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Quaternary eruptive history and hazard-zone model at Nevado del Tolima and Cerro Machin Volcanoes, Colombia

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Abstract

The ice-clad and fumarolic Nevado del Tolima volcano (4° 39′N, 75° 20′W) south of Nevado del Ruiz, is offset toward the southeast from the axis of the volcanic Ruiz–Tolima massif with respect to the major NE-trending strike-slip Palestina fault. It is composed of four units: (1) a pre-Tolima plateau-like basement of basaltic andesite lava flows of early Quaternary age; (2) a dissected, ancestral Tolima stratovolcano, cut by a presumed collapse caldera of middle Pleistocene age; (3) an older Tolima stratovolcano of late Pleistocene age, partly destroyed by a summit caldera; and (4) composite domes of the cone-shaped young and present Tolima.

Young Tolima volcano is an andesitic and dacitic composite cone formed over the past 40,000 years within a 3-km-wide caldera that opened around 0.14 Ma. Deposits of welded and nonwelded pumice- and scoria-flows were emplaced toward the southeast (Rio Combeima) and northeast (Rio Totare). Repeated growth of lava domes over the past 16,000 years is witnessed by thick block-lava flows on the southern and eastern flanks and by block-and-ash or scoria-rich pyroclastic-flow deposits. This activity occurred during at least six eruptives stages as follows: El Placer, ca. 16,200–14,000 yr B.P.; Romerales, ca. 13,000–12,300 yr B.P.; Canalones, ca. 11,500–9750 yr B.P.; Mesetas, ca. 7200–4600 yr. B.P.; Encanto, ca. 3600–1700 yr B.P., and Nieves, historical. Interactions with the ice cap probably triggered debris flows that partly filled the Combeima and Totare valleys and formed the Holocene terraces on the upper Pleistocene volcaniclastic fans of Ibagué and Venadillo as much as 60 km from the source. The latest major activity was a plinian eruption, which deposited a pumice-fall layer ca. 3600 yr B.P. (0.5 km^3 actual volume) mainly toward the west and northwest. Minor tephra-falls and debris flows occurred during the historical period before the reported 1918 and 1943 small (phreatic ?) events.

A general hazard-zone map shows areas potentially affected by future eruptions both at Nevado del Tolima and at active Cerro Machin 12 km southward. The extent of areas likely to be affected by tephra-falls, debris flows, pyroclastic flows or surges, debris avalanches and lava flows is shown. Subplinian and plinian eruptions of Nevado del Tolima were used to represent the moderate and large events to be expected. 300,000 people live within a 35-km distance from those volcanoes, which have exhibited a behaviour more explosive than Nevado del Ruiz. Despite the small-sized ice cap, debris flows are the most probable hazard for even a minor eruption, because of the very steep slope gradient, and because of probable interactions of hot eruptive products with ice and snow. Additionally, scoria flows and debris avalanches can be directed toward the southeast and could be transformed into debris flows that would devastate the Combeima valley and suburbs of Ibagué city, where about 50,000 people live.

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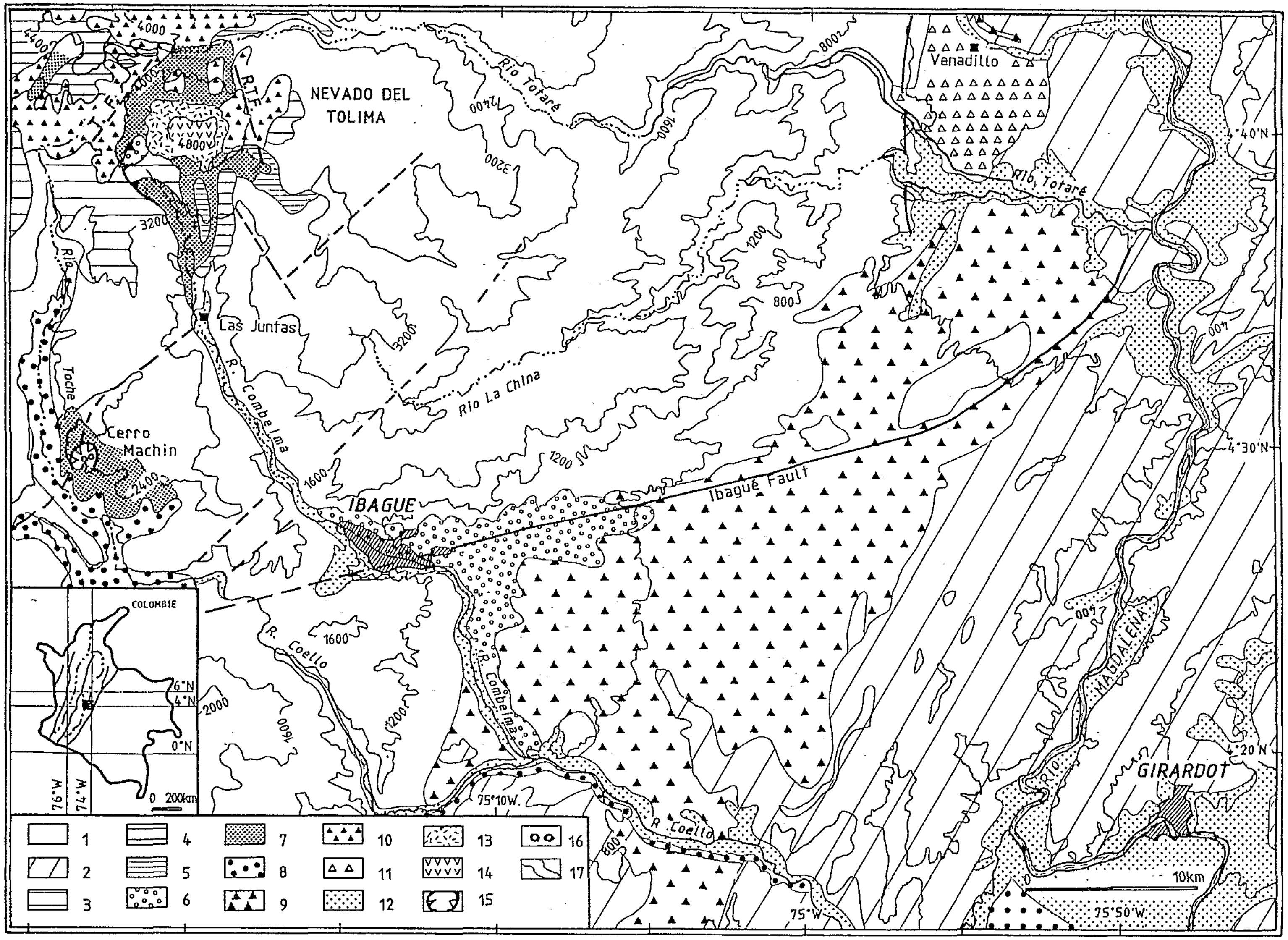
1. Introduction

Ice-clad and fumarolic Nevado del Tolima (4 39′N, 75 20′W, 5200 m; Figs. 1, 2) is the second highest volcano within the Ruiz–Tolima massif, 25 km south of Nevado del Ruiz in the Central Cordillera of the Colombian Andes. It belongs to the most recent generation of composite andesitic and dacitic stratovolcanoes of late Pleistocene and Holocene age (Thouret et al., 1990). In addition, the relatively unknown but active Cerro Machin volcano (2600 m, 12 km southwest of Tolima; Fig. 1) consists of twin dacitic domes that are still fumarolic and are nested in a 3-km-wide caldera. Both volcanic centers are located near a heavily populated area (approximately 300,000 people). About 50,000 people live at high risk along the Rio Combeima, within reach of devastating debris flows, only 10 to 30 km southeast of the Nevado del Tolima volcano (Figs. 1, 3 and 9).

