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Mojanda volcanic complex (Ecuador): development of two adjacent contemporaneous volcanoes with contrasting eruptive styles and magmatic suites

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Abstract — In Ecuador, Volcan Mojanda, previously thought to be a single edifice, consists of two contemporaneous volcanoes, Mojanda and Fuya Fuya. Despite their proximity and contemporaneity, these volcanic centres continuously showed contrasting eruptive dynamics and geochemistry.

Andesitic lava flows form the main part of basal Mojanda (Moj I). Following caldera collapse, a small andesitic stratocone (Moj II) was built, consisting mainly of basic andesite lava flows, scoria flow deposits and a thick summit series of vitric breccias. This cone was partly destroyed by phreatoplinian eruptions that led to the formation of a small, summit caldera.

Fuya Fuya grew on the western flank of basal Mojanda and was contemporaneous with Mojanda II. Its activity began with andesitic and dacitic viscous lava flows and domes (FF I) and continued with a period of intense pyroclastic activity (FF II), during which two voluminous Plinian airfalls of rhyolitic pumice (R1 and R2) were erupted. Later, the activity of Fuya Fuya became effusive with the building of an intermediate andesitic edifice, the San Bartolo cone (FF III).

Subsequently, a Mount St. Helens-like collapse event occurred in Fuya Fuya which was responsible for the loss of a large part of FF III and the western part of Mojanda. This avalanche (unit FF IV) was accompanied by voluminous pyroclastic flows and was followed by the construction of a dacitic dome complex (FF V) within the avalanche caldera.

Both the Fuya Fuya and Mojanda magmatic suites show adakitic characteristics. This adakitic character is more marked for the Fuya Fuya volcanics than for the Mojanda rocks, suggesting different sources. Nevertheless, several arguments suggest that both volcanoes are related in their development and magmatic evolution. For example, the older rhyolitic Plinian deposits (R1) of Fuya Fuya contain juvenile andesitic clasts that have petrogenetic affinity with the Mojanda suite, a characteristic also observed in the ash flow deposits emitted after the avalanche event in Fuya Fuya. © 1998 Elsevier Science Ltd. All rights reserved

Resumen — En el Norte del Ecuador, el Complejo Volcanico Mojanda está formado por dos centros eruptivos contemporáneos, el Mojanda *sensu stricto* y el Fuya Fuya. No obstante su cercanía, estos centros mostraron una historia y estilo eruptivo diferentes.

En el Mojanda, lavas andesíticas y dacíticas componen la mayor parte del volcán de base (Moj I). Después de la formación de una caldera, se construyó un nuevo cono (Moj II), comprendido de lavas, de flujos de escoria y una serie de brechas en la cumbre cuyas composiciones son de andesitas basálticas. Este cono fue parcialmente destruido luego por la formación de una pequeña caldera.

El Fuya Fuya se construyó sobre el flanco oeste del Moj I, y fue contemporáneo con el Mojanda II. Su actividad empezó con viscosas extrusiones y domos de química andesítica y dacítica (FF I), seguidos por una intensa actividad piroclástica (FF II) durante la cual fueron emitidas dos caídas plinianas de pómez riolítica (R1 y R2) de gran volumen. Después, la actividad se volvió más efusiva con la construcción de un edificio andesítico intermediario, el cono San Bartolo (FF III). La historia del San Bartolo terminó con el colapso de la parte superior y del flanco oeste de este cono, el cual incluyó tambien una parte del Mojanda II. El colapso genero una avalancha (FF IV) que fue acompañada por voluminosos flujos piroclásticos y fue seguida por la construcción de un complejo de domos (FF V) en la caldera de avalancha.

Las series magmáticas de los dos centros muestran tendencias adakíticas las cuales están más marcadas en el Fuya Fuya que en el Mojanda, lo que sugiere origenes distintos. Sin embargo, existen argumentos para concluir que los dos volcanes comparten relación a veces en su desarrollo y evolución magmática. Por ejemplo, el depósito pliniano R1 del FF II contiene clastos juveniles andesíticos derivados del Mojanda, una caracteristica que se repite en los flujos piroclásticos emitidos después del evento de avalancha en el Fuya Fuya. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

In Ecuador, the Andes are divided into two chains, the Western and Eastern Cordillera, separated by the Interandean Depression (Fig. 1). Fifty-five major volcanic centres are recognized, distributed along these two chains, within the Interandean Depression and in the back-arc region. Together, they form a continuous volcanic belt, 300 km long and 120 km wide (Hall, 1977; Barberi *et al.*, 1988). Since 1532 AD, seven of the twenty-six Ecuadorian volcanoes which are considered as potentially active (Hall and Beate, 1991) have experienced eruptions.

Volcan Mojanda, located 60 km northeast of Quito, has one of the largest edifices in the northern Interandean Depression. Prior to the present study, little was known about this edifice which was thought to be a single volcano

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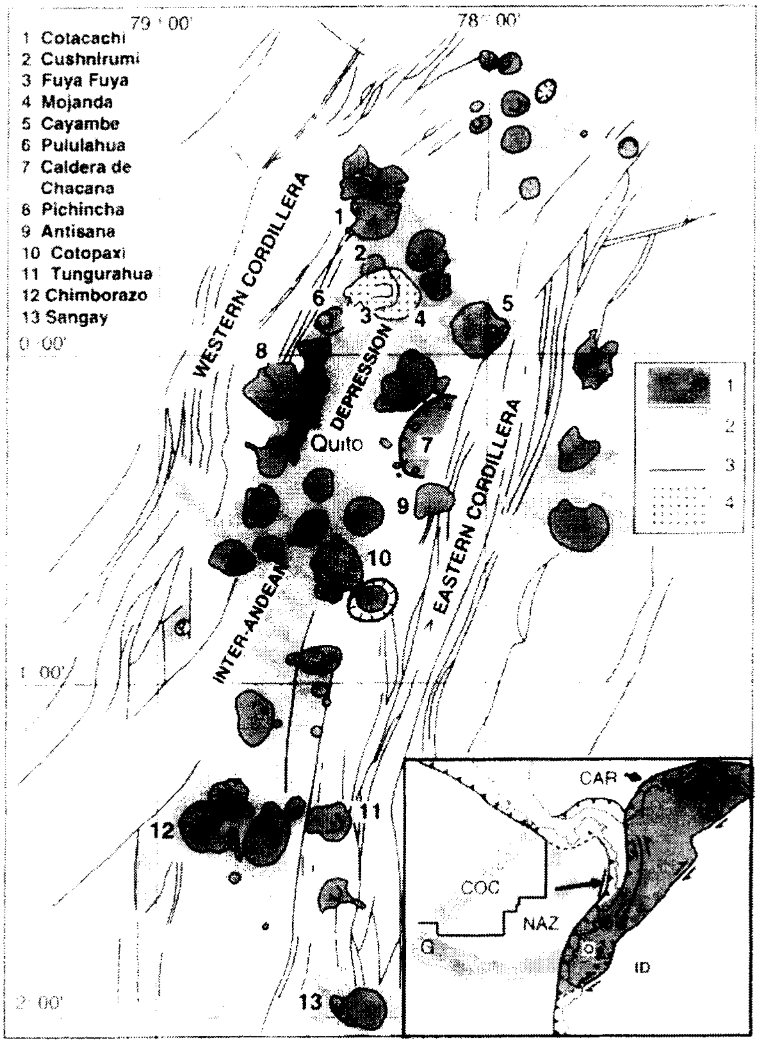

Fig. 1. Volcanoes of Ecuador, from Litherland and Egüez (1993), modified. Names of the 13 main edifices are mentioned. 1: Quaternary volcanics, proximal deposits. 2: Quaternary volcanics, distal deposits. 3: fault. 4: Mojanda-Fuya Fuya volcanic complex. Insert: Regional tectonic sketch map. CAR=Caribbean Plate; COC=Cocos Plate; NAZ=Nazca Plate; G=Galapagos Islands; ID=Interandean Depression; Q=Quito.

(Sauer, 1971; Hall, 1977). The present fieldwork shows that it consists of two major adjacent volcanic centres that had contemporaneous but different histories. We emphasize the notable differences that exist between them, especially their eruptive dynamics and geochemical characteristics. The stratigraphic control is based on the study of forty-six field sections, twenty-two of which are presented here. The detailed petrology of the rocks, based on 79 whole-rock analyses and mineralogical data, will be addressed in another paper. Here, only the broad petrographic nature of the recognized volcanologic units is presented.

