow margins and interiors, indicating they were probably extruded in a deeper submarine environment below the volatile fragmentation depth (VFD) (Fisher, 1984; Fisher and Schmincke, 1984; Song and Lo, 1987). In thin sections, pillow interiors are seen to contain abundant plagioclase microlites showing a pilotaxitic texture and orientation parallel to the margins. Chilled glassy margins show a hyalopilitic texture, with smaller and less numerous, randomly oriented, acicular plagioclase microlites. Some occurrences along the bank of the lower reaches of the Hsiukulanchi could be pillow lavas, but they were altered by later hydrothermal alteration to an extent that the identification of pillow structures is ambigious.

3.5. Pillow breccias and hyaloclastites

The term ‘pillow breccia’ is taken from Carlisle (1963) and refers to hydroclastic breccias in which numerous small, cogenetic pillows and pillow fragments are dispersed. Meanwhile, the term ‘hyaloclastite’, as used here, refers to fine-grained fragments of glass products quenched by hydroclastic processes (Batiza and Vanko, 1983; Fisher and Schmincke, 1984; Kokelaar, 1986).

Pillow breccias and hyaloclastites of the central Coastal

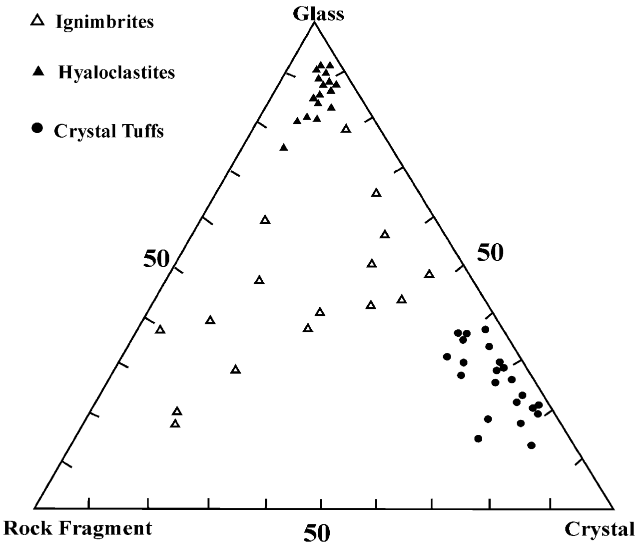

Fig. 5. The components of crystal tuffs, hyaloclastites and ignimbrites are plotted in the glass-crystal-rock fragment triangular diagram. The crystal tuffs are rich in crystal components, the hyaloclastites are rich in glass fragments and the components of ignimbrites show wide distribution.

Range have been found in several places such as Lohochi, Sanfuchuan and Shitikuanchi (Fig. 2). They are commonly overlain by, or intercalated with, pillow lavas and volcanic breccias that are localized in the lower parts of the sequence (Fig. 3). The pillow breccias are monogenetic volcanic breccias composed of pillows and/or broken pillow fragments set in a matrix of fine-grained hyaloclastite. They show massive or faint stratification defined by size grading. The size of the pillow fragments ranges from just a few up to 30 cm. The major constituent minerals are plagioclase, augite and hypersthene set in a glassy groundmass.

The hyaloclastites are very homogeneous and massive and are often mistaken for massive lava flows in the field. They contain about 80–90% glassy fragments (Fig. 5) that are dark and less than 2 mm in length. The shapes of the glassy shards are spherical, drop-like, or blocky. Sizes are variable, as detected by scanning electron microscopy (SEM). These shards were produced by the interaction between water and rising magma (Wohletz, 1983; Song and Lo, 1987). The mineral assemblages of hyaloclastites are the same as those of pillow lavas and breccias. Amygdules are less common and smaller (less than 5%) in hyaloclastites and pillow breccias of the lower sections. However, the vesicles increase in abundance (over 20%) in the upper section and are filled with chalcedony and calcite (Fig. 4C). The glassy groundmass of the hyaloclastites and pillow breccias suffered from palagonitization and changed from transparent to translucent yellowish brown.

3.6. Basaltic lava flows and paleosols

The basaltic lava flow is distinguished from the andesitic lava flows as an independent lithofacies by their association with paleosols. It is massive with poorly developed columnar joints and is about 10 m in thickness. The phenocrysts of basaltic lava flows are olivine, augite and plagioclase with fine-grained, lath plagioclase groundmass.

The paleosols, intercalated between basaltic lava flows, are reddish in color and are about 2 m in thickness (Fig. 4D). The base of the paleosol layers is irregular contacts and grades into basaltic lava flow. Upper contacts of the paleosols are sharp, more reddish in color than the bases, and have a baked texture. In thin section, paleosols are found to contain relics of basalt fragments set in a matrix of iron oxide. This evidence supports the notion that the paleosols must be the products of weathering of basaltic lava flows. The baked texture at the contacts with overlying basaltic flows shows that the latter are the product of subaerial eruption. This evidence demonstrates that the arc volcanism in the Coastal Range of eastern Taiwan became subaerial in the latest stage.