The paper is based on 6 months of field work at Tolima by the first author (1981–1984, 1987, and 1990) and 3 months by the other authors (1982, 1984, 1988), on published reports by Thouret et al. (1985 Thouret et al., 1989), and some in papers by Herd (1982) and CHEC (1983). This paper aims to give an overall summary of the volcanic history, with emphasis on a hazard appraisal suitable for similar ice-clad volcanoes elsewhere in the world. The detailed stratigraphic record of the recent eruptive history, relevant to a sound assessment of volcanic hazards, is based on two methods: (1) a detailed tephra-stratigraphy keyed to 13 stratigraphic sections measured around the Nevado del Tolima, twenty ^{14}C ages on charcoal and peat within selected tephra layers, and 10 K-Ar ages on lava flows; (2) hazard-zone mapping based on air-photo interpretation, on one SPOT satellite image (1987), and on numerical models aimed at roughly depicting areas likely to be affected by pyroclastic flows and debris flows.

Among the results of the present work, the Quaternary eruptive history of the Nevado del Tolima has been divided into two units and four phases; its detailed eruptive history over the last 16,000 years has been divided into two phases and six stages. The reconstructed history indicates that future eruptions at Tolima could be much more dangerous than the 1985 eruption at nearby Nevado del Ruiz. Not only has Nevado del Tolima triggered debris flows, but it produced a series of major explosive events that were long-lasting and voluminous. The probability of an eruption at Nevado del Tolima is difficult to assess, but the present apparent dormant interval already exceeds the average time interval between the major eruptive stages. The detailed tephrostratigraphy helps to assess potential hazards from future eruptions. We also provide a general map that identifies areas of potential hazard and roughly ranks those hazards from lava flows, tephra falls, pyroclastic flows, blasts, debris avalanches and debris flows around Nevado del Tolima and Cerro Machin. Calculations for the Nevado del Tolima ice cap also enable us to present a model for debris flow initiation based on water volume available and released for debris flow generation from the Nevado del Ruiz ice cap in 1985 (Thouret, 1990).

Fig. 1. Generalized stratigraphic and geomorphic map of the volcanic Tolima–Cerro Machin massif and of the volcaniclastic piedmont. **I. Non-volcanic rocks of the Andean Cordilleras** 1 = Igneous and metamorphic basement of the Central Cordillera (Precambrian, Paleozoic and Cretaceous–Eocene age). 2 = Folded sedimentary series of Cretaceous–Eocene age of the Eastern Cordillera. **II. Lava flows from the Ruiz–Tolima massif** 3 = Andesites and basaltic andesites of the pre-Tolima massif (> 1.3 Ma). 4 = Andesites of the ancestral and older Tolima and Quindio stratovolcanoes (1.3 to 0.14 Ma). 5 = Andesites and dacites of the young Tolima composite volcano (ca. 40,000 yr B.P. to Holocene time). **III. Pyroclastic rocks and deposits** 6 = Nonwelded or poorly welded pumice-, ash- or scoria-rich pyroclastic-flow deposits from the summit caldera (ca. < 0.14- to ca. > 0.04 Ma). 7 = Pyroclastic-flow, surge and fall deposits of the young Tolima and Cerro Machin domes (< 16,200 yr B.P.). 8 = Pumice- and ash-flow deposits from the Cerro Machin caldera (ca. 5000–3600 yr B.P.). **IV. Volcaniclastic and mixed deposits from volcanic and glacial sources** 9 = Lower to middle Pleistocene breccias and reworked pyroclastic-flow deposits of the Ibagué fan, overlying Neogene volcaniclastic sediments. 10 = Intercalated tephra and glacial deposits of upper full-glacial (ca. 40,000–14,000 yr B.P.) and of late-glacial age (ca. 14,000–10,000 yr B.P.). 11 = Debris-flow deposit and mixed alluvium on fans of Holocene age. 12 = Young alluvium and debris-flow deposits confined to valleys. 13 = Glacial deposits of Little Ice Age and pre-historical or historical tephra and mixed avalanches. 14 = Permanent snow-capped and ice-clad Nevado del Tolima. **V. Landforms** 15 = Collapse caldera of older Tolima volcano and explosive caldera of Cerro Machin volcano. 16 = Youthful domes and lava domes of young Tolima volcano and Cerro Machin. 17 = Topographic scarps associated with major faults: *T.F.* = Toche Fault; *R.T.F.* = Recio–Tolima Fault.


NEVADO DEL TOLIMA
RTF
4800
4000
4400
3200
2400
1600
1200
800
Rio Totaré
Venadillo
4°40'N
Rio La China
Las Juntas
R. Combeima
Rio Toche
Cerro Machin
IBAGUE
Ibagué Fault
4°30'N
R. Coello
MAGDALENA
Rio
GIRARDOT
4°20'N
75°10'W.
75°W
75°50'W.
10km
COLOMBIE
6°N
4°N
0°N
74°W
76°W
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2. Physiographic and geologic setting

The andesitic and dacitic composite Nevado del Tolima volcano covers approximately 150 km^2 and has an approximate volume of 75 km^3. It is built on the vast basaltic andesite and andesite Ruiz–Tolima plateau (1500 km^2) of late Pliocene and early Pleistocene age (> 1.4 Ma, Table 1; Thouret et al., 1990). Tolima is composed of a deeply dissected, old stratovolcano built in a presumed collapse caldera of mid-Pleistocene age southwest of the summit, and overlain by a young cluster of composite lava domes and extrusions, which are nested within a probable summit caldera of late Pleistocene age. Its cone-shaped summit rises to an elevation of 5200 m, some 1600 m above the igneous and metamorphic basement of the Central Cordillera. A thick cover of recent pyroclastic debris and glacial deposits mantles a cluster of extrusions, lava domes and breccia pipes. Toward the west, products of the young Tolima cone overlap the Nevado del Quindio lava flows of middle Pleistocene age. The south flank consists of a huge pile of steep-sided, dacitic lava flows that form a 2500-m-high staircase above the deeply incised Combeima valley. The 200-m-deep, funnel-shaped crater indents the upper south flank. A solfatara field and hydrothermal springs are found on the northeast and south slopes.

Tolima volcano is offset 15 km southeast from the main volcanic range, where it is located along the NW-trending normal Otún–Pereira fault. The Palestina fault, a NNE-trending right-lateral strike-slip fault, crosses the whole Ruiz–Tolima volcanic massif and is displaced by the Otún–Pereira fault (Figs. 1, 3; Thouret et al., 1990). In addition, a series of NE-trending strike-slip 'Toche' faults on the west flank parallels the major Palestina fault and separates the Nevado del Quindio from Tolima volcano. The NNW-trending strike-slip 'Recio–Tolima' fault lies east of the edifice, where it divides the El Bosque granodioritic batholith of Eocene age from the metamorphic Cajamarca Group of Paleozoic age. The NE-trending Toche fault is still active.

3. Four stratigraphic units and volcanic periods

As a result of a span of eruptive activity at least 1.4 m.y. long, deposits and landforms of the Nevado del Tolima volcano record four major sequences of edifice growth and destruction, termed 'pre-Tolima', 'ancestral Tolima', 'older Tolima', and 'young Tolima' (Table 1; Figs. 1, 3). The 'young Tolima', a cone-shaped cluster of composite lava domes and breccia pipes of Late Pleistocene to Holocene age, can be subdivided into two edifices, the 'young' and 'present Tolima'. They are nested in a 3-km-wide explosive summit caldera that was probably formed at the end of the older Tolima volcanic period (Late Pleistocene; Table 1).