MORPHOLOGY AND STRUCTURE OF THE OVERALL VOLCANIC COMPLEX

The Mojanda volcanic complex is slightly oval-shaped (25 km N–S by 30 km W–E) and rises to a maximum elevation of 4263 m at Cerro Fuya Fuya. Its base lies at 3000 m to the east, 2600 m to the north, 2400 m to the south and 2200 m to the west (Fig. 2). It has a small summit caldera, 2.5 by 3 km wide, presently occupied by a lake, the Laguna Grande de Mojanda (Fig. 2). The complex lies upon tectonized basalts and argillites of Cretaceous-Paleogene age (Litherland and Egüez, 1993) and upon thick detrital deposits which constitute the Guayllabamba series. To the south, east and north, its lower slopes have low gradients (5–8°) and are covered by thick sequences of pyroclastic deposits, whereas the western flanks show an uneven, more dissected topography. Lava flows predominate on the intermediate slopes ($\sim 15°$ dip) up to the summit area which is elongate in the E–W direction (about 10 km E–W vs 5–6 km N–S) and contains many peaks between 3900 and 4263 m. These peaks correspond to the highest outcrops of thick breccia sequences on the eastern side (for example Cerro Negro and Cerro Yanaurcu, Fig. 2) and to a series of domes on the western side, of which Fuya Fuya and Colangal domes are the main structures. The radial upslope convergence shown by the intermediate flank lava flows and surrounding pyroclastic deposits indicates the existence of two volcanoes, whose centres are located

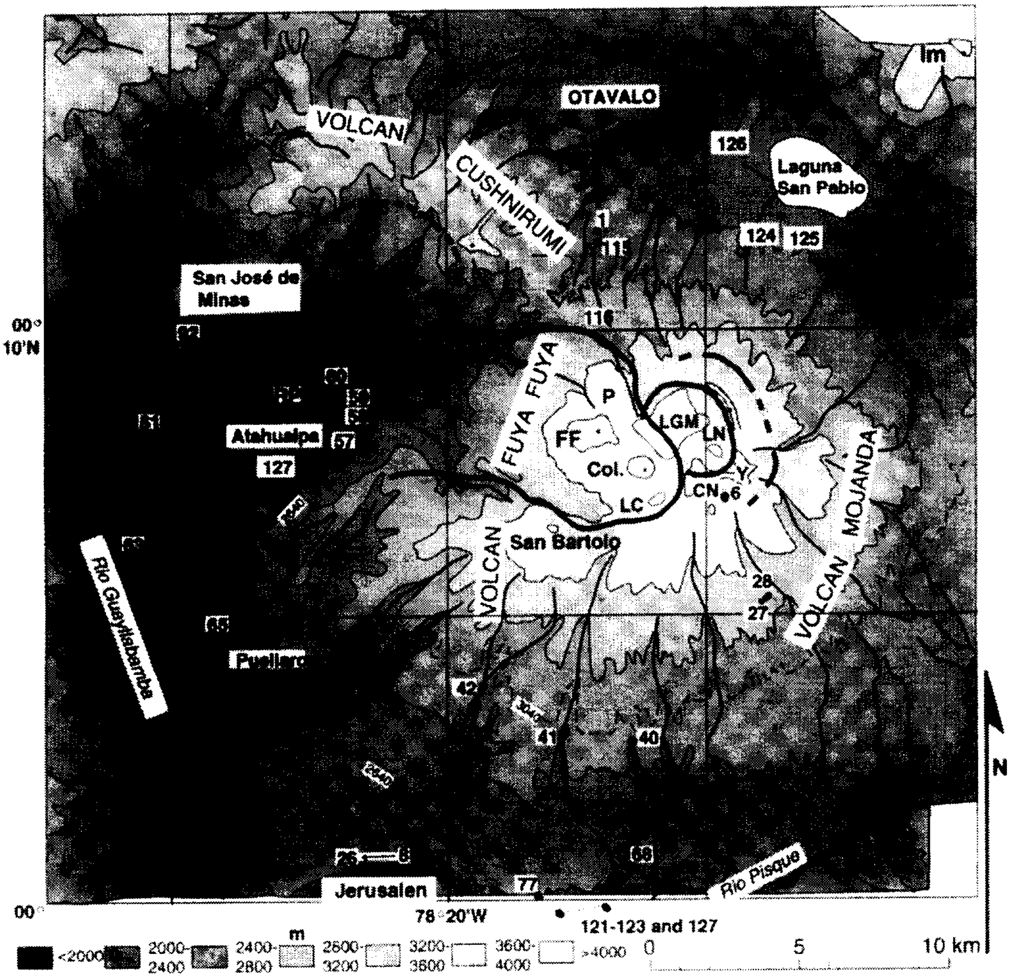

Fig. 2. Physiographic map of the Mojanda volcanic complex with location of sites and sections referenced in text. CN=Cerro Negro; Col=Colangal dome, FF=Fuya Fuya summit dome; LC=Laguna Chiquita; LGM=Laguna Grande de Mojanda; LN=Laguna Negra; P=Panecillo dome; RP=Rio Piganta; Y=Yanaurcu Peak. Bold lines: caldera structures.

only 4 km apart. Here, the name Mojanda is used for the eastern volcano, while the western edifice is named Fuya Fuya.

At Mojanda, the basal lava flows are radially distributed, implying a centre near the Laguna Grande de Mojanda. Remnant sommas between 3750 and 4000 m elevation suggest an older caldera, 5 km wide, concentric to the younger summit caldera whose steep northeast, east, and south interior walls form a semi-circular crest line with elevations between 3900 and 4260 m. In the south part of the summit caldera, a small lake, the Laguna Negra, occupies the remnants of a 1.5 km wide crater-like depression which is thought to be the youngest volcanic structure related to the Mojanda activity.

Westwards, the caldera wall is breached and occupied by a complex of dacitic lavas and domes which make up the upper part of the Fuya Fuya edifice. It formed in a 6 km wide depression that is open and inclined to the west and bordered by abrupt north and south interior walls, showing that the Fuya Fuya edifice experienced a large sector collapse before the emplacement of the domes.

Northwestwards, Cushnirumi Peak and associated mountains are the remnants of an older, dissected volcano. A greatly eroded, but still observable collapse structure opens to the southwest, suggesting that this volcano was also largely destroyed by an avalanche event.

UNITS OF THE MOJANDA VOLCANIC CENTRE

Basal lava flows (unit M I)

The volcanic basement of the Mojanda edifice consists mainly of two-pyroxene andesitic lava flows and rare intercalated breccias (unit M I-1, Fig. 3). On the lower eastern and southern flanks, these lavas are overlain by younger pyroclastic and epiclastic products that cover the Tupigachi Plain and the southern lower slopes around Malchinguí. A break in slope at about 3400 m elevation probably marks the lava's outer limit, giving Mojanda volcano a base of 16 by 18 km (Fig. 3). On the upper northern side of the cone, brecciated amphibole-bearing lava flows, up to 80 m thick and dacitic in composition (SiO_2=64–66.5 wt%, analyses recalculated to 100%, LOI free), descend almost to Otavalo (unit M I-2, Fig. 3). These are the last lava flows of basal Mojanda and were followed by caldera formation. This older caldera, about 5 km in diameter, is almost entirely buried by younger deposits and consequently little evidence remains of its

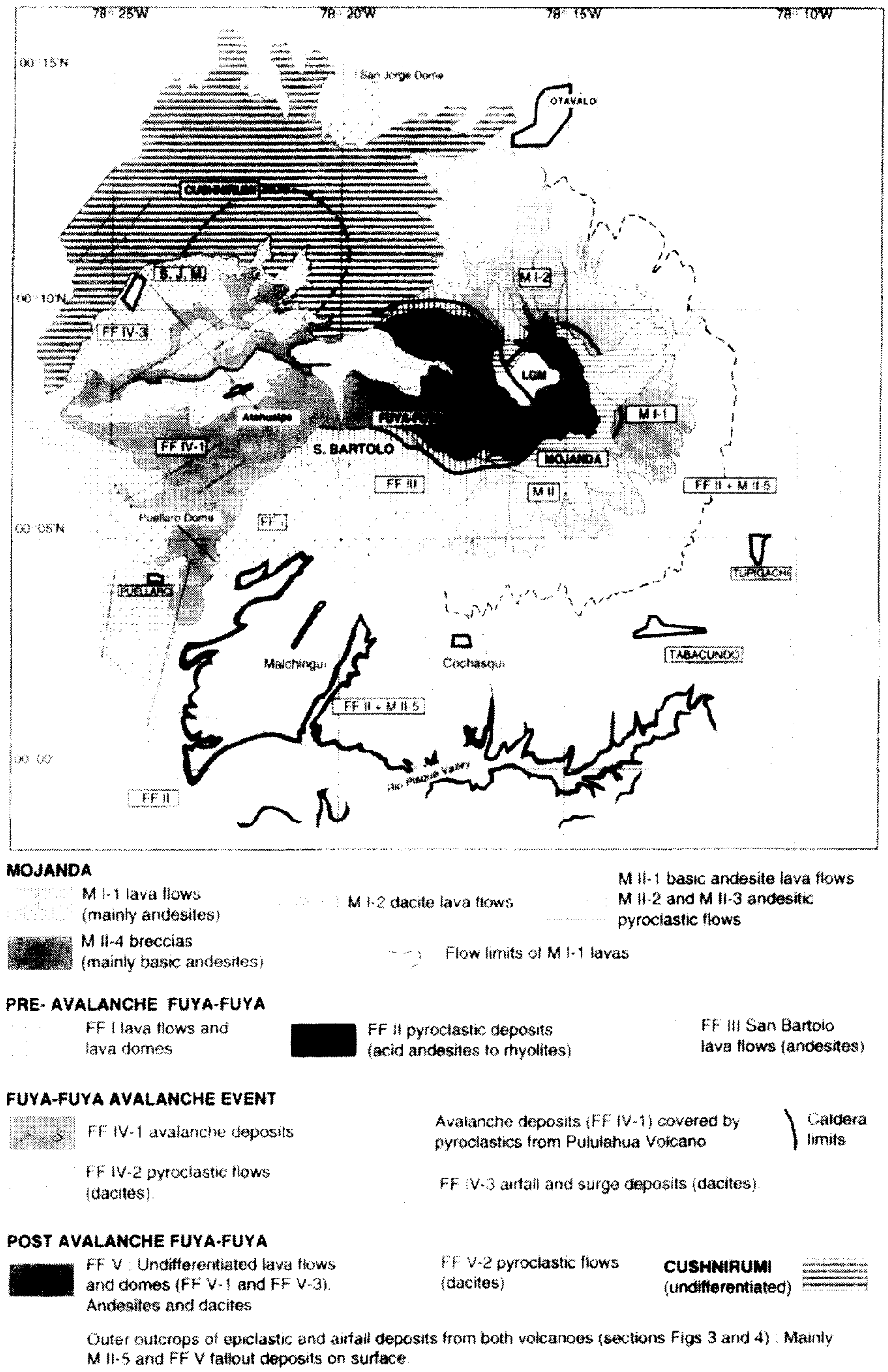

Fig. 3. Simplified geological map of the Mojanda volcanic complex.

eruptive or avalanche deposits. Nevertheless, voluminous lahar deposits of dacitic pumice are observed in the Pisque and Guayllabamba valleys, suggesting a possible relationship with this caldera.