3.7. Monolithologic volcanic breccias

Volcanic breccias are important components of volcanic sequences that constitute the Tuluanshan Formation in the Coastal Range of eastern Taiwan (Fig. 3). There are two types of lithology found in the field. One is monolithologic, while the other is polylithologic or heterolithologic. The monolithologic volcanic breccias may represent material transported directly from the vent regions to the site of deposition with minimal resedimentation. In contrast, the polylithologic volcanic breccias may represent material eroded from older volcanic sequences and transported by debris flows, triggered by eruption or slope failure, and redeposited at the present site.

Two kinds of monolithologic volcanic breccia can be distinguished on the basis of the proportion of blocks to matrix. For high block/matrix ratios, massive breccias consist of angular to subangular blocks in a matrix of poorly sorted tuff. The size of the blocks generally ranges from 5 to 30 cm in diameter. Most of the breccias are massive with poor to faint bedding, although normal (or rarely inverse) grading is apparent in some beds. Some blocks in this breccia exhibit radial prismatic fractures (Fig. 6A) indicative of in situ cooling from high temperatures. This kind of breccia is interpreted as block and ash flow deposit, probably produced by a dome-collapse pyroclastic flow. The clast-supported, very closely packed breccia is entirely composed of angular blocks, the average size of which is 5–10 cm, indicating they probably originated by lava autobrecciation or represent distal exposures of a lava dome (Riggs and Busby-Spera, 1991).

The low block/matrix ratio breccias are matrix-supported, with the matrix composed of poorly sorted tuff. The blocks are commonly angular to subrounded in shape, their sizes ranging from 5 to 15 cm. They also contain radial prismatic fractures that suggest that the low-ratio breccias were probably generated by pyroclastic flows or by the mixing of water with emplaced pyroclastic debris (Smith, 1986).

Fig. 6. (A) Blocks exhibiting radial prismatic fractures in the monolithologic volcanic breccia. (B) Well-developed columnar-joint megablock set in the matrix of heterolithologic volcanic breccia. The size of the megablock is about $10 \times 10\ \mathrm{m}^2$. (C) Welded ignimbrites with white plastically deformed glassy and pumice fragments. (D) Double graded tuff crop out in the middle section of Lohochi. The lower unit is more massive and coarse than the upper unit in the double graded beds.

3.8. Polylithologic volcanic breccias

Massive, matrix- to clast-supported, subangular to rounded polylithologic volcanic breccias constitute a large proportion of some outcrops, especially in the uppermost sequence of the Tuluanshan Formation (Fig. 3). They are poorly bedded and sorted and contain various kinds of blocks, including blackish, greenish and reddish andesitic fragments, which may have eroded from different sources. Greenish andesitic fragments contain celadonites formed by reaction of the andesites with sea water (Chen and Chen, 1984). The reddish blocks are the products of thermal oxidation in the subaerial environment (Cas and Wright, 1987).

Clasts range in size from a few centimeters to over 10 m in diameter and are dominated by andesite. Megablocks (over 10 m in diameter) show well-developed columnar joints (Fig. 6B). In addition, columnar-jointed smaller blocks are distributed northeasterly away from the megablocks and are believed to have been derived from the larger blocks. The block size and the proportions of blocks to matrix in the breccias decrease from the southwest to the northeast of the Shimen area. This evidence suggests the polylithologic volcanic breccias exposed in the Shimen area are volcanic debris avalanche deposits, and that they were derived from the Chimei area (Ui, 1983; Siebert, 1984; Song and Lo, 1988).

3.9. Ignimbrite

The ignimbrite has a maximum exposed thickness of 36 m at Shihtiping, which is about three kilometers to the north of the mouth of the Hsiukulanchi River. It is made of thin layers that belong to the low aspect ratio type of ignimbrite (Walker, 1980). Locally, thin air-fall and pyroclastic surge deposits are found immediately below or intercalated with the ignimbrites and are thought to be early or simultaneous products of the same eruption. Ignimbrites are white, poorly sorted and are predominantly composed of vesiculated glassy shards and pumices with small amounts of lithic fragments. Vesiculated glassy shards and pumice clasts generally increase in size upsection, and lithic fragments tend to increase in size and abundance downsection in

Table 3
Characteristics of lithofacies associations in the central Coastal Range, eastern Taiwan

Facies association	Principal lithofacies	Minor lithofacies	Other notable features
Near-vent volcanic facies	Diabases thick lava flows dike swarms	Monolithologic volcanic breccias	1. Hydrothermal alteration of rocks 2. Porphyry copper
Medial volcanic facies	Thick volcanic breccias	Thin lava flow	1. Particle size of blocks decreasing with distance away from source
Distal volcanic facies	Thick tuff beds	Heterolithologic volcanic breccias	1. Well bedded structures 2. Erosion surface
Submarine eruptive facies	Pillow lava hyaloclastite thick lava flow	Pillow breccias volcanic breccia tuff with double-graded structure	1. Secondary mineral fillings in vesicles
Subaerial eruptive facies	Ignimbrite ash-fall deposits	Basaltic lava flow paleosols	1. Reddish blocks in volcanic breccias 2. Welded structure and impact-structure in ignimbrites

individual exposures of ignimbrite. Most pumice fragments and glassy shards are rounded, whereas lithic fragments are angular. The glassy shards and pumice fragments show plastic deformation and welded structures (Fig. 6C) indicating that the ignimbrites were probably deposited at high temperature.