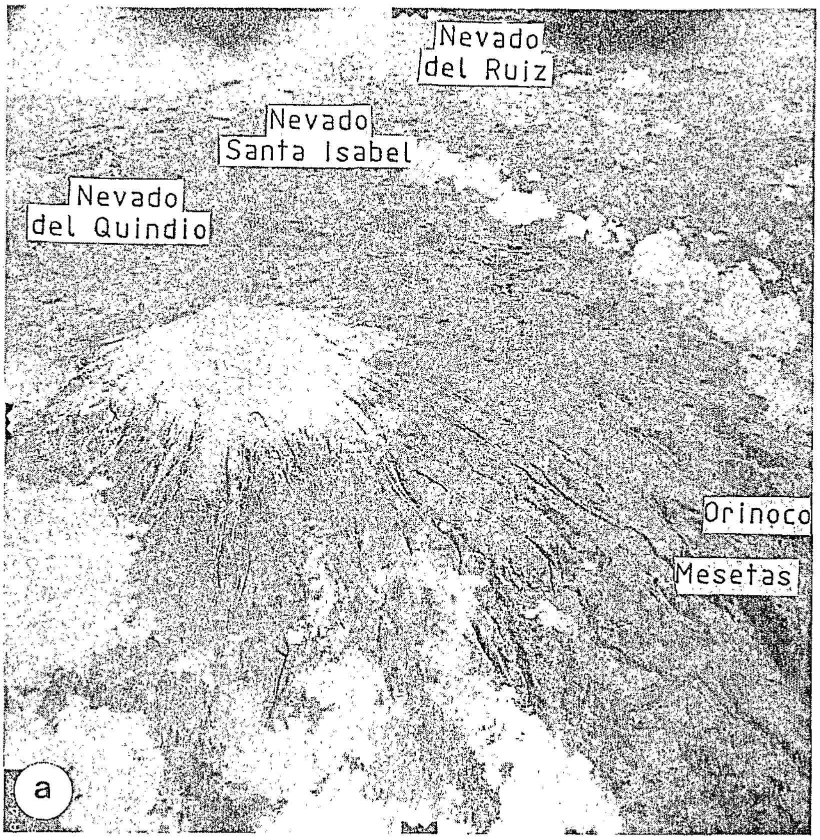
4. Pre-Tolima volcanic plateau

A high and subdued volcanic plateau referred to as 'pre-Tolima' reflects a sequence of extensive basaltic andesite and andesite lava and pyroclastic flows, erupted from small shields or scattered vents aligned on fissures of early Quaternary age during the > 1.4-Ma-old Totare eruptive stage. These lava flows are typically 6–8 km long, 1–2 km wide, and 100–200 m thick, and they exemplify inverted topography 300–400 m above the Totare–Totarito rivers (Figs. 2, 3, 4c).

5. Ancestral and older Tolima volcanoes, and a caldera

The ancestral and older Tolima stratovolcanoes were built by eruptions comprising at least two eruptive

Fig. 2. (A) Oblique aerial view of Nevado del Tolima looking north. The ice cap conceals youthful, short lava flows and domes. An apron of pyroclastic debris covers all the flanks to the north, west and east, and block-lava flows extend to the east (Orinoco, Mesetas). Nevado del Quindio is partly visible to the northwest, as well as the Nevado Santa Isabel and Nevado del Ruiz in the background. (B) Nevado del Tolima (5200 m) looking south. The cone is recent in age, and its sides are oversteepened and eroded. Intrusions 500 m high, breccia-necks and short dacitic lava flows of the young-Tolima-age cone are nested in a summit caldera (at about 4400 m), the rim of which is seen to the east. The scar of a rockslide-debris avalanche is visible to the west. Margin of Little Ice Age moraines are immediately below the steep and crevassed ice cap. The entire young Tolima volcano overlies extensive lava flows and pyroclastic debris of the older Tolima volcano. It rises above the dissected ancestral stratovolcano and the pre-Tolima volcanic plateau to the north.


Nevado
del Ruiz
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a

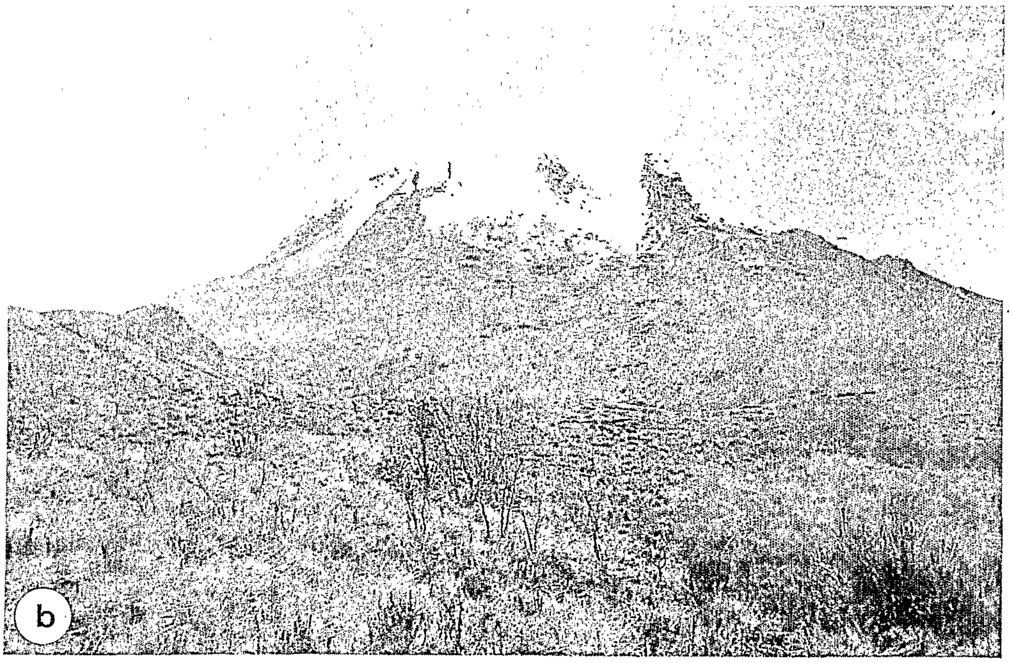

b

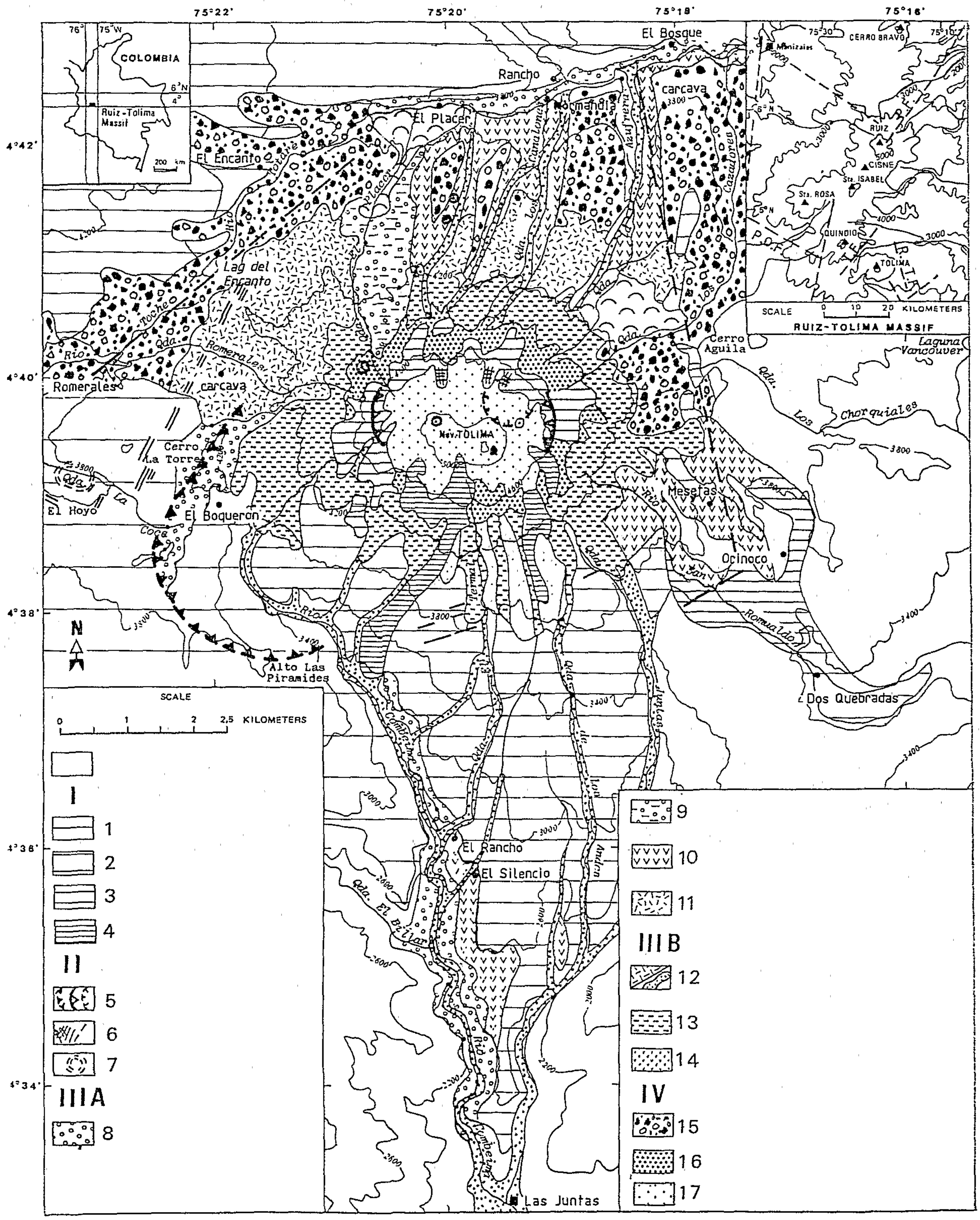
Table 1

Record of volcanic periods, eruptive stages and stratigraphically recognized events, Nevado del Tolima