Upper Mojanda volcano (unit M II)

Unit M II corresponds to a thick series of deposits, the products of eruptive events at Mojanda. They began with lava emission (M II-1) and associated scoria flows (M II-2) and block and ash flows (M II-3) and were followed by breccia formation (M II-4) and associated scoria fallouts (M II-5). Some of these events were contemporaneous, having left their deposits high on the edifice, while the deposits of others travelled down to the middle and lower slopes of the edifice.

Lava flows (M II-1). New activity filled the caldera of Mojanda I with thin lava flows and built a new cone 6–7 km wide, which spread over the caldera margin to the south and northeast. The flows descended only to 3800 m elevation in the south, but to the northeast one flow reached the lower slopes (Fig. 3). They consist of augite and olivine basic andesites (SiO_2=55–56 wt%) and are well exposed in the south wall of the summit caldera, where they are overlain by the breccias that form Cerro Negro (M II-4). The observed thickness of this lava series is about 100–150 m, but its total thickness is certainly greater, as it filled up the older caldera and overflowed its margins.

Scoria flow deposits (M II-2). Scoria flows belonging to Mojanda II activity travelled as far as 10 km from the summit on the south flank. These deposits, interbedded with thin andesitic ash and lapilli fall layers, contain decimetric-size scoria, bombs, and vitric blocks in a brown or red-brown ashy matrix. The juvenile clasts are two-pyroxene basic andesites (SiO_2=56.0–57.2 wt%). At site 40, four flow deposits and two scoria-rich mudflow deposits are observed in a 22 m thick section, lying in a paleovalley carved into the M I lava flows (see location, Fig. 2; strat. column, Fig. 4).

Block and ash flow deposits (M II-3). On the lower southern slopes at 2440 m, a sequence of block and ash flow deposits interbedded with surge deposits is 25 m thick. Near site 68, up to five successive flow units were observed, which overlie a remarkable 2.5 m thick pumice fall layer (the R2 rhyolite from Fuya Fuya, see below) and underlie ash and lapilli layers which characterize the last activity of Mojanda (unit M II-5). Blocks of plagioclase-orthopyroxene-amphibole-bearing andesites (SiO_2=61.5 wt%) dominate these deposits (Fig. 4).

Summit breccias and dikes (M II-4). Mojanda's uppermost slopes (~ 10 km^2) are covered by a ~300 m thick series of well-cemented breccias that form the south and east walls of the summit caldera. These rocks are basic andesites in composition. In both the southwest corner of the caldera and north of Laguna Grande, they overlie the M II-1 lavas. These breccias have a coarse stratification that dips radially outward (20 to 35°), suggesting that its emission centre was at Laguna Negra (Fig. 5a, b).

The western part of the breccia sequence is truncated by the Fuya Fuya avalanche caldera (Fig. 3). The Cerro Negro cliffs, which form part of the avalanche scar, expose six massive tephra units from this sequence, 3 to 15 m thick, each separated by lava flows (strat. column, Fig. 4). The crude layering is defined by parallel beds, a few decimeters to 6 m thick, and interbedded lava flows (Fig.

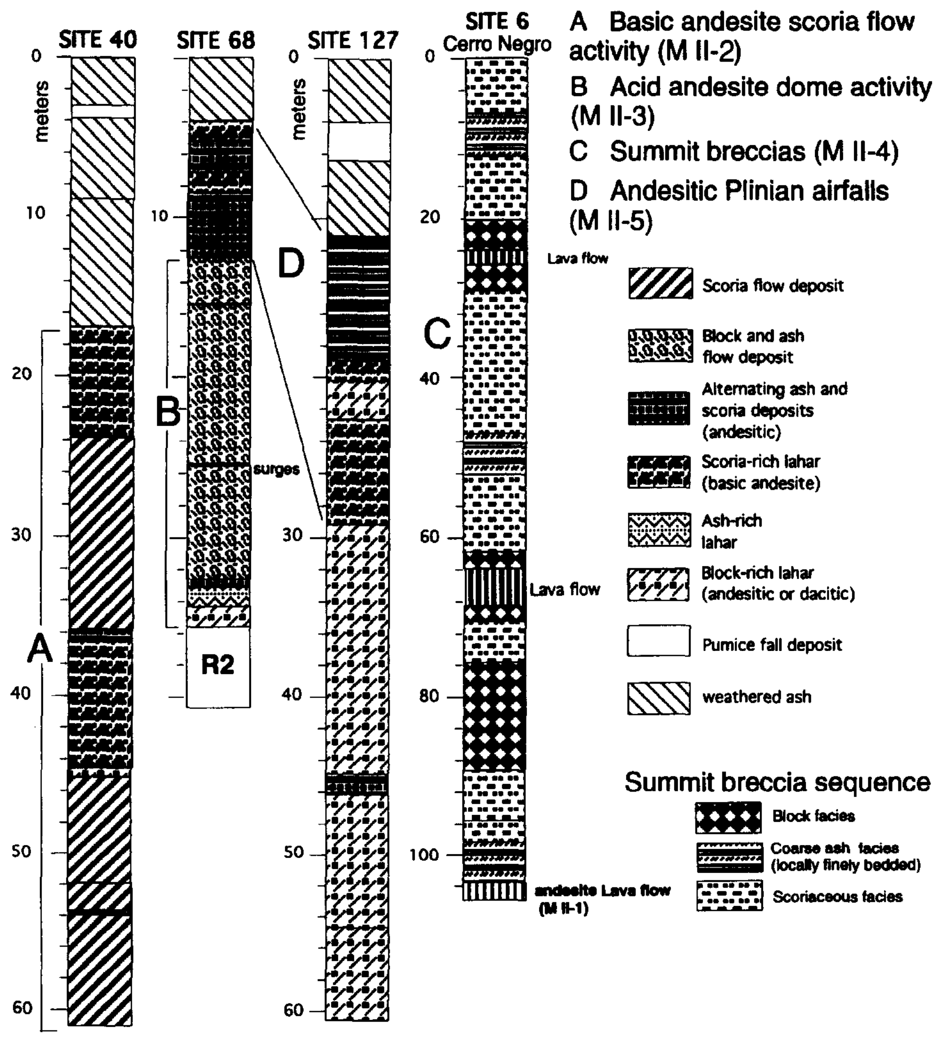

Fig. 4. Representative stratigraphic sections of Mojanda pyroclastic deposits (M II-2 to M II-5 units). Location of sites in Figure 2.