Co-ignimbrite lag-fall deposits and fine-depleted ignimbrites also have been found at Shihtiping. The lag-fall deposit is dominantly composed of lithic fragments, whose sizes range from 10 cm to over 1 m and whose matrix is composed of ash. These deposits show impacted and deformed structures. The impacted blocks are fractured, but the fractures do not penetrate into the vicinal layers. Fine-depleted ignimbrites are mostly composed of white, clast-supported blocks, having the same lithology as the ignimbrite, but without the ash matrix.

3.10. *Tuff*

Two types of tuff can be identified in the field. One is characterized by the double-graded structure, whereas the other is characterized as bedded tuff rich in crystals (crystal tuff). Double-graded tuff consists of many individual graded beds that show an overall fining upward, forming a larger graded sequence. It can be divided into two parts: (1) a massive to poorly bedded and sorted lower section, and (2) an upper, thinly bedded portion (Fiske and Matsuda, 1964). The double-graded tuff outcropping in the Loho area is fine- to coarse-grained, greenish-gray in color and well laminated (Figs. 3 and 6D). A lower and an upper portion can also be distinguished. The lower one is composed of a massive, thick bed of lapillistone with thinly bedded volcanic breccia in the lower part. The upper portion is composed of well-laminated graded beds of fine- to coarse-grained tuffs (Song and Lo, 1987). The clasts are dominantly glassy shards and lithic fragments with small amounts of crystals. The shapes of the glassy shards are blocky and drop-like with an abundance of vesicles, which indicates they were formed during a shallow-water volcanic eruption. Therefore, the double-graded tuff presumably represents a subaqueous pyroclastic flow (Bond, 1973; Song and Lo, 1987).

Crystal tuffs contain crystals and crystal fragments within a groundmass of glassy and lithic fragments (Schmid, 1981; Cas and Wright, 1987). The crystal tuff that outcrops at Shihtiping consists of thinly to thickly bedded, well sorted, fine- to medium ash layers that are intercalated with ignimbrite. It consists of about 55–80% crystal grains (Fig. 5). Sedimentary structures include massive, parallel lamination and herringbone cross bedding. The thinly bedded, parallel laminated crystal tuff was probably formed as a fallout deposit. Herringbone cross bedding is the typical sedimentary structure within a tidal environment (Reineck and Singh, 1975). The essential mineral constituents are plagioclase and hornblende with small amounts of hypersthene, augite and magnetite, which is the same as the mineral assemblages of the ignimbrite.

The probable origins of crystal tuff include: (a) the eruption of highly crystallized magmas; (b) physical fractionation and sorting processes associated with pyroclastic eruption and transportation processes; and (c) epiclastic reworking and redeposition (Cas and Wright, 1987). The phenocryst abundance of ignimbrites in the Coastal Range of eastern Taiwan varies from 25 to 50%, which is far less than the amount of mineral grains in the crystal tuff. The thinly bedded, massive and parallel laminated crystal tuffs are probably fallout deposits indicating they were formed by physical fractionation, winnowing out of a large proportion of fine glassy ash and sorting of mineral grains during flight. However, the crystal tuff with herringbone cross bedding may originate from the erosion of ignimbrite and redeposition in tidal environments.