EPOCHS	VOLCANIC PERIOD AND PHASES	ERUPTIVE STAGE	AGE OF RECOGNIZED EVENTS	DEPOSITS, LITHOLOGY, AND LANDFORMS
Historical	PRESENT TOLIMA destructive and constructive phases	Las Nieves	1918 ? 1943 ? 1826, 1828	t (d,a) t (d,a)
HOLOCENE upper		Encanto	ca. 1700, 2 100, 2500 yr B.P.	t (d), do (d,a), df
HOLOCENE middle		Mesetas	ca. 3 600- 3700 ca. 4 700 - 4900	t (d), do (d,a), df s-r pf, t (a), df
HOLOCENE lower			ca. 6 250 ±50 ca. 7 200 ± 50	b-a-a pf, T (a,d), df do (d,a), blf (a), df da
	YOUNG TOLIMA destructive and constructive phases	Canalones	ca.9750 - 10,000 ca. 10,800 - 11,500	t, ps (a,d), lf (a), df T, ps, nw., w.pf (a,d), df
		Romerales	ca. 12,300 - 13 000	T, ps (a,d), nw. sf (a), nw. pf (a,d), df
		El Placer	ca. 14,000-16,200	lf (a)
PLEISTOCENE Late	OLDER TOLIMA destructive phase	Combeima	> 0.04 and < 0.14 Ma	w. SF (a), nw. SF(a), nw PF (d), df summit caldera
Upper	OLDER TOLIMA constructive phase	El Rancho	0.14 ± 0.03 Ma 0.2 ± 0.09 0.37 ± 0.1	LF (a,d) stratovolcano
Middle	ANCESTRAL TOLIMA destructive phase	Boqueron	> 0.4 ± 0.07 Ma < 0.68 ± 0.15	brecc., PF, vc.s., df presumed collapse caldera
Lower	ANCESTRAL TOLIMA constructive phase	Porfias-Honduras	1 ± 0.05 1.3 ± 0.15	stratovolcano LF (a, ba)
Lower Quaternary	Constructive phase PRE-TOLIMA	Totare	≥ 1.4 Ma	LF (ba, a)

Meaning of symbols: t = tephra-fall deposits (T when volume > 0.1 km^3); ps = pyroclastic-surge deposit; pf = pyroclastic-flow deposit (PF when volume > 0.1 km^3); s-r pf = scoria-rich pyroclastic-flow deposit (SF, PF when volume > 1 km^3); b-a-a pf = block-and-ash pyroclastic-flow deposit; w. = welded; nw. = nonwelded; lf = lava flow (LF when volume > 1 km^3); blf = block-lava flow; da = debris-avalanche deposit; brecc. = pyroclastic breccia deposit; df = debris-flow deposit; vc.s = volcaniclastic sediments; do = lava dome or dome; d = dacite; a = andesite; ba = basaltic andesite.

Fig. 3. Stratigraphic, volcanologic and geomorphic map of Tolima volcano. (empty box) Igneous and metamorphic basement of the Central Cordillera. **I. Lithologic and stratigraphic units from four eruptive periods** 1 = Undifferentiated lava flows of pre-Tolima (> 1.4 Ma). 2 = Andesite and dacite lava flows of ancestral and older Tolima (1.3–0.14 Ma). 3 = Two-pyroxene andesite lava flows and block-lava flows of young Tolima (ca. 40,000 to ca. 10,000 yr B.P.). 4 = Andesite-dacite lava flows and andesite block-lava flows of present Tolima (< ca.10,000 yr B.P.). **II. Volcanic and tectonic features.** 5 = Rims of (a) presumed ancestral Tolima collapse caldera (about 0.7–0.4 Ma); (b) probable older Tolima summit caldera (ca. 0.14–0.04 Ma); (c) recent rockslide debris-avalanche. 6 = Domes and lava domes, necks and dykes; probable fractures. 7 = Fumarolic crater; craters created by probable phreatomagmatic eruptions. **III. A. Pleistocene to Holocene pyroclastic and volcanogenic deposits** 8 = Welded scoria-flow, nonwelded pumice-rich pyroclastic-flow deposits, and breccias from a probable summit caldera (ca. 0.14 to ca. 0.04 Ma). 9 = Welded scoria-flow and plinian pumice-fall deposits from the young-Tolima-age large crater (ca. 16,200--14,000 yr B.P.). 10 = Nonwelded pumice-rich and block-and-ash pyroclastic-flow deposits from the young Tolima volcano (ca. 16,200–10,000 yr B.P.). 11 = Tephra-fall and pyroclastic-surge deposits from the present Tolima volcano (< 10,000 yr B.P.). **III. B. Recent debris-flow deposits of volcanic and glacial sources.** 12 = Upper Holocene debris-flow deposits resulting from landslides and rock avalanches; channeled debris-flow deposits. 13 = Upper Holocene fans of pyroclastic debris reworked by ice and snow melt processes or by magma–ice interactions. 14 = Very young debris-flow deposits and tephra-laden snow-and-ice avalanche deposits. **IV. Glacial sediments and Nevado del Tolima ice cap.** 15 = Moraines of the upper full-glacial (21,000–14,000 yr B.P.), late-glacial (14,000–10,000 yr B.P.) and lower Holocene glacial stages. 16 = Frontal moraines of the Little Ice Age (ca. 1600 to 1900 A.D.). 17 = Present Nevado del Tolima ice cap. Inset plot 'Ruiz–Tolima massif', 7 volcanoes and major tectonic features: *P.F.* = Palestina Fault; *O.-T.-F.* = Otún–Pereira Fault; *T.F.* = Toche Fault; *R.-T.F.* = Recio–Tolima Fault.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Ruiz-Tolima Massif
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Normandia
El Placer
El Encanto
Lag del Encanto
Rio Toche
Qda. Romerales
Romerales
carcava
Cerro La Torre
El Hoyo
Qda. La Coca
El Boqueron
Nev. TOLIMA
Cerro Aguila
Laguna Vancouver
Qda. Los Chorquiales
Mesetas
Orinoco
Rio San Romualdo
Dos Quebradas
Alto Las Piramides
Rio Combeima
Qda. El Bizcochuelo
Qda. Juntas
Qda. Termales
Qda. Andino
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Table 2A
K-Ar ages* at and around Nevado del Tolima