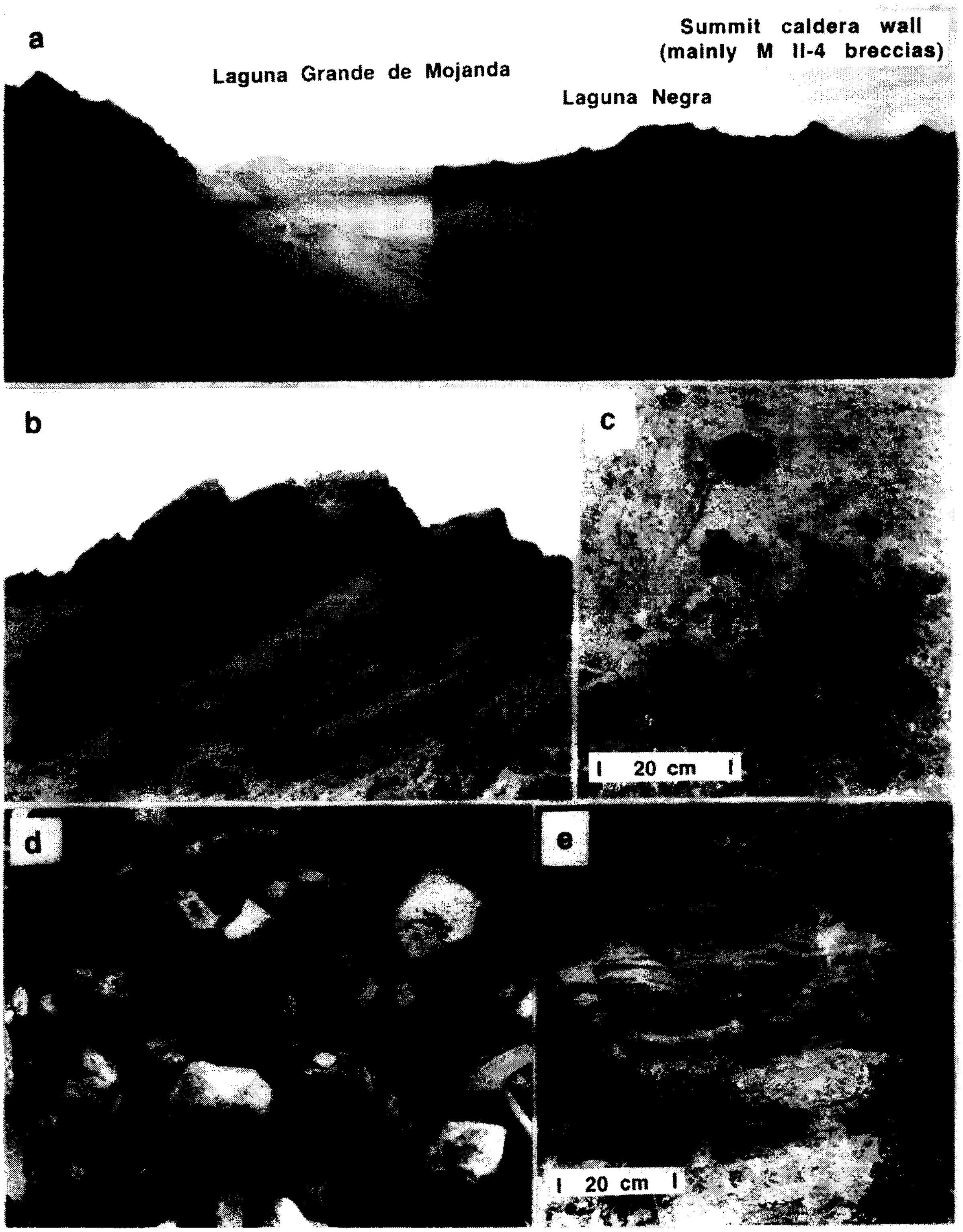

Fig. 5. Photographs representative of Mojanda summit breccias M II-4. a) view of the summit caldera. b) partial view of the summit breccia sequence. c) scoria facies from the M II-4 deposits. d) block facies. e) bed showing the coarse ash facies (ash and lapilli) overlain by surge deposits.

5b). In these tephra, accidental clasts are scarce. Three facies were recognized:

1) A coarse breccia facies consisting of jigsaw-shaped vitric blocks in an indurated matrix (blocky facies: Fig. 5d). Blocks are angular and generally decimeter in size; exceptionally, they reach 1.5 m in size. They may comprise up to 80 vol.% of these breccias.
2) Tuff deposits consisting of coarse ash to lapilli-size vitric clasts and shards in a granular, dark green to brown palagonitized matrix. Juvenile clasts are aphyric, non-vesicular, quenched and may be blocky or platy in shape, or conversely they are irregularly-shaped vitric clasts, incipiently or poorly vesiculated (5 to 40 vol.%), following the Houghton and Wilson classification (1989). Locally, these deposits are finely bedded and show surge structures (Fig. 5e).

3) Massive, unsorted, indurated breccia beds. These beds contain lapilli-size clasts (5–20 vol.%), in a granular pale-grey to yellow matrix composed of palagonitized vitric ash, broken minerals (abundant clinopyroxene), and zeolites. Palagonite and the intensive zeolitization give the rock its typical pale color. Clasts are dominantly vesicular scoria lapilli with subordinate amounts of angular, glassy andesite, which together show a wide range in vesicularity (scoriaceous facies, Fig. 5c).

In the caldera wall and floor, basic andesite dikes, 2–5 m thick, cut the breccias in a N–S direction.

Fallout deposits (M II-5). The last products emitted by Mojanda volcano are a series of ash and lapilli airfalls whose composition is similar to that of the M II-4 breccias. Their deposits are observed all around the cone, except to the west in the area affected by the Fuya Fuya avalanche. On the south flanks, they commonly overlie thick fallout deposits of the intermediate stages of Fuya Fuya and are overlain by two notable biotite pumice fall layers of regional extent which originated in the Chacana caldera (Fig. 1), known locally as the Pifo beds and dated at ~0.165 Ma (Hall and Mothes, 1996).

The best stratigraphic section occurs at Jerusalen, located 15 km S–SW of the summit (sites 8–26, Fig. 2; section, Fig. 6). Here, the M II-5 unit is 26 m thick and consists from base to top of: (1) beige to tan andesitic ash associated with brown lapilli fall and surge deposits (sub-unit A; 6 m thick); (2) a 5 m thick scoria-rich debris flow deposit (sub-unit B); (3) a composite sequence, 5 m thick, of centimetric to metric layers of black, grey or beige ash, dark scoria lapilli and pumice lapilli (sub-unit C); (4) water-reworked material comprised of rounded pumice overlain by a transitional zone in which layers of brown andesitic ash, light grey ash, and tan-grey and white pumice lapilli alternate (sub-unit D, 4 m thick). Typical beds contain quenched clasts and surge structures, suggesting the presence of water (Fig. 7d). These beds alternate with "dry" layers of scoriaceous lapilli and pumice.

Correlation of the M II-5 deposits in the south (e.g. the Jerusalen section and sites 77, 121, 122 and 123) with sections in the north (sites 124 to 126) are shown in Fig. 6. At similar distances from the summit area, the combined thicknesses of the M II-5 airfall layers are about 20 m to the southwest and only 8–10 m to the south. To the north, at 7 km from its source, the average thickness of this sequence is only 3 m. This distribution confirms a southwestward wind direction during the eruption.

Stratigraphically, the M II-5 series begins toward the end of the FF II phase of activity, since its deposits either are interbedded in the upper FF II beds or overlie it.

UNITS OF THE FUYA FUYA VOLCANIC CENTRE

Basal lava flows and domes (unit FF I)

Fuya Fuya's basal edifice is a sequence of large viscous extrusions, andesitic to dacitic in composition (SiO_2=62–68 wt%), which were emplaced on the western flank of the basal Mojanda edifice, after the M I-1 phase. The FF I lava flows and domes extend up to 12 km southwestward from Fuya Fuya's summit and do not appear to the north of the avalanche caldera. On the basis of petrologic data, two eroded excentric domes — the Puellaro dome and the San Jorge dome (Fig. 3) — were associated with this activity.

Plinian and dome deposits (unit FF II)

Intermediate and distal products corresponding to FF I dome construction and destruction and associated Plinian activity constitute the varied deposits (unit FF II) which extend over the lower southern and southwestern slopes of the volcanic edifice. For example, at Jerusalen, a 70 m thick sequence is exposed, made up of lahar deposits, Plinian pumice beds, and block and ash flow deposits (Fig. 6):

Pumice lahar deposits. The lower 13 m of the Jerusalen section consist mainly of alternating beds, 10–150 cm thick, of dacitic (SiO_2=64.5 wt%) pumice lahar deposits and reworked ash. Laharic deposits containing andesitic blocks up to 40 cm in diameter also occur in this series which underlies waterlain ash layers (cinerites), sandstones, and calcareous beds.

Plinian pumice beds. Two pumice beds (R1 and R2), rhyolitic in composition, are the most remarkable deposits of the Jerusalen section (Figs. 6, 7b). These major Plinian deposits cover the entire Mojanda region and have been recognized southwards to Quito. The lower R1 deposit is a composite unit: at Jerusalen, its base consists of a 90 cm thick layer of white rhyolitic pumice lapilli (SiO_2=73–74 wt%) which becomes progressively enriched upwards with grey andesitic lapilli (SiO_2=62 wt%). In the upper 20 cm, the rhyolitic material disappears and the deposit consists only of dark grey andesitic ash, scoria lapilli, and cauliflower bombs (Fig. 7c). Near Guayllabamba, 20 km from Fuya Fuya's summit, the largest scoria clasts are up to 8 cm across. The upper part of the R1 deposit is 2.8 m thick and consists of a homogeneous pumice fall deposit (SiO_2=74 wt%) with a few lithic clasts.

At site 77, R1 is a complex sequence, 15 m thick. A 2 m thick basal series of grey and white ash and pumice lapilli (A on section site 77, Fig. 6) ends with the deposition of an ash layer bearing fragments of andesitic cauliflower bombs. Above a series of pumice-rich lahar deposits (layer B, 3 m thick), the main pumice layer occurs, here 1.2 m thick (C). This is overlain in turn by a series of thin surge beds (0.2 to 8 cm thick), thin ash-rich lahar beds (D, total thickness 4 m) and a finely stratified succession of grey (andesitic) and white (rhyolitic) ash (E, 3.5 m thick; Fig. 6).