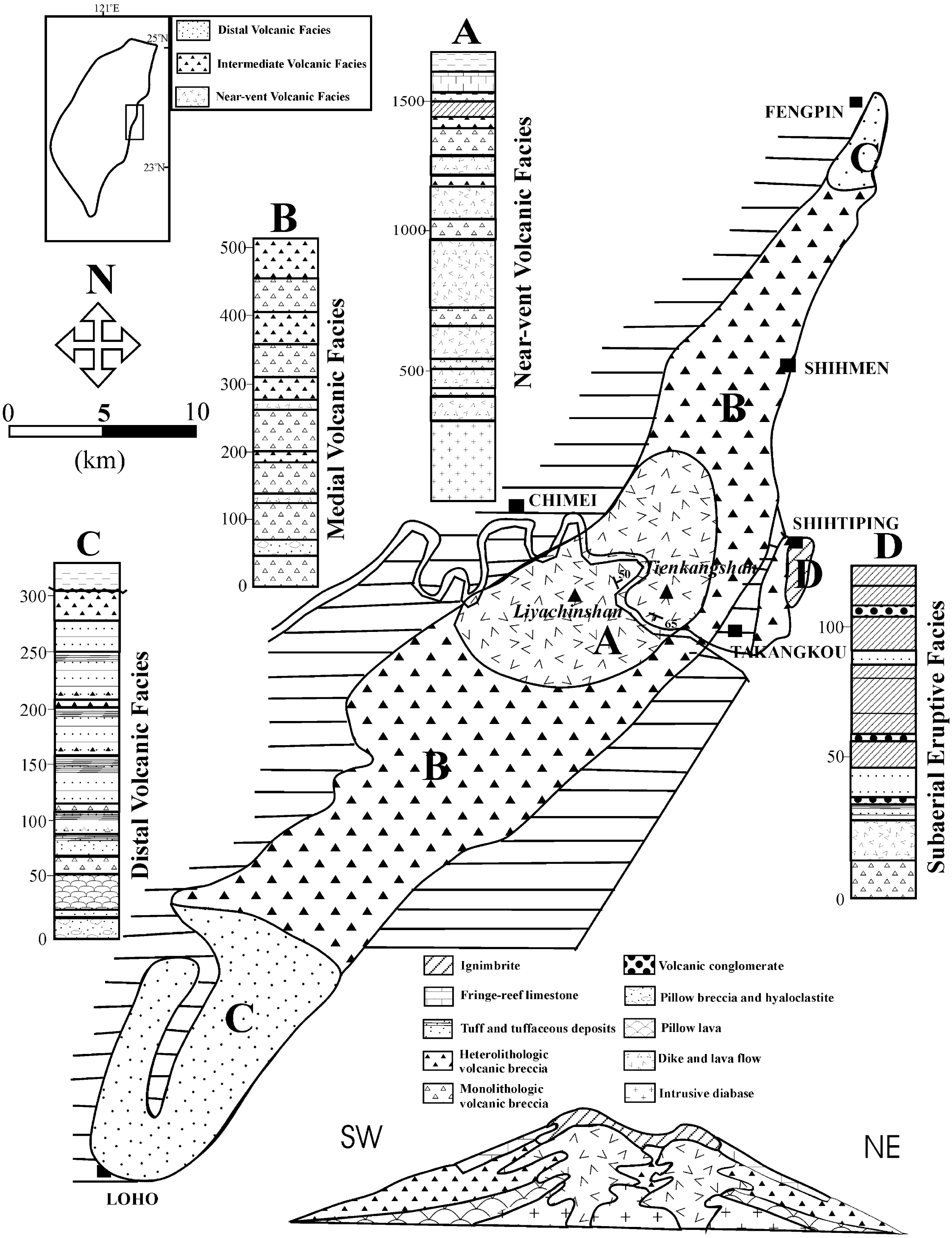

Fig. 7. Facies associations indicate that the Chimei area was probably a volcanic center in the central Coastal Range, eastern Taiwan. Also shown the lithologic columns of each facies association. Cross-section depicts the reconstructed paleo-topography of a volcano in the central Coastal Range, eastern Taiwan.

4. Lithofacies associations

Paleoenvironments and depositional processes cannot be interpreted from a single volcanic lithofacies, because similar lithofacies may be produced by more than two processes. Therefore, to arrive at a sound interpretation and reconstruction of the paleoenvironment, significant associations of lithofacies need to be established. The volcanic deposits in the central parts of the Coastal Range of eastern Taiwan have been categorized into five distinct lithofacies associations (Table 3): (1) near-vent volcanic facies; (2) medial volcanic facies; (3) distal volcanic facies; (4) submarine

Table 4
Measurements of block-size distribution in four sections in the central Coastal Range, eastern Taiwan. Number indicates the location showing in Fig. 2

Lintzuchi (1)		Lifengchi (2)		Kaoliaochi (3)		Lohochi (4)	
Average[a] (cm)	Maximum[b] (cm)	Average[a] (cm)	Maximum[b] (cm)	Average[a] (cm)	Maximum[b] (cm)	Average[a] (cm)	Maximum[b] (cm)
10–20	70	10–20	40	5–10	25	< 1	3
10–30	120	15–20	50	5–10	30	5–10	15
10–40	70	5–10	40	5–15	45	1–3	5
10–30	50	10–20	40	3–10	30	< 1	1
15–20	60	5–15	50	3–10	30	1–5	10
20–30	90	5–20	50	5–10	25	1–2	5
15–30	50	15–20	50	5–10	40	3–5	10
10–20	30	10–20	75	3–15	50	< 1	1
10–40	60	10–20	30	5–15	25	10–20	40
5–20	35	20–25	60			< 1	30
10–20	80	10–20	80			1–3	5
10–25	45	10–30	60			3–5	8
5–15	30	15–20	45				
20–30	65						
20–30	75						

[a] Average means the ranges of average block-size in diameter measuring in single bed.

[b] Maximum means the maximum block size in diameter in each bed.

eruptive facies and (5) subaerial eruptive facies. Associations 1–3 are distinguished based upon their position relative to the volcanic center, whereas associations 4 and 5 are recognized by their eruptive environments.

4.1. Near-vent volcanic facies association

This association comprises the lithofacies of irregular stock intrusions, thick to thin lava flows, dike swarms and thin beds of volcanic breccias (Table 3; Fig. 7). The volcanic breccias are predominantly monolithologic. Pervasive low-grade hydrothermal alteration characterizes the near-vent facies association.

Another characteristic of this facies association is the presence of porphyry-copper mineralization. The porphyry-copper bearing stocks, called ‘Chimei Copper Deposits’ by Tan (1970), were prospected and reported on both banks of the Hsiukulanchi River downstream of Chimei. Most of them are associated with diabase intrusions and are unrelated to the andesitic lava flows. Other mineral deposits near Chimei include concentrations of chalcopyrite-galena in veinlets, placer gold, gypsum and cinnabar (Tan, 1970). These mineral deposits are too small to be mined economically.