Sample laboratory	Number, year of collection	Latitude-longitude altitude	Location ; stratigraphic unit and petrography	k % (%)	40 Ar (10^{-9} g.g.$^{-1}$)	40 ar atm (%)	Age (Ma)
R. 11104	CC 82-79 1982	4°42'N, 75°20'W 3 770 M	Reña Placer, Totare valley ; lava flow from pre-Tolima ; andesite	2.84	0.275	94.5	1.4 ± 0.25 whole rock
F. 12210	CC 83-134 1983	4°43'N, 75°16'30"W 3 500 m	Porfias, Totare valley ; lava flow from the lower section of old Tolima ; basaltic andesite	0.766	0.069	92	1.3 ± 0.15 plagioclase
F. 12211	CC 83-137 1983	4°43'N, 75°17'W 3 600 m	Honduras, Totare valley ; lava flow from the lower section fo old Tolima ; basaltic andesite	0.703	0.063	88	1.29 ± 0.10 plagioclase
R. 11103	CC 82-10 1982	4°42'N, 75°19'W 3 650 m	Normandia, Totare valley ; lava flow from the lower section fo old Tolima ; andesite	2.15	0.140	82	1 ± 0.05 whole rock
R. 11106	CC 82-92 1982	4°35'N, 75°20'30"W 2 350 m	Juntas, Combeina valley, lava flow from the middle section of old Tolima ; dacite	2.07	0.098	75.4	0.68 ± 0.15 whole rock
F. 11290	CC 83-147 1983	4°36'30"N, 75°22'W	El Muerto, Combeina valley, lava flow from the upper section of old Tolima ; dacite	2.05	0.050	92	0.4 ± 0.07 plagioclase
F. 12202	CC 87-41 1987	4°36'N, 75°20'W 2 200 m	El Silencio, Combeina valley ; lava flow from the upper section of old Tolima ; andesite	1.45	0.037	97	0.37 ± 0.1 plagioclase
F. 11286	CC 82-22 1982	4°41'N, 75°19'30"W	Termal Placer, North flank ; lava flow of the lower section of young Tolima ; dacite	1.33	0.017	97	0.2 ± 0.09 whole rock
F. 11291	CC 83-60 1983	4°41'N, 75°20'W 4 000 m	Alto Placer, North flank ; lava flow of the lower section of young Tolima ; dacite	2.05	0.025	97.8	0.14 ± 0.03 plagioclase
F. 11292	CC 83-64 1983	4°40'30"N, 75°19'30"W 4 500 m	Las Nieves, North flank ; lava flow from a dome of young Tolima ; dacite	1.98	0.01	99.8	0 ± 0.05 whole rock

*Conventional K-Ar ages are calculated with the 1977 constants. The analytical techniques were described elsewhere (Cantagrel and Baubron, 1983).

stages over a great part of the Pleistocene (about 1.3 to about 0.14 Ma: K-Ar ages, Table 2). These stratovolcanoes are separated by a major destructive phase marked by the occurrence of a probable mid-Pleistocene collapse caldera.

5.1. *Ancestral Tolima volcano*

During the ancestral Tolima period, extensive andesite and dacite lava flows as well as pyroclastic flows were erupted. The lava flows are 7–10 km long, 1 km wide, 100–200 m thick, and dip gently on the northeastern, northern and south-southwestern flanks of the volcano down to an elevation of 3400 m. These lava flows erupted during the Porfias–Honduras eruptive stage, over a time period of ca. 1.3–1 Ma (Table 2). These flows now form the subdued or deeply dissected flanks of the ancestral Tolima stratovolcano.

A sequence of thick pumice and lithic-rich pyroclastic-flow deposits reflects the destructive phase of the explosive Boquerón stage (approximately 0.7 to 0.4 Ma: Tables 1, 2), that records the partial destruction of ancestral Tolima and the probable collapse of a caldera 7 km in diameter. These deposits crop out both on the presumed caldera rim southwest of the present summit in the headwaters of Rio Toche (Boquerón), and within

Fig. 4. (a) Thick sequence of reworked pyroclastic-flow deposits and volcaniclastic deposits (person for scale in circle) that form the vast middle to upper Pleistocene Ibagué fan. These result from the caldera-forming eruptions of Nevado del Tolima (road to Róvira, 35 km southeast from the source). (B) Ignimbrites from the Combeima eruptive stage (ca. 0.14–0.04 Ma): (b) 100–200-m-thick, poorly welded scoria-and-ash or pumice pyroclastic-flow deposits, in the Rio Combeima valley to the southeast at El Rancho–El Silencio (2800–2400 m); (c) 25–50-m-thick welded scoria and lithic breccia pyroclastic-flow deposits, in the Rio Totare valley to the northeast at El Placer–El Bosque (3700–3400 m).

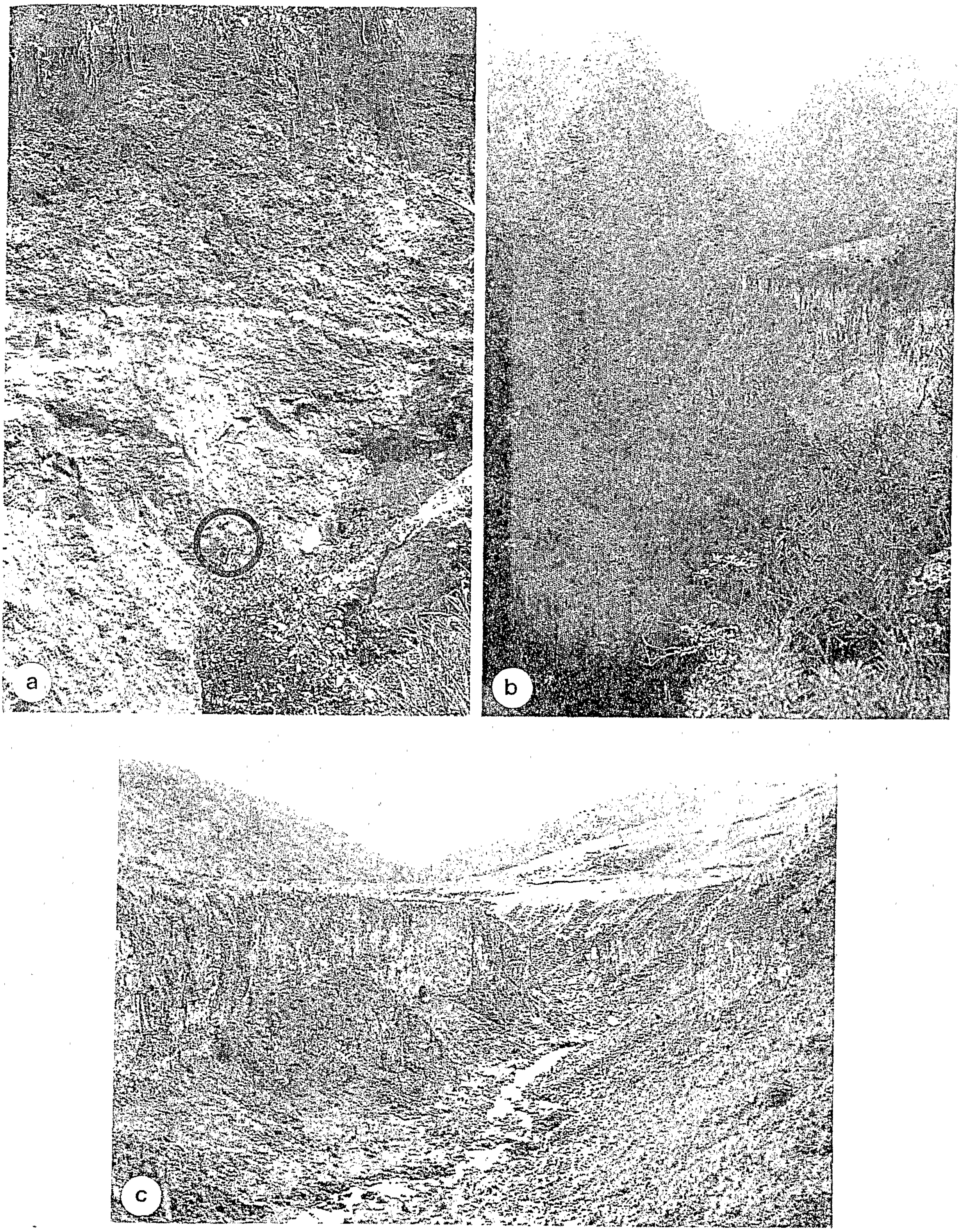


Figure 4

the Ibagué volcaniclastic fan (Figs. 1, 3, 4). Today, the deposits are deeply dissected and separated from their source, and in places they may have been buried by the young Tolima deposits on the western and southern slopes.

The evidence for a large collapse caldera during the middle Pleistocene, similar to the Mount St. Helens collapse (Voight et al., 1981), includes the following.

First, a 500–700-m-high, arcuate wall-like ridge, 6 km southwest of the summit, cuts a 500-m-thick sequence of lava flows and about 100 m of pyroclastic-flow deposits of ancestral Tolima above the Rio Combeima. This semi-circular scarp, representing the presumed caldera rim, can be followed from the south to the southwest and perhaps to the north (Figs. 1, 3, 5). At the foot of the northern flank of the summit, the presumed caldera boundary is suggested by a few amphibole andesite and dacite lava domes, with stubby lava flows and thick lithic-rich pyroclastic flows that probably overflowed the rim.