The R2 bed is a homogeneous rhyolitic pumice lapilli fall bed (SiO_2=73.5 wt%) characterized by a higher

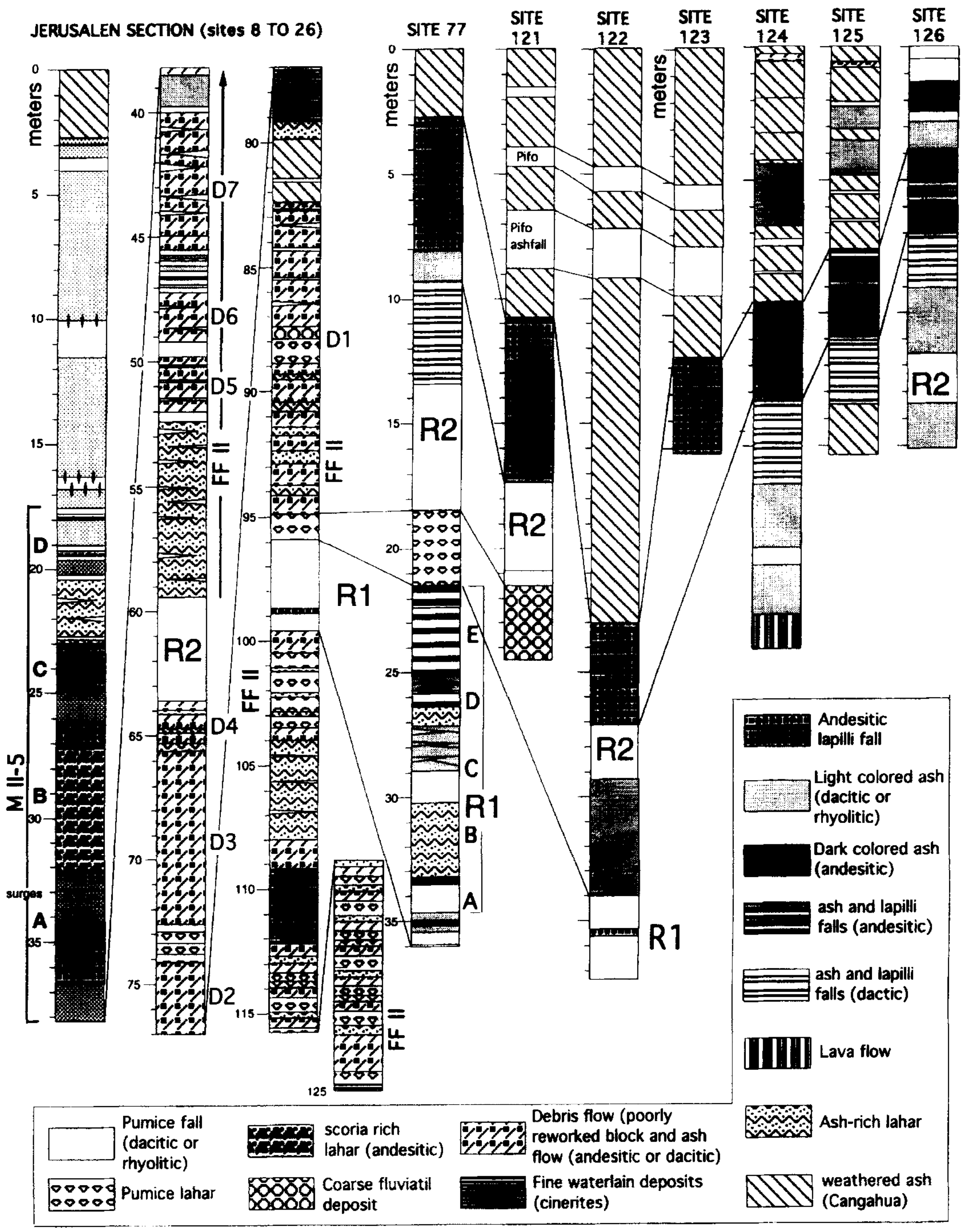

Fig. 6. Stratigraphic columns showing pyroclastic deposits from Mojanda and Fuya Fuya volcanoes, prior to the avalanche event. Note the rhyolitic pumice related to the Chacana caldera (Pifo beds).

content (~ 5 vol.%) of altered lithic fragments. Its thickness ranges from more than 5 m at site 77 to 4.2 m at Jerusalen (Fig. 7b) and to 2 m on the north flank of the volcano, near Laguna San Pablo.

Block and ash lahar deposits associated with minor pumice fall deposits. At Jerusalen, the R1 and R2 beds and dacitic pumice deposits of lesser thickness (0.4–0.7 m) are interbedded in a series of acid andesitic to dacitic lahar deposits, commonly 0.5 to 2 m thick. In each deposit, the blocks are dominantly glassy with radial fractures, characteristic of a dome origin. Some units, consisting of angular, monolithologic blocks in an ashy matrix, are interpreted as deposits derived from block and ash flows that transformed to lahars. Overall, seven sequences were recognized (D1 to D7, Fig. 6); the thickest sequence (D1) overlies the R1 layer and contains ten or more units which are interbedded with primary Plinian and reworked ash layers.

San Bartolo lava flows (unit FF III)

Cerro San Bartolo is a thick package of acid andesitic and dacitic lavas (SiO_2=61.5 to 65 wt%) of limited extent. It represents the remnants of a cone which covered most of the former FF I unit. These lavas and the remnants of

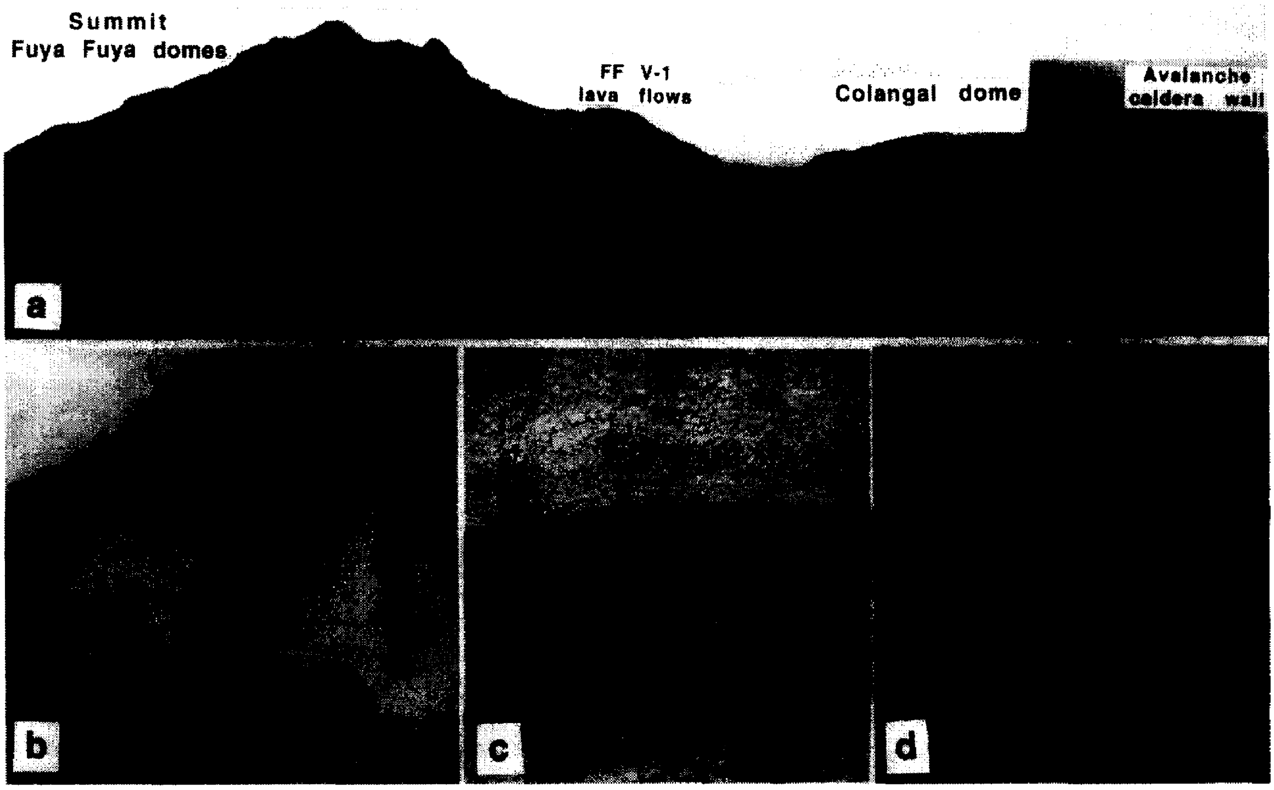

Fig. 7. a) Panoramic view of post-avalanche Fuya Fuya dome complex, from San Bartolo crest line. b) Part of the Jerusalen section showing the R2 pumice bed from FF II phase. c) Detail of the R1 deposit at Jerusalen section: transition between the lower bed, enriched in andesitic clasts, and the main pumice deposit (see text). d) Scoria lapilli beds and surges from the M II-5 deposits in Jerusalen section.

underlying domes are well exposed in the southern wall of the avalanche caldera that truncates this cone. North of the avalanche caldera, the San Bartolo cone is represented by the Pilisuco crest line, lavas along the edge of the sector collapse (Fig. 8), and block and ash flow deposits bearing breadcrust bombs which outcrop below the FF IV-2 ash flow deposits related to the avalanche, at site 115 (Fig. 2).