4.2. Medial volcanic facies association

The medial volcanic facies association is characterized by thick volcanic breccias, both monolithologic and polylithologic, that are distinguishable from other facies associations (Table 3; Fig. 7). This facies association is predominantly distributed about 4–15 km to the southwest and northeast of the Chimei area (Fig. 7). It forms the major mountainous area of the central Coastal Range of eastern Taiwan because of its strong resistance to erosion. As distance from the source increases, the amount of re-sedimented pyroclastic and epiclastic volcanic debris increases as the size of the blocks and the thickness of the lava flows decreases (Table 4). The sedimentary structures of volcanic breccias are massive with poor sorting in the near source area, whereas layering and sorting becomes more prominent with increasing distance from the source.

Lens-shaped bodies of limestone occur at the boundary of near-vent and medial volcanic facies. They are considered to represent fringe reefs that formed when the arc volcanism evolved into the shoaling stage (Song and Lo, 1987). Consistent with this, many of the limestone blocks are found in the upper parts of the polylithologic volcanic breccias of the medial volcanic facies association.

4.3. Distal volcanic facies association

The distal volcanic facies association is typically less complex and is mainly distributed in the areas farthest from the Chimei Igneous Complex (Fig. 7). It is composed of thicker, more laminated tuffs with minor pillow lavas, breccias, and hyaloclastites (Table 3; Fig. 7). The tuffs include double-graded, parallel bedded, faintly laminated and massive beds. Double-graded tuffs are found predominantly in the Loho section of south Chimei, whereas massive tuffs are abundant in the Fongpin area north of Chimei. Pillow lavas and breccias and hyaloclastites occur only in the lower section of the Loho sequence (Fig. 3).

Volcanic breccias are produced by pyroclastic flows and epiclastic processes. Pyroclastic flow deposits in the distal volcanic facies association are thinner and generally contain smaller lithic clasts than their counterparts. The lithic clasts are monolithologic with angular fragments. Epiclastic volcanic rocks are polylithologic and are mostly exposed in the upper parts of the sequences. They are massive or faintly laminated and poorly sorted. Some beds show an imbricated structure. The lithic clasts of epiclastic volcanic rocks range from 3 cm to over 1 m in diameter and comprise a variety of rock types as distinguished by color. They were probably eroded from the topographic highs of rocks of the near-vent volcanic facies association.

4.4. Submarine eruptive facies association

The presence of 'fingerprints' of submarine eruptions such as the lithofacies of doubly graded tephra sequences (Fiske and Matsuda, 1964), pillow lavas, breccias and hyaloclastite, indicate that part of the volcanic rocks exposed in the central Coastal Range of eastern Taiwan formed in submarine environments. Those lithofacies are mainly exposed in the lower parts of the volcanic sequences. The double graded tuffs were produced by subaqueous pyroclastic flow deposits (Fiske and Matsuda, 1964). They are interpreted to represent a waning stage of subaqueous volcanism with deposition from thin turbidity flows following the deposition of the massive beds of volcaniclastic deposits (Fiske and Matsuda, 1964).

Pillows are generally regarded as the most distinctive feature of lavas that erupted under water. When lava extrudes on steep flanks or when flanks become oversteepened and partially collapse during the growth period of pillow volcanoes, pillow breccias are formed (Fisher and Schmincke, 1984). The hyaloclastites originated mainly by the spalling of glassy crusts of pillows or sheeted lava during cooling contraction of the flow interiors or by expansion of growing pillow tubes (Schmincke et al., 1978). The pillow lavas are associated with pillow breccias and hyaloclastites in the Loho section (Fig. 3).

Volcanic rocks exposed in the Chimei area, however, are predominantly composed of thick sheet flows with a few suspected pillow lavas. Thus, no thick pillow sequences resulted from the submarine volcanism, perhaps due to high effusive rates and high viscosity of the magmas extruded by the submarine eruptions in the arc of central Coastal Range (Staudigel and Schmincke, 1984).

4.5. Subaerial eruptive facies association

The sequences exposed in the uppermost sections of the central Coastal Range are interpreted as subaerial eruptive facies characterized by ignimbrite, pyroclastic surge deposits, fall lapillistone, paleosols associated with basaltic lava and reddish blocks in epiclastic volcanic breccias (Table 3; Fig. 7). Ignimbrite exposed at Shitiping overlies the bi-directionally cross-bedded tuffaceous sandstone, which eroded from arc volcanic rocks and was deposited in a tidal environment. Thinly layered pyroclastic flow deposits indicate that the ignimbrite formed during low aspect ratio eruptions. Depositional structures of the ignimbrites include cross lamination, parallel lamination, normal and reverse graded bedding, impacted block-sag structures and deformation, welded structures and erosion surfaces. The welded structures and impacted block-sag structures were produced by hot pyroclastic flow and ballistic processes in a subaerial eruptive environment, although some hot pyroclastic flow deposits have been reported in submarine environments (Kokelaar et al., 1984, 1985). The erosional surfaces overlying the tidal tuffaceous sandstones and hot depositional structures suggest that this ignimbrite originated in the subaerial environment.

Paleosols formed when the rocks were exposed to and subaerially weathered. Basaltic lava flows overlying paleosols are found in the Sanfuchuan area of the central Coastal Range and indicate that the basaltic rocks erupted in the subaerial environment.