Deposits related to caldera collapse are concentrated southwest of the summit on the outer slope of the inferred high arcuate rim (Fig. 3). They could have resulted from a debris avalanche related to the partial collapse of the older edifice. In addition, a 200-m-thick sequence of volcaniclastic sediments visible within the Ibague fan (Rio Combeima, 35 km to the southeast, road to Róvira, Fig. 4), shows several units of reworked block-and-ash, ash or lithic-rich pyroclastic-flow deposits, and intercalated debris flow or hyperconcentrated streamflow deposits, as well as alluvium from volcanic and glacial sources. This sequence may represent the median and distal part of ignimbrites and co-ignimbrite (?) breccias from the older Tolima volcano (Figs. 3, 4, 5).

The presumed rims of the caldera in part parallel tectonic features as follows: a series of regional conjugate N15–45E faults, some of which are still active, intersects N15–40W fractures that also govern the trend of the Rio Combeima drainage (Figs. 1, 3). In addition, dacitic domes, dykes and hydrothermally altered breccia pipes are aligned on the NNE-trending fracture system. One recent phreatomagmatic crater opened near the southern end of the Toche fault southwest of the rim (El Hoyo, Fig. 3).

The pyroclastic deposits inferred to be related to the caldera collapse have an estimated bulk volume of 15 km^3 (see the reworked pyroclastic deposits of the Ibagué fan, n°9 on Fig. 1). The probable collapse occurred between approximately 0.7 Ma and 0.4 Ma (Tables 1, 2). Although not well constrained, this chronological range is consistent with the age inferred for other collapse calderas in the Ruiz–Tolima volcanic massif, such as the Letras caldera surrounding the Cerro Bravo volcano (Thouret, 1988; Thouret et al., 1990).

5.2. Older Tolima volcano

Andesite lava flows were erupted west and east of the summit and flowed down to elevations as low as 2400 m to the south during the El Rancho eruptive stage (0.4–0.14 Ma; Table 2). On the south side, many andesite and dacite lava flows are thick and mostly short (2–4 km), but some reach as far as 8 km away from the vent (Fig. 3). They probably filled a pre-existing valley, elongated over 12 km southeast of the vent, and the flows erupted into fault-controlled topographic lows. They also formed a huge pile of steep stairs in the headwaters of the Rio Combeima valley and finally concealed the 2000-m-high, inferred fault scarp on the left side of the valley (Figs. 1, 3, 5).

Between the Ibagué fan (27 km distant; Figs. 1, 3) and Las Juntas–El Rancho, the Rio Combeima valley is partly filled with a composite ignimbrite sequence. This sequence is made of welded and nonwelded units of scoria-and-ash and pumice pyroclastic-flow deposits, as well as co-ignimbrite breccias. The sequence is 100 to 250 m thick and contains more pumice than lithics: the lapilli within the flows are typically inversely graded. Their age is about 0.2 ± 0.1 Ma, as indicated by deep incisions in the thick series of andesite lava flows of the El Rancho eruptive stage (0.37 ± 0.1 Ma, K-Ar, El Silencio, 2400 m; 0.2 ± 0.09 Ma, 0.14 ± 0.03 Ma, 0.1 ± 0.05 Ma, K-Ar, El Rancho, 3100 m and Las Nieves, 3400 m; Table 2).

Destructive phase, Combeima eruptive stage and a summit caldera

A destructive phase late in the older Tolima period is indicated by the formation of a summit caldera in late Pleistocene time. Although the caldera has been almost entirely buried by recent lava flows and pyroclastic deposits of the young Tolima, the volume and geometry of the pyroclastic-flow deposits erupted suggest that a destructive phase led to the formation of a summit caldera near the end of the older Tolima vol-

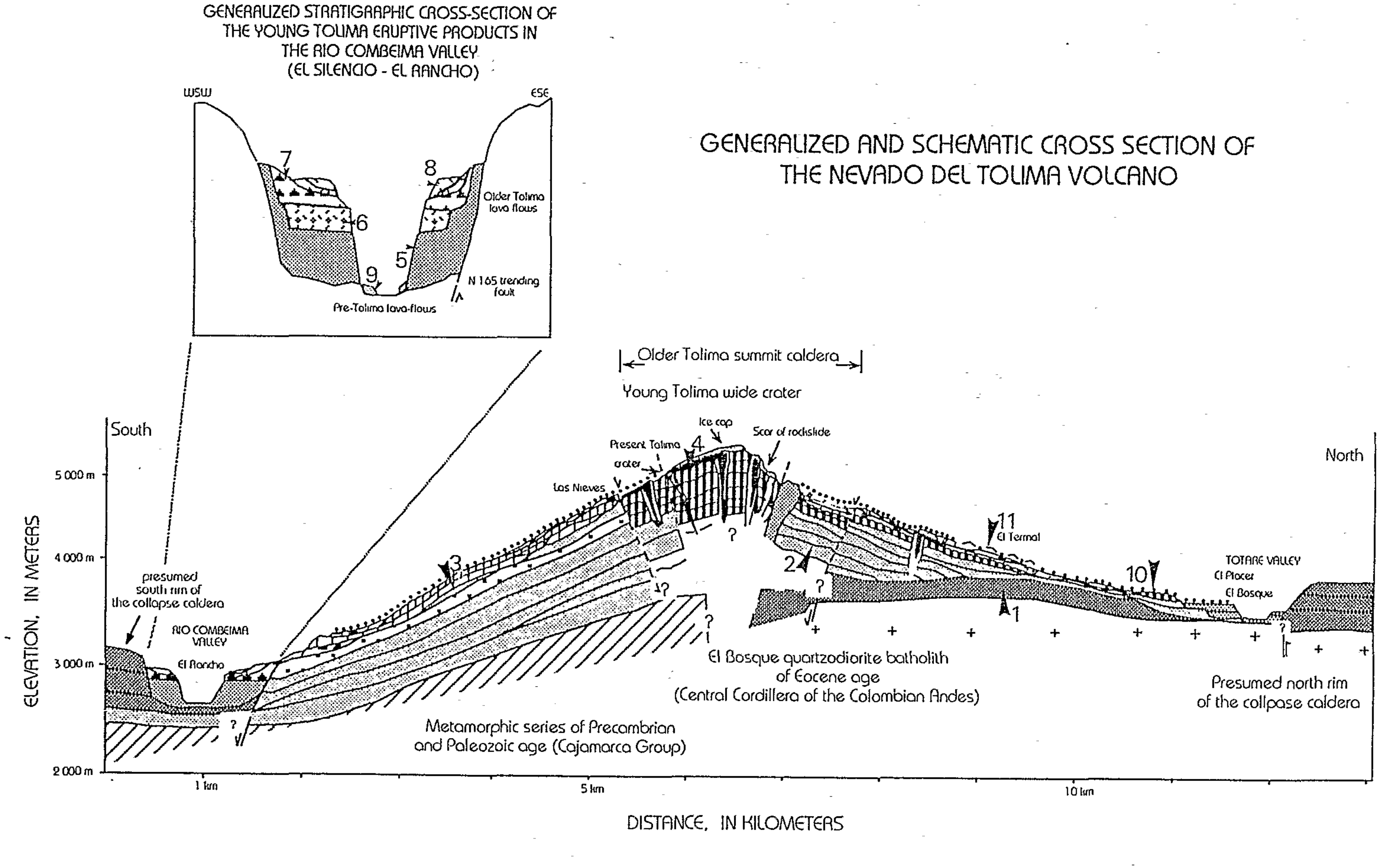


Fig. 5. Generalized and schematic cross-sections of Tolima volcano and of the Rio Combeima valley. **I. Volcanic rocks and deposits of four eruptive periods** 1 = Basaltic andesite lava flows forming the pre-Tolima plateau. 2 = Andesite lava flows and pyroclastic rocks forming the ancestral and older Tolima stratovolcanoes. 3 = Andesite and dacite lava flows forming the composite, young Tolima volcano. 4 = Cluster of lava domes, intrusions and breccia-necks forming the composite, young and present Tolima summit volcanoes. **II. Pyroclastic and volcaniclastic debris and glacial sediments of young Tolima age** 5 = Pyroclastic-flow deposits of the caldera-forming Combeima eruptive stage. 6 = Scoria (a), pumice (b) pyroclastic-flow deposits of the El Placer, Romerales and Canalones eruptive stages. 7 = Block-and-ash or scoria-and-ash pyroclastic-flow deposits of the Mesetas and Encanto eruptive stages. 8 = Plinian and subplinian tephra-fall deposits of the Encanto and Las Nieves eruptive stages. 9 = Debris-flow deposits of Holocene age. 10 = Glacial deposits of upper full-glacial and late-glacial age. 11 = Scar, mounds and deposits of a recent rock avalanche.

canic period (Fig. 5). This explosive phase occurred during a major eruptive stage termed Combeima, approximately 0.14 to 0.04 My ago (Tables 1, 2).