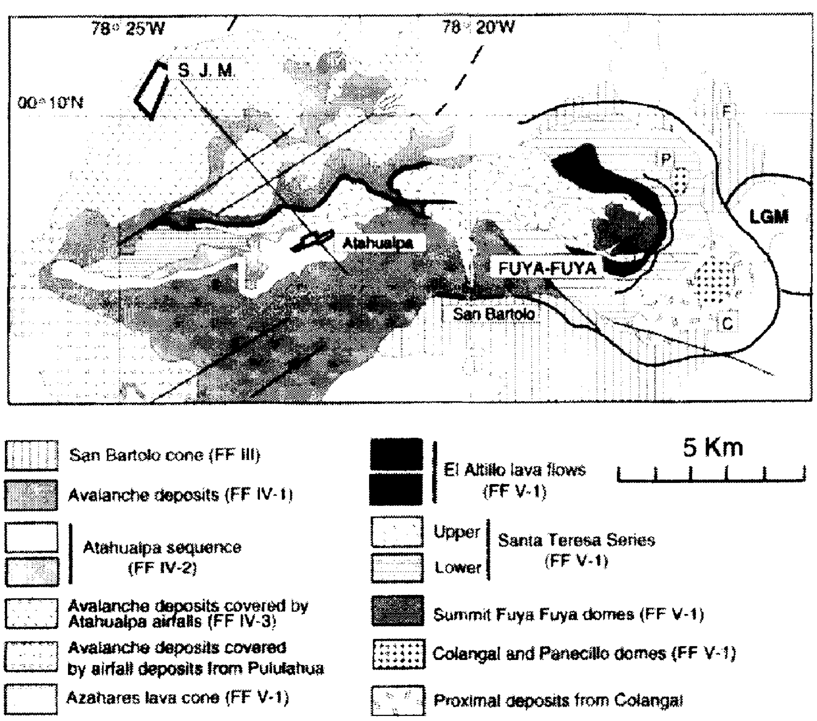

Fig. 8. Geological sketch map of the complex's summit area. SJM=San José de Minas; C=Colangal dome; P=Panecillo dome. LGM=Laguna Grande de Mojanda.

Deposits related to the avalanche event (unit FF IV)

Avalanche deposits (FF IV-1). The Fuya Fuya caldera formed as a result of a large avalanche similar to that of the 1980 Mt. St. Helens event. The debris avalanche followed valleys westwards, until it was stopped by the deep Guayllabamba canyon. The proximal deposits consist of large, fractured, and tilted packages of lava flows whose original orientation was only slightly disturbed during sliding. For example, the hills south of Atahualpa appear to represent large sectors that collapsed in mass. Along the Puellaro to San Jose de Minas road and in the Guayllabamba canyon, the deposits contain finely crushed rock debris; fractured blocks in a pulverized matrix is the common lithology at many outcrops. The avalanche flowed around the Puellaro dome, filled and dammed the Guayllabamba River canyon to over 120 m in depth, and covered more than 125 km^2.

Pyroclastic flow deposits and associated ash and pumice fall deposits following the avalanche (FF IV-2 and FF IV-3). Subsequently, ash flows, here called the Atahualpa sequence (FF IV-2), traveled in two directions: northwards, following the declivity between the Mojanda and Cushnirumi edifices, and westwards, following the paleovalley of the Rio Piganta (Figs. 3 and 8; strat. columns, sites 57–58 and 60, Fig. 9). To the north, pumice flow deposits are exposed along the road from Otavalo to Laguna Grande de Mojanda (site 1, Fig. 2) and have thicknesses that vary from 6 to 30 m. They are dacitic (SiO_2=66.5 wt%) in composition, but heterogeneous pumice clasts show a dark grey banding of less vesiculated, andesitic material (SiO_2=61.5 wt%). Charcoal from site 1 has given an age >35,000 years (ORSTOM C14 Laboratory at Bondy, analysis no. OBDY 1318). To the west, these deposits are well exposed below Atahualpa village,

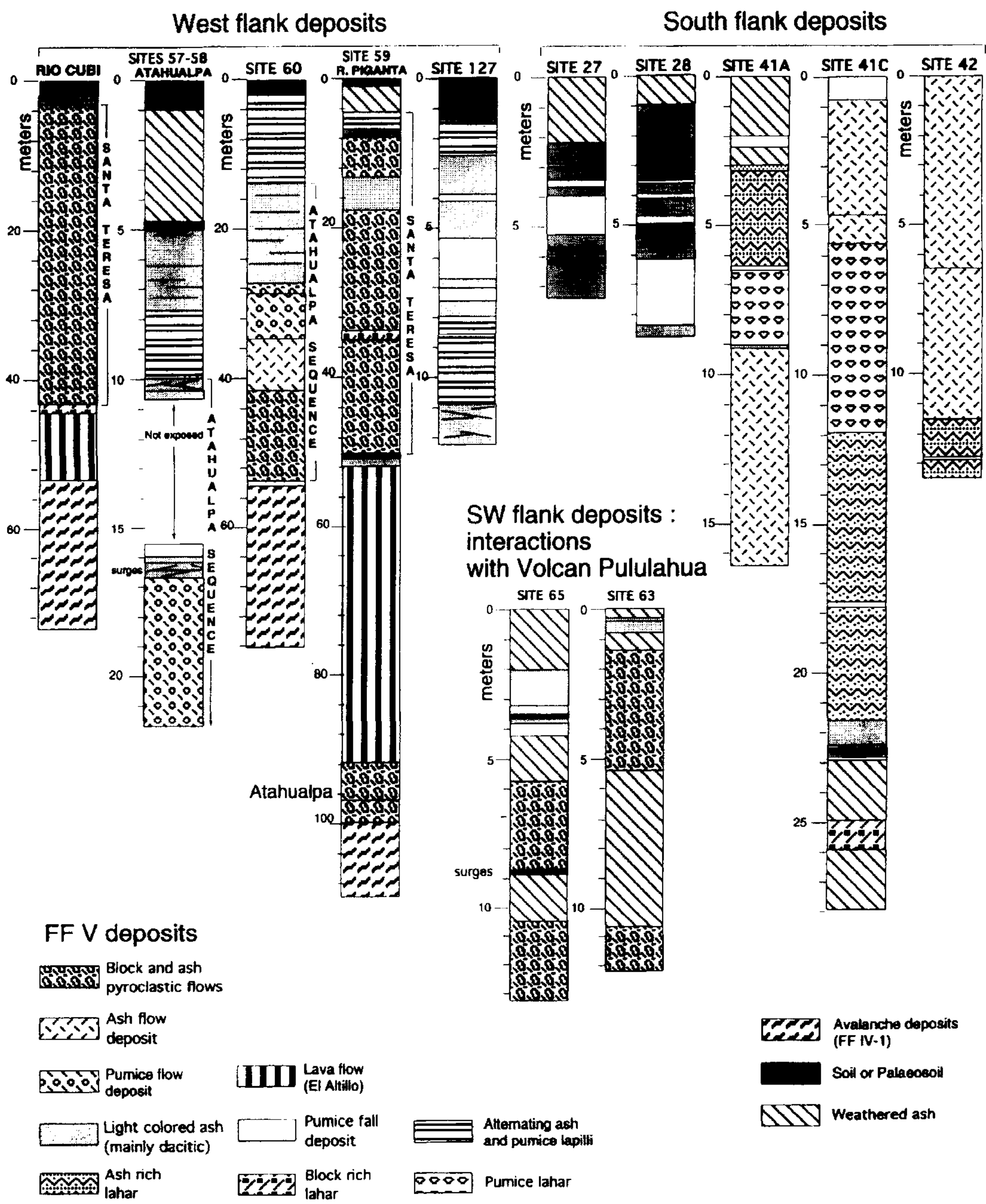

Fig. 9. Stratigraphic columns showing post-avalanche deposits of Fuya Fuya.

where they are 50 m thick and directly overlie the avalanche deposits (site 57–58 and 60, Figs. 2 and 9). The deposits also contain heterogeneous pumices with decimetric-wide andesitic bands. At El Troje, 1.5 km north of Atahualpa, the sequence consists of three well-exposed flows, the lowest showing a larger content of vitric blocks (section, site 60, Fig. 9).

The Atahualpa sequence underlies a 10 to 25 m thick series of pumice and ash fall deposits (FF IV-3). In the San Jose de Minas area, these and associated surge deposits cover at least 50 km^2 and directly mantle the avalanche products that are 2–3 m thick on slopes to more than 20 m thick in depressions.

Post-avalanche Fuya Fuya complex: lava flows, domes, and related pyroclastic products (unit FF V)

Lava domes and lava flows (FF V-1). A new composite cone, 5 km wide and ~ 1000 m high, grew within the avalanche caldera (Fig. 8). It consists of two series of thick, viscous lava flows and domes. The basal series, exposed in the Azahares Canyon, is mainly hornblende dacites. The second series, the El Altillo lavas, contains both andesites and dacites and forms a small, 3 km wide edifice nested in the Azahares series. Both series were glacially eroded.

From the avalanche caldera, two El Altillo lava flows traveled as far as 14 km from the vent (Figs. 3 and 8). One of these flows, up to 30 m thick, filled a paleovalley that ran parallel to the present Piganta River; it represents a continuous stratigraphic marker overlying the Atahualpa ash flows and associated airfall deposits. Three central lava domes of Fuya Fuya and two satellite domes, the Colangal and Panecillo domes, represent the last extrusions of the Fuya Fuya complex (Figs. 7a and 8). Panecillo is a well-preserved, cone-shaped extrusion, whereas Colangal is a 1.5 by 2.5 km wide and 400 m-high complex of lava domes, with at least two explosion craters on its north side.