A thick epiclastic volcanic breccia with reddish blocks forms the uppermost part of the Shihmen Volcanic Breccia, below the ignimbrite. These reddish blocks are the products of thermal oxidation of iron and, hence, diagnostic indicators of subaerial eruptions (Cas and Wright, 1987). They were derived from exposed volcanic terrains suggesting the volcano in the central Coastal Range of eastern Taiwan became emergent during this stage.

5. Growth of the volcanic complex

The volcanic complex in the central Coastal Range of eastern Taiwan began to erupt at about 30 Ma at a water depth below the volatile fragmentation depth (VFD), as defined by Fisher (1984), which is about 500 m below the water surface (Fisher, 1984; Fisher and Schmincke, 1984) depending on the type of magma. The volcanic products accumulated to a thickness of over 4000 m by ~5 Ma. Eruptions were intermittent and occurred mainly under submarine conditions, evolving in the late stage to subaerial conditions (Fig. 8).

The early eruptive products consisted dominantly of thick massive lava flows and minor pyroclastic flows, pillow lavas and hyaloclastites (Fig. 3). A very low explosion index (tephra/tephra + lava), scarcity and small size of vesicles in pillow lavas and hyaloclastites suggest that the eruptions were effusive and non-explosive.

The arc seamount of the central Coastal Range of eastern Taiwan, when compared to oceanic seamounts such as the Hawaiian seamount chain, is much smaller in size and effusion rate (Crisp, 1984), and contain fewer pillow lavas in its submerged parts (Moore and Fiske, 1969; Staudigel and Schmincke, 1984). These characteristics probably reflect a predominance of more acidic magma in an island-arc seamount.

The volcanic complex, overlying the thick lava flows, is composed predominantly of volcaniclastic deposits with subordinate thinly layered lava flows. The volcaniclastic deposits consist of abundant volcanic breccias in intermedial volcanic facies association and tuffs and tuffaceous rocks in a distal volcanic facies association. The blocks of

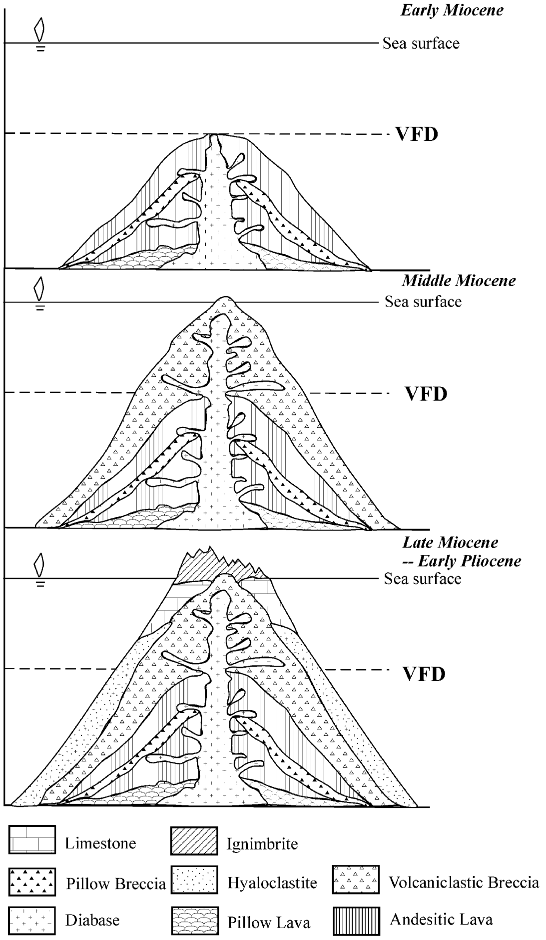

Fig. 8. Model for the evolution of volcanism of the central Coastal Range, eastern Taiwan. VFD: volatile fragmentation depth, generally shallower than 500 m. (Fisher, 1984; Fisher and Schmincke, 1984). The volcano commenced eruption in deep-water environment in early Miocene, then evolved to shallow marine in middle Miocene, finally erupting in subaerial conditions in late Miocene to early Pliocene.

volcanic breccias contain more abundant and larger vesicles than the underlying volcanic products. Along with a high explosion index, this implies that this stage evolved in a marine environment at depths shallower than the VFD.

The abundant volcaniclastic deposits were probably produced by phreatomagmatic and magmatic eruptions or steam explosions in addition to mass-wasting processes (Cas and Wright, 1987). The abundance of polylithologic volcanic breccias and tuffaceous rocks in the upper part might indicate that the mass-wasting processes were very common during long quiescent periods.

There are many reddish blocks in the uppermost part of the Shihmen Volcanic Breccia. They are the products of thermal oxidation whereby high-temperature volcanic materials quickly react with oxygen in the air (Cas and Wright, 1987). Ignimbrites and surge deposits with eutaxitic texture and welded structures in the Shihtiping Tuff may indicate emplacement as subaerial pyroclastic flow deposits at high temperatures, although some ignimbrite deposits have been reported from the subaqueous environment (Howells et al., 1985; Self et al., 1981; Yamada, 1984; Kokelaar et al., 1984, 1985).