Evidence for a 3-km-wide summit caldera is twofold (Figs. 3, 5).

First, eroded but still prominent crests cut in voluminous lava and extrusions surround both the northwestern and northeastern flanks of the summit cone (Fig. 2b). Further, pyroclastic-flow deposits having a bulk volume of 5 km^3 suggest the formation of a summit caldera on the older Tolima stratovolcano, located at about 4400–4800 m in elevation, based on the projection of the depositional tops of these high-aspect-ratio ignimbrites (Fig. 5). This ignimbrite sequence of Rio Totare is probably younger than ca. 0.14 Ma and older than ca. 40,000 yr B.P., and hence is probably younger than the ignimbrite sequence in the Rio Combeima valley and in fact may be significantly younger. The Rio Totare ignimbrite rests on the El Rancho lava-flow sequence, is slightly inset in a previously glaciated valley (Fig. 4b) of middle full-glacial age (about 40,000–21,000 yr B.P.), and is covered by moraines of upper full-glacial age (ca 21,000–14,000 yr B.P.: Thouret et al., 1992). In contrast, the topography of the Rio Combeima ignimbrite sequence is already inverted within the valley (Fig. 4a), and its proximal part is concealed by young lava flows of the El Rancho eruptive stage and removed by glaciers of full-glacial age down to 3100–2900 m in elevation.

Because the estimated 5-km^3 bulk volume of the pyroclastic deposits within both deep valleys may not fully account for the total volume of the caldera, the huge pyroclastic deposits within the upper volcaniclastic fan of Ibagué (Fig. 1) may include volcanic debris shed from the volcano during the major Combeima eruptive stage. The thick composite sequence and the extent (>50 km^2) of the pumice-flow deposits imply a large volume explosive event. Both the ejected lithics within the ignimbrite sequence and the volume of juvenile magma within the pumice and ash-rich pyroclastic flows may account for the missing volume.

5.3. Young Tolima volcano

Pyroclastic deposits of young Tolima age (ca. 16,000–10,000 yr B.P.) partially concealed the inferred collapse caldera of mid-Pleistocene age, the summit caldera of late Pleistocene age, and the older stratovolcano. Despite dissection or overprinting by extensive late glacial and Holocene glaciers (Fig. 9), the recent eruptive history ($<16,200$ yr B.P.) can be determined by tephrostratigraphy, glacial stratigraphy, and ^{14}C dates from 13 measured stratigraphic sections of the tephra sequence that blankets all the flanks of the cone (Table 3, Figs. 5, 6).

At least six eruptive stages of alternating constructive and destructive activity are distinguished (Table 1). From oldest to youngest, the stages are termed 'El Placer', 'Romerales', 'Canalones', 'Mesetas', 'Encanto', and 'Nieves'. They encompass events which repeatedly built or destroyed two clusters of lava domes and the summit caldera, and at least one wide crater on top of the older Tolima volcano.

Two alternatively constructive and destructive phases

A cluster of lava domes and neck-like breccia pipes formed mostly north of the present summit, first before and over the El Placer eruptive stage (ca. 16,200–14,000 yr B.P.), and again during the Romerales eruptive stage (ca. 13,000–12,300 yr B.P.) and the Canalones eruptive stage (ca. 12,300–9750 yr B.P.). The intrusion of a series of very recent domes on the northern and eastern slopes is witnessed by a few bodies of hydrothermally altered breccia that rise as much as 400 m above the north flank (Fig. 2b). Short lava flows were erupted on the south, east and west flanks, whereas 1-km-wide and 50–100-m-thick block-lava flows (mixed, basic and acid andesites) flowed over 3.5–5 km to the east (Dos Quebradas, Rio San Romualdo; Figs. 2, 3).

Tephrostratigraphic correlations indicate that the eruption of block-lava flows occurred slightly after 14,000 yr ago. In contrast, explosive activity and collapse of other domes are indicated by block-and-ash pyroclastic-flow deposits and associated thin pyroclastic-surge deposits. These deposits overlie or are slightly inset in older pyroclastic deposits that are ca. 12,300 to $>10,000$ yr B.P. old (Combeima valley, Figs. 3, 5).

Three explosive stages

A series of small-volume pyroclastic-flow deposits suggests that a wide crater (Fig. 5) was violently opened during the 16,200–14,000-yr B.P.-old El Placer eruptive stage. Scoria and ash flow deposits are 50 m

Table 2B

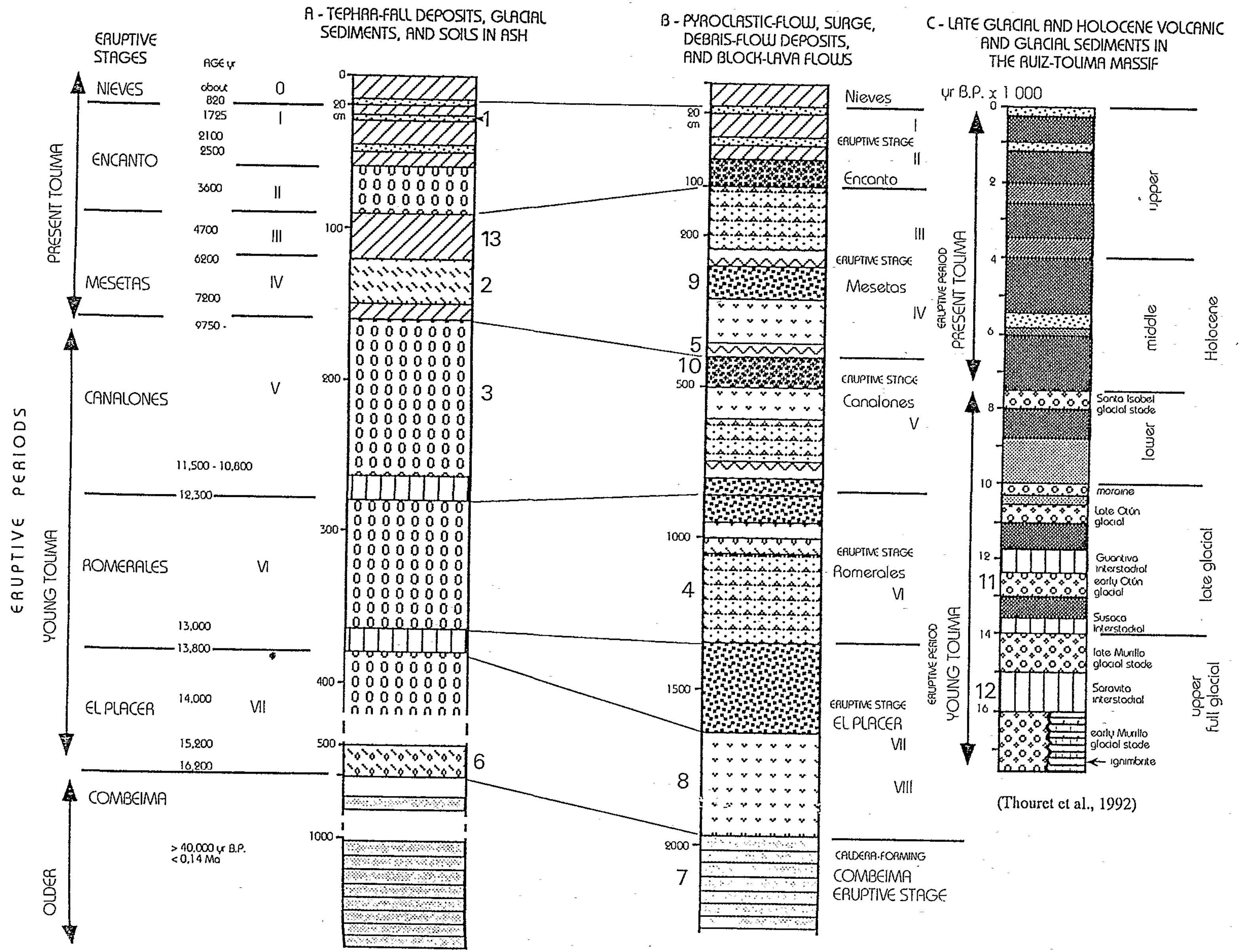
C^{14} ages* at and around young Nevado del Tolima and Cerro Machin