Pyroclastic flows and fallout deposits (FF V-2). Pyroclastic products, related to the explosive activity of the intra-caldera Fuya Fuya dome complex, were mainly carried to the west. Block and ash flows, erupted after the El Altillo lavas, form the Santa Teresa series in the Cubi and Piganta valleys (sites 51 and 59, Figs. 2 and 9). These pyroclastic flow deposits consist of vitrophyric dacite blocks (up to 70 vol.%) and subordinate pumice in a light pink to blue-grey ashy matrix (30 to 40 vol.%). They are associated with deposits of surges, airfalls, and lahars. The maximum thickness of the Santa Teresa series is 50 m.

On the south flank, three dacitic ash flow deposits (SiO_2=65–68 wt%) occur. These deposits, here called the Cochasqui sequence (sites 41–42, Fig. 2; strat. columns, Fig. 9), clearly differ from the block-rich flows channeled to the west from the avalanche caldera. They contain centimetric-size pumice clasts, and are associated with pumice-rich laharic deposits and fall deposits. An unusual aspect of these products is the presence of grey and white banded pumice, especially in the lapilli fall layers. The extrusion of the Fuya Fuya domes was accompanied by numerous pyroclastic deposits found both on the southern and northern flanks (sites 27 and 28, Fig. 9; 124 to 126, Fig. 6), which are difficult to correlate with one another. Ashfall thicknesses suggest that wind-transported products were preferentially carried to the north and northeast. Nevertheless, in the latter area, ashfalls from other volcanoes such as Imbabura or Cayambe (Monzier *et al.*, 1996) may have contributed to the deposits.

INTERPRETATION: VOLCANO DEVELOPMENT AND ERUPTIVE STYLES

Mojanda I built an 18 km wide stratocone that probably attained an elevation of 4600 m, implying a volume of about 140 km^3. The M I-1 activity was essentially effusive and thus formed a thick sequence of andesitic lavas (56% SiO_2). A K/Ar age of 0.59 ± 0.06 Ma is given by Barberi *et al.* (1988) for an andesite from the Mojanda volcano, probably from this basal edifice (no precise location). The subsequent M I-2 activity corresponds to brecciated dacitic lava flows (66% SiO_2) that descended the north flank. The M I activity terminated with the formation of the older 5 km wide caldera.

The activity of Mojanda II began with lava emissions (M II-1) that turned progressively explosive, despite the relatively basic character of the M II-2 rocks. The presence of scoria, breadcrust bombs, quenched clasts, and surge structures suggests strong explosive episodes in an open-conduit regime with magma-water interactions. Additionally, accidental blocks in the deposits imply the destruction of andesitic domes or lava plugs obstructing the chimney. These deposits formed by collapse of the denser parts of the convective column, during brief, vertically-directed eruptions, similar to those produced at St. Vincent in the Lesser Antilles in 1979 (Shepherd and Sigurdsson, 1982) or at Mayon in 1968 (Moore and Melson, 1969). A large crater was probably opened by each explosive episode and then filled by lava flows or domes, in a cyclic process similar to that observed in many andesite volcanoes, (e.g. Fuego de Colima in Mexico; Robin *et al.*, 1991). The end of this phase of activity was marked by diminishing magma-water interaction which led to dome extrusion and the formation of block and ash flows (M II-3). From the M II-1 to the M II-3 volcanic phases, the magma composition evolved from basic andesite (SiO_2=55 wt%) to acid andesite (SiO_2=62 wt%).

The nature of the Yanaurcu and Cerro Negro breccias of the M II-4 phase suggests a unique origin: 1) Their hyaloclastic texture as well as the mineralogy of the hydrated matrix suggest magma-water interactions. 2) They are characterized by steep dips, summital distribution and remarkable thickness. 3) They are monolithologic and the clasts show a wide range of vesicularity. Phreatomagmatic eruptions are known to produce a wide variety of clast shapes and vesicularities (Wohletz, 1983). Hyaloclastites originate by cooling-contraction granulation which results in angular, blocky, jigsaw-shaped clasts (Honnorez and Kirst, 1975), although fragmentation mechanisms are complex in detail (Kokelaar, 1986; Houghton and Wilson, 1989). Additionally, compared to basaltic hyaloclastite sequences, silicic hyaloclastites are more varied, consisting of lithic blocks, lapilli and ash (Furnes *et al.*, 1980; Fisher and Schmincke, 1984). Given the hyaloclastic nature of the M II-4 deposits found only in the summit areas, apparently vesiculated magma was extruded into snow, leading to shattering of the andesitic flows and the formation of these breccias. Geochemically, the M II-4 breccias show a return to mafic magmatism following the M II-3 dome phase.

Mojanda's activity declined shortly thereafter but left a thick M II-5 andesitic fallout sequence. During this phase, the snow cap was probably destroyed by explosions and the resulting water had a great influence on eruptive dynamics, as implied by hydroclastic surface features of the clasts and the presence of surge and lahar deposits within the sequence. Dry airfall deposits interbedded within the sequence show that H_2O/magma ratios were variable. This long-lasting cycle of phreatoplinian and Plinian events was associated with the formation of the summit caldera. Ash dispersion as far away as 30 km indicates that some of these explosions were of very large magnitude.

After the construction of Mojanda I and contemporaneous with M I-2, activity broke out on the western flank of Mojanda's edifice which led to the emplacement of the FF I lavas and domes. The pumice-rich lahars at the base of the Jerusalen section (Fig. 6) may be the products of this eruptive stage.

The distal products related to the domes as well as the voluminous Plinian deposits such as R1 and R2 clearly indicate that during the FF I and II phases the activity was strongly explosive and characterized by acid extrusions from a shallow, gas-rich magma chamber. The FF II deposits were emplaced in the course of two long cycles that are stratigraphically and chemically distinct. Each cycle began with a large Plinian eruption, that produced a thick pumice fall bed of rhyolitic composition (R1 and R2), and ended with episodes of dome construction and collapse (D1 to D7: three episodes in the first cycle and four in the second). The R1 and R2 Plinian episodes were probably associated with the formation of calderas which were filled by new domes, as suggested by the block and ash flow sequences of the D1 to D7 deposits. Additionally, the presence of 10 minor pumice falls of dacitic composition in the Jerusalen section (the largest, underlying D6, being 70 cm thick) demonstrates continuing cycles of Plinian activity followed by dome growth.

San Bartolo cone represents the intermediate construction stage of the Fuya Fuya complex. The distribution and inclination of the lava flows exposed in the avalanche caldera walls suggest that it was a well-formed stratocone whose centre was 1 to 1.5 km to the south of the present Fuya Fuya summit (Fig. 10). Before its partial destruction by the subsequent collapse event, it reached $\sim$4600 m in elevation, was 10 km wide, and had a volume of $\sim$40 km^3, forming a cone similar to the adjacent Mojanda II edifice. Associated block and ash flow deposits show that this volcano had also experienced explosive episodes.

The sector collapse which destroyed the greater part of the San Bartolo cone and affected the western part of the Mojanda II cone left a major avalanche deposit downvalley to the west, as well as a large amphitheater in the summit area. Voluminous ash flows, airfalls, and surges (units FF IV-2 and 3) immediately followed the avalanche event, forming a sequence similar to that erupted at Mt. St Helens (Rowley *et al.*, 1981) and Popocatepetl (Robin and Boudal, 1987). Most of these products were directed to the west, but large quantities of ash and pumice were also carried to the north.

During the Late Pleistocene, a new complex of viscous lava flows and domes was emplaced in the Fuya Fuya avalanche caldera. In subsequent explosive activity, block and ash flows were directed down the drainage to the west (Santa Teresa pyroclastic flows). Other ash flows, of lesser volume, traveled southwards (Cochasquí ash flows). During this late pyroclastic activity, numerous fall deposits accumulated over the entire summit area of the volcanic complex. Whereas the Santa Teresa block and ash deposits represent the destruction of El Altillo's summit domes, the Cochasquí ash flows are more likely related to Plinian eruptions associated with the Colangal extrusions. This is suggested by the quite similar compositions of the Cochasquí ash flows and the Colangal dome, which are also the most differentiated products (SiO_2=69 wt%) of recent Fuya Fuya. A charcoal date from a Cochasquí ash flow has shown an age >43,500 years (Centre for Isotope Research, University of Groningen; ref. GrN 22435). As the Colangal and Panecillo domes are the last extrusions of the complex and are little glaciated, probably these ashflows barely preceded the extrusions, and thus these domes occurred shortly before the Holocene.

CONCLUDING REMARKS

Two major closely associated volcanic centres constitute what was previously considered to be the solitary Mojanda volcano. Although no radiometric dates are presently available, we can assert that the development of these two volcanoes, only 4 km apart, was broadly contemporaneous (Fig. 11). More precisely, the eruptive phases of both volcanoes alternated, and at times were simultaneous, from the time of the older Fuya Fuya lavas (FF I) until the cessation of Mojanda's activity.