The presence of impacted fractured sag-blocks, plastic deformation and erosional surfaces in the ignimbrite also support the assumption that the ignimbrite is the product of subaerial volcanism. Basaltic lava flows overlying the paleosols are inferred to have been erupted in subaerial conditions.

6. Paleotopographic reconstruction

Although the volcanic edifice is not totally exposed and has in part been destroyed by erosion and collision, the facies associations (Fig. 7) allow the interpretation of the volcanic rocks in the central Coastal Range of eastern Taiwan as forming a seamount that evolved from a submarine to a subaerial stage. This seamount may be part of a seamount chain forming an extension of the North Luzon Arc. Based on comparison to the Bashi segment of the Luzon arc, which comprises the islands north of Luzon and south of Taiwan, the island-arc seamount chain is considered to have been located on the Philippine Sea Plate.

On the basis of the distribution and structures of intrusive rocks, lava flows and volcaniclastic rocks, at least two eruptive centers, the Liyachinshan and Tienkangshan have been identified (Fig. 2). Diabase stocks and swarms of dikes repeatedly intruded into the host of lava flows and volcaniclastic rocks. They may represent repeated extrusions of magma into a pile of subaqueous lava flows and minor pillow lavas accumulating around deep marine central vents of the Liyachinshan and Tienkangshan volcanoes. The lava flows are commonly interbedded with volcaniclastic rocks. Bedding surfaces of volcaniclastic rocks in the banks of the Hsiukuluanchi River dip in two opposite directions (Fig. 2), to the north and to the south. The different orientations of the bedding planes indicate the volcaniclastic rocks came from two different sources. In addition, the stratigraphic piles of these two volcanoes interfinger.

On the basis of the aforementioned analysis of lithofacies and facies associations, a paleotopographic reconstruction of the volcano in the central Coastal Range is proposed (Fig. 7). This composite volcano includes two volcanic centers to which the Liyachinshan volcano mainly supplied the volcanic deposits to the south, whereas the volcanic products of the Tienkangshan volcano are largely distributed to the north. Eruptions started in deep marine conditions. As the volcano grew into the shoaling environment, the eruptions became violent and explosive and produced large volumes of pyroclastic rocks, which represent the main cone-building period of the volcanoes. When the volcano became too steep, slope failure occurred. Large amounts of volcaniclastic rocks were deposited in the later stages of the shoaling condition, probably due to slope failure or phreatomagmatic eruptions. Fringe reefs developed as the

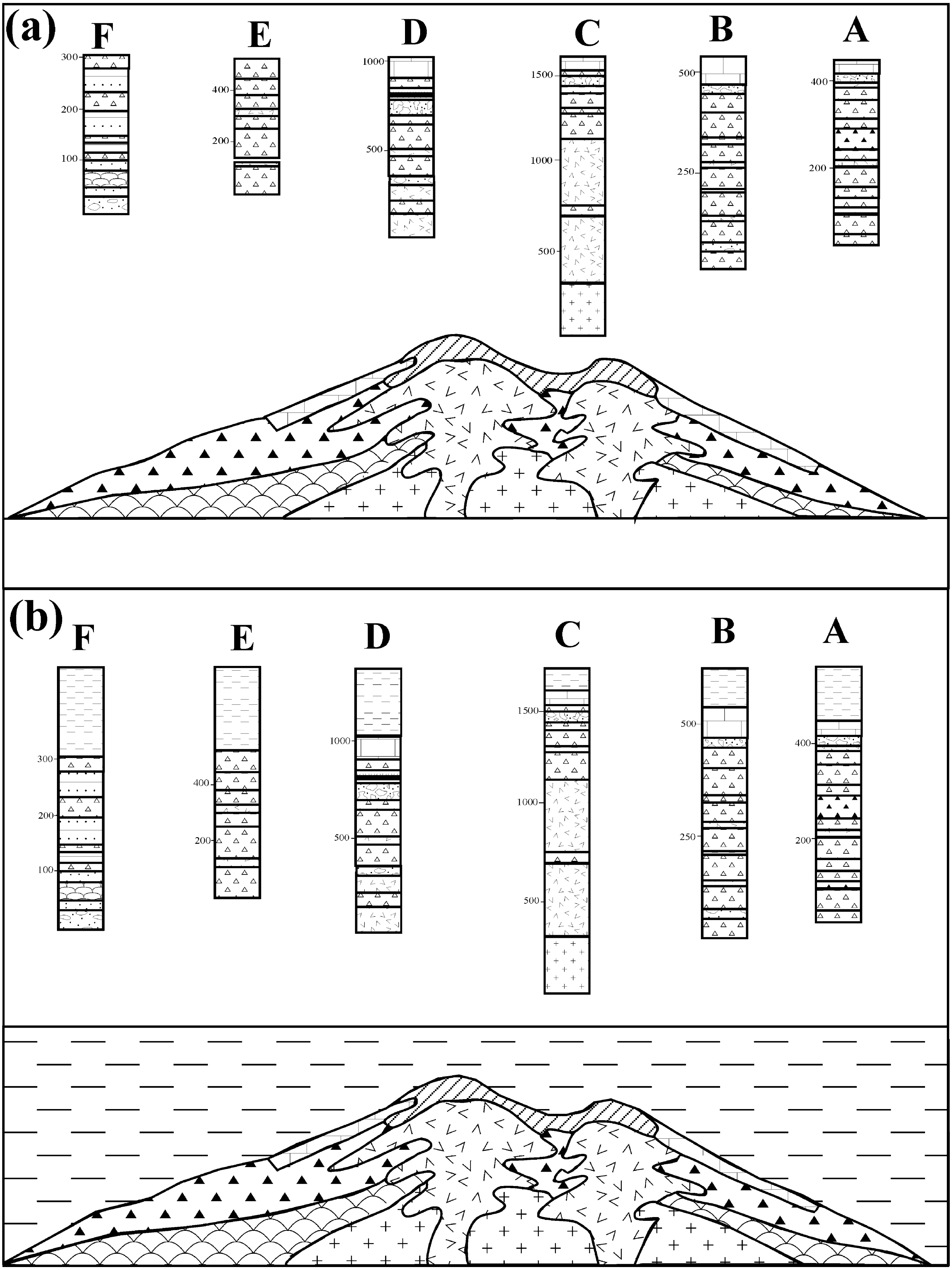

Fig. 9. Paleo-topography of the central Coastal Range, (A) before collision; and (B) after collision showing that the volcano had subsided due to the arc-continent collision. The location and legends of lithologic columns are the same as in Fig. 3.

volcanoes grew near the water surface and into the subaerial environment.

7. Subsidence of the volcanic edifice

Due to the southward propagation of the oblique arc-continent collision, volcanism in the Coastal Range of eastern Taiwan ceased after 6 Ma in the north, at 5 Ma in the central area and at 3.5 Ma in the south (Song, unpublished data). Afterward, sediments deposited in the volcanic terrain abruptly changed from volcaniclastic to terrestrial sediments, which were largely derived from the Asian continental margin and are characterized by quartz-slate arenites (Teng, 1981; Chen, 1988; Lundberg and Dorsey, 1990; Dorsey, 1992). On the basis of the analysis of benthic foraminifera, the basal mudstone directly overlying the volcanoes was deposited in water depths of 1000–2000 m (Huang et al., 1988, 1992). However, the latest eruptions occurred under subaerial conditions and the nannofossil zone of the topmost volcanic rocks is NN11 (6.5–5.5 Ma). The age of the basal mudstone is NN14 (4.5–4 Ma) (Chi et al., 1981). Therefore, the volcanoes might have subsided at least 1000 m in a period of 1–2 Ma after the cessation of volcanic activity and prior to sediment deposition.

The sediments overlie the volcanic edifice from proximal to distal regions in the central Coastal Range (Fig. 9). In the Loho section, sedimentation in the distal area began at about nannofossil zone NN14 and accumulated 1200 m of sediment (Chi et al., 1981). In the proximal area in the Hsiukuluanchi River section, sedimentation started in nannofossil zone NN15 and accumulated about 300 m of deposits (Chi et al., 1981). Hence it appears that the volcanic edifice subsided as a whole and the deposition of the sediments overlying the volcanoes onlaps the volcanic slope from the distal to the proximal area.

Mechanisms for the subsidence of the volcanic edifices in the Coastal Range of eastern Taiwan were proposed by several investigators: (1) extension, rifting, and crustal thinning of the Luzon arc massif formed a series of small rift or pull-apart sub-basins (Dorsey, 1992); (2) flexural subsidence of oceanic lithosphere in a foreland-style basin due to loading in the expanding accretionary wedge of proto-Taiwan (Dorsey, 1992); and (3) strike–slip faults developed in the volcanic island to accomodate transtension movements and thus formed pull-apart, intra-arc basins on the collapsed volcanic island (Huang et al., 1995). The present study is inadequate to identify which model is most likely to have caused subsidence. The flexural subsidence model, however, appears to be a suitable mechanism to explain the subsidence of the whole volcanic edifice.

8. Conclusions

On the basis of the lithofacies analysis, the volcanic and volcaniclastic rocks in the central Coastal Range, eastern Taiwan are divided into ten lithofacies. Furthermore, these lithofacies are grouped to form five facies associations in order to reconstruct the paleotopography and evolution of volcanism. The volcano in the central Coastal Range, eastern Taiwan is a composite volcano and includes two volcanic centers. The Liyachinshan volcano mainly supplied the volcanic deposits to the south, whereas the volcanic products of the Tienkangshan volcano are largely distributed to the north.

The volcano of the central Coastal Range began erupting on a deep ocean floor during the early Miocene, and extruded voluminous massive lava flows with minor pillow lavas and breccias. Then, it evolved to a shallowing environment during the middle to late Miocene and erupted abundant volcaniclastic rocks. Finally, subaerial eruption occurred at the end of the Miocene and yielded limited amounts of ignimbrites and basaltic lavas associated with paleosols. After the cessation of volcanism due to Taiwan arc-continent collision, the volcanoes rapidly subsided and were later overlain by thick terrigenous sediments. The flexural subsidence model appears to be a suitable mechanism to explain the subsidence of the whole volcanic edifice, although the present study is inadequate to identify which model is most likely to have caused subsidence.

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