For example, while the M II-3 pyroclastic deposits were laid down after the Plinian R1 and R2 beds in Fuya Fuya (FF II phase), the south wall of the avalanche caldera exposes basic andesite lavas and airfall layers of

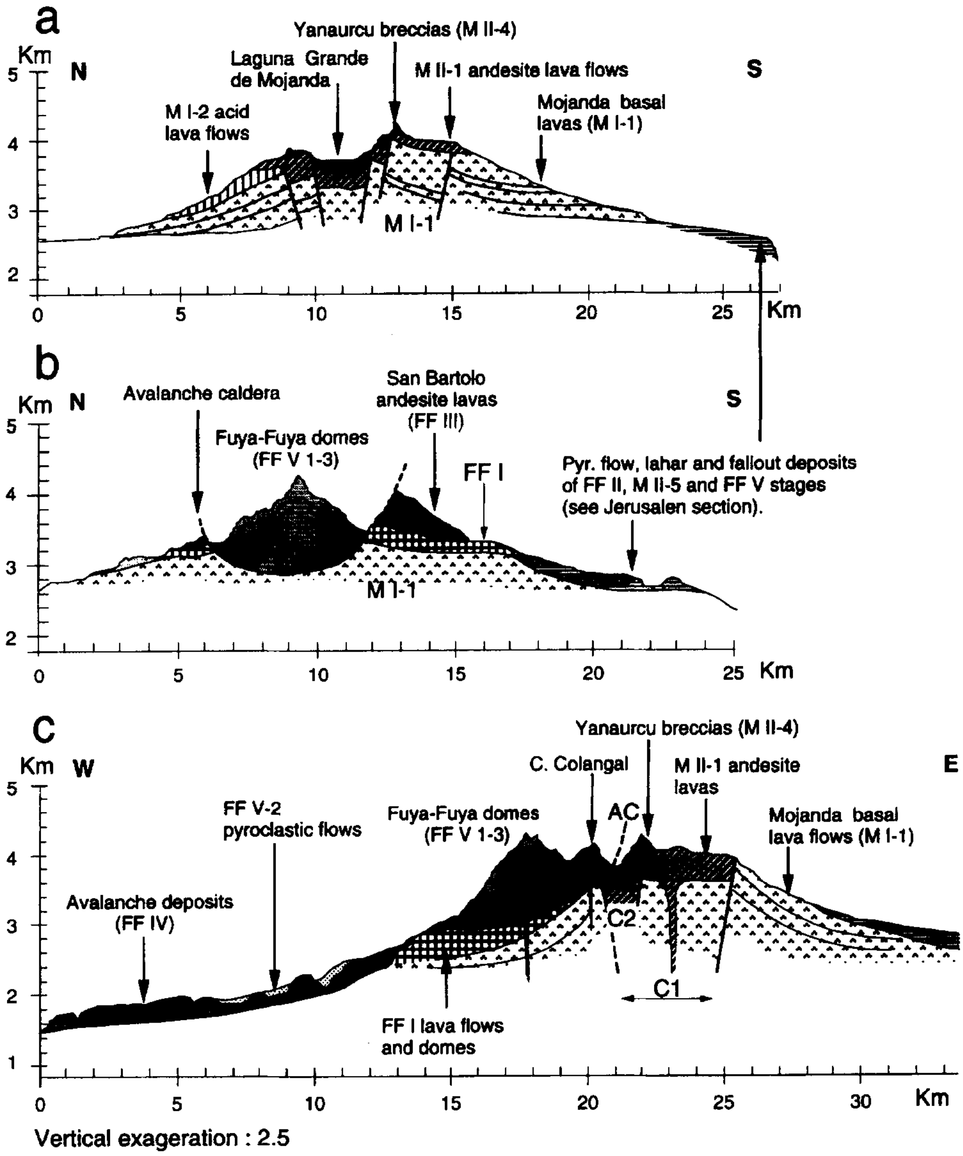

Fig. 10. Cross sections through a) Mojanda volcano, b) Fuya Fuya volcano and c) both volcanic edifices. C1=former Mojanda caldera; C2=summit Mojanda caldera. AC=Fuya Fuya avalanche caldera.

Mojanda II below the R2 pumice layer. As another example, many field sections (Figs. 4, 7, and 9) show that the M II-5 deposits overlie the main part of the FF II deposits, but pumice fall layers, clearly from the Fuya Fuya's pre-caldera Plinian activity (i.e. probably from the FF III phase), are *interbedded with* the M II-5 andesitic phreatoplinian deposits. Thus, both volcanic centres, characterized by different histories and contrasting eruptive styles, were largely contemporaneous in their development (Fig. 11).

It is also remarkable that despite their proximity and contemporaneous activity, each volcano shows a distinct magmatic lineage. Major and trace element analyses for 79 samples have been carried out on the volcanic complex and a detailed petrologic study will be given in another paper. Here, our purpose is to show the geochemical differences that occur from one centre to the other. Both magmatic suites lie in the medium-K calc-alkaline field, but the Mojanda rocks are clearly more K-enriched than the Fuya Fuya rocks for the same SiO_2 value. A discriminant test to differentiate the two suites is the Sr/Y vs Y diagram (Fig. 12). Fuya Fuya rocks have a clear adakitic character (Kay, 1978; Defant and Drummond, 1990), whereas the Mojanda suite has characteristics intermediate between the normal continental andesite-dacite calc-alkaline and the adakitic lineages. Thus, the contrasting development of the two centres is related to different magmatic suites, implying that more than one magmatic reservoir must have existed below the volcanic complex.

Nevertheless, on two occasions, interactions between both volcanoes were probable. 1) The andesitic magma that apparently mixed with R1 rhyolitic magma at the beginning of the FF-II phase has Mojanda's chemical characteristics. Based on the generalized stratigraphy (Fig. 11), this andesitic magma was probably related to the M II-1 (or M II-2?) andesitic phase in Mojanda. 2) Andesitic bands in the dacitic pumice of the post-avalanche Atahualpa ash flows also show a Mojanda

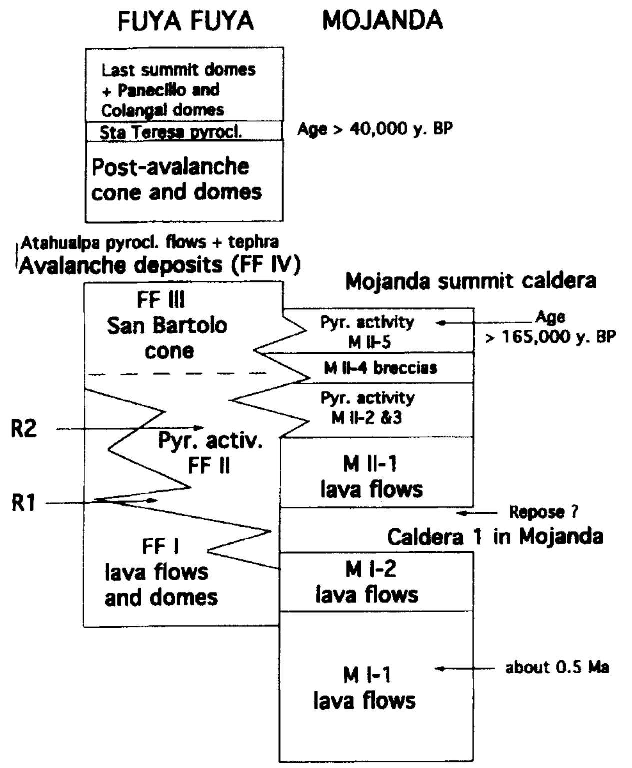

Fig. 11. Generalized stratigraphy of the whole volcanic complex.

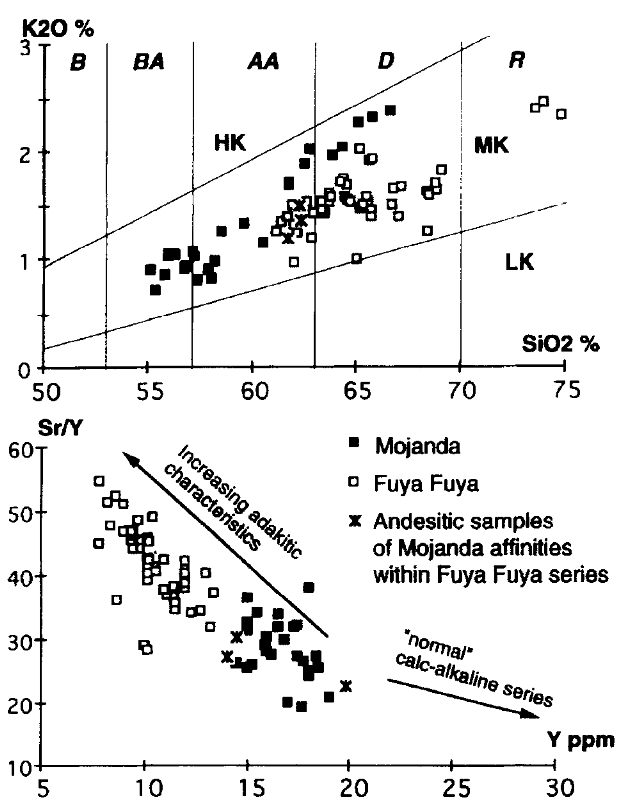

Fig. 12. K_2O–SiO_2 and Sr/Y — Y geochemical diagrams. A=basalts, BA=basic andesites, AA=acid andesites, D=dacites; R=rhyolites. HK, MK and LK define the areas of high, medium, and low-potassium contents.

chemical affinity (Fig. 12), suggesting a causal relationship between a Mojanda magmatic episode and the Fuya Fuya sector collapse. This agrees with the short time interval, if any, that separated the summit caldera formation in Mojanda and the Fuya Fuya sector collapse. At least twice, new magma batches of the Mojanda suite probably intruded the shallow Fuya Fuya reservoir and triggered the two largest eruptions documented at Fuya Fuya, i.e. those related to the R1 ashfall and to the large avalanche.

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