Sample Laboratory	Number year	Latitude-longitude altitude	Location, stratigraphic unit and position of the material dated	C^{14} age yr B.P.	Calendar age
GrN 12485	Col 404 1982	4°40'N, 75°23'W 3 640 m	Romerales, SW Tolima ; peat below tephra fall deposit (320-325 cm), unit VIII	16,220±80	
GrN 12486	Col 405 1982	id.	id., peat in between tephra-fall deposit (205-210 cm), unit VIII	15,200±140	
GrN 11701	Col 314 1981	4°42' N, 75°19' W 3 550 m	Normandia, NE Tolima, peat above tephra-fall deposit (295-300 cm), unit VII	13,780±60	
GrN 12488	Col 407 1982	4°45' N, 75°19' W 3 600 m	Paso Español, north Tolima, peat in-between pumice-fall layers (200-204 cm), unit VII	13,020±60	
GrN 12484	Col 403 1982	4°40' N, 75°23' W 3 600 m	Valle Romales, SW flank of Tolima, peat below tephra-fall deposit (205-210 cm), unit VI	12,950±70	
GrN 12483	Col 402 1982	4°40' N, 75°23' W 3 600 m	id., peat below tephra-fall deposit (190-195 cm), unit VI	12,360±100	
Grn 9813	Col 303 1981	4°45' N, 75°21' W 3 800 m	San Carlos, north Tolima ; peat below tephra-fall deposit (162-165 cm), unit V	11,490±60	
GrN 12 487	Col 406 1982	4°45' N, 75°19' W 3 600 m	Paso Español, north Tolima ; below tephra-fall deposit (142-146 cm), unit V	10,800±60	
GrN 14070	Col 571 1984	4°40' N, 75°22' W 4 000 m	Cárcava Romerales, west flank of Tolima ; charcoal in soil in a tephra sequence (310-313 cm), unit IV	9750±370	
GrN 10211	Col 291 1981	4°45' N, 75°20' W 3 800 m	Quebrada Africa, north Tolima ; charcoal in soil in a tephra sequence (75-80 cm), unit IV	7260±110	
GrN 10827	Col 309 1982	4°40' N, 75°23' W 4 000 m	Cárcava Romerales, west flank of Tolima ; charcoal in tephra sequence (210-212 cm), unit IV	6245±45 6205±45	(-5365, -4975) (-5325, -4950)
GrN 15737	Col 610 1984	4°27'30" N, 75°22'30" W 1 500 m	Cajamarca, San Lorenzo, SW Cerro Machin ; wood in pumice-flow tuff (ca 50 cm)	4980±25	(-3950, -3655)
GrN 13407	Col 434 1982	4°39' N, 75°18' W 3 720 m	Quebrada Mesetas, east flank of Tolima ; charcoal between two scoria-flow deposits (255 cm), unit III	4720±170	(-3850, -3150)
GrN 5172 collected by T. Van der Hammen	Col 62 1959	4°15' N, 74°55' W 600 m	Quebrada Catarniquera, Chicoral, Ibagué fan ; wood in distal pumice-flow tuff of Cerro Machin (ca. 8 m)	3780±95	(-2535, -1950)
GrN 13509	Col 579 1984	4°25' N, 75°23' W 1 600 m	Cajamarca, rio Coello ; wood in pumice-flow tuff of Cerro Machin (ca. 10 m)	3675±35	(-2310, -1885)
GrN 9199	Col 270 1980	4°48' N, 75°24' W 3 950 m	Road to Otún lake, north Tolima ; charcoal below a pumice-flow layer ; unit II (90 cm)	3620±70	(-2185, -1780)
GrN 14064	Col 531 1984	4°40' N, 75°23' W 4 000 m	Romerales arriba, west flank of Tolima ; charcoal in tephra-fall deposit and young soil ; unit I (60 cm)	2510±120	(-800, -420)
GrN 13053	Col 561 1984	4°39' N, 75°18' W 3 850 m	Linea Mesetas, east flank of Tolima ; charcoal in tephra-fall deposits and young soil ; *unit I (70 cm)*	2125±35	(-380, -10)
GrN 14065	Col 532 1984	4°38' N, 75°22' W 4 100 m	Boqueron Termales, SSW flank of Tolima ; charcoal in soil and ash-fall deposit ; unit I (29-32 cm)	1725±25	(80, 425)
GrN 15740	Col 613 1984	4°29' N, 75°24' W 2 200 m	Cerro Machin caldera, close to the domes ; *charcoal in tephra-fall deposit,* uppermost soil (30 cm)	820±100	(1030, 1325 A.D.)

*Isotope Physics Laboratory, University of Groningen, Westersingel 34, 9718 CM Groningen, The Netherlands. Calibration of radiocarbon dates after Klein et al., 1982.

thick, 5 km long and 0.5 km wide, and overlie the Rio Totare ignimbrite to the northeast (3700–3400 m). These deposits are nonwelded but are better preserved than the smaller pumice-rich pyroclastic-flow deposits that overlie the Rio Combeima ignimbrite to the southeast (Figs. 3, 4, 5, 7). A projection of the depositional

I - COMPOSITE STRATIGRAPHIC SECTIONS



(Thouret et al., 1992)

top of these pyroclastic-flow deposits suggests that a wide crater already occupied the central position north of the present crater and at about 5000 m in elevation (Fig. 5). The welded scoria-flow deposits above the Rio Totare ignimbrite are older than 14,000 yr B.P. This age is supported by the relative position of tephra layers, and because they are covered by moraines of the late full-glacial period (Thouret et al., 1992; Fig. 6). Such scoria flows may have been emplaced by a fountain-like eruption or from a low column above the vent, because the resultant pyroclastic flows suggest a high temperature for emplacement of basic magma. The grey and black, two-pyroxene andesitic, scoriaceous blocks and black bombs indicate that the eruption involved a deep basic magma feeding system.

The Romerales eruptive stage included at least one large plinian eruption, as indicated by 10–20-m-thick pumice-and-ash pyroclastic-flow deposits. These deposits fill paleovalleys in both the Rio Totare ignimbrite and the glacial deposits of upper full-glacial age (21,000–14,000 yr B.P.). These deposits can be correlated with a 70–100-cm-thick, dacitic pumice lapilli-fall layer, exposed in most of the 13 measured stratigraphic sections about 5 to 15 km from the summit toward the northeast and northwest. This layer is unit VII (Figs. 6, 7) which is dated ca. 13,000 yr B.P. by stratigraphic correlations with other tephra layers in the Ruiz–Tolima massif (Table 3).

The Canalones eruptive stage is inferred from a composite sequence of pyroclastic flows. A pumice-and-ash flow deposit, 3.5 km long, 1–1.5 km wide and 20–30 m thick, overlies the scoria-flow deposits of the El Placer and Romerales eruptive stages on the north-northwestern flank of the summit. Its base is poorly welded and crudely columnar base (Fig. 7). On the northern and northeastern flanks, several thick pumice-and-ash pyroclastic-flow and surge deposits overlie the El Placer scoria flows (Quebradas Canalones, Azufrera; Figs. 3, 6, 7). They also are inset into late-glacial moraines of the 13,000–12,300 yr B.P. 'early Otún' glacial stage (Thouret et al., 1992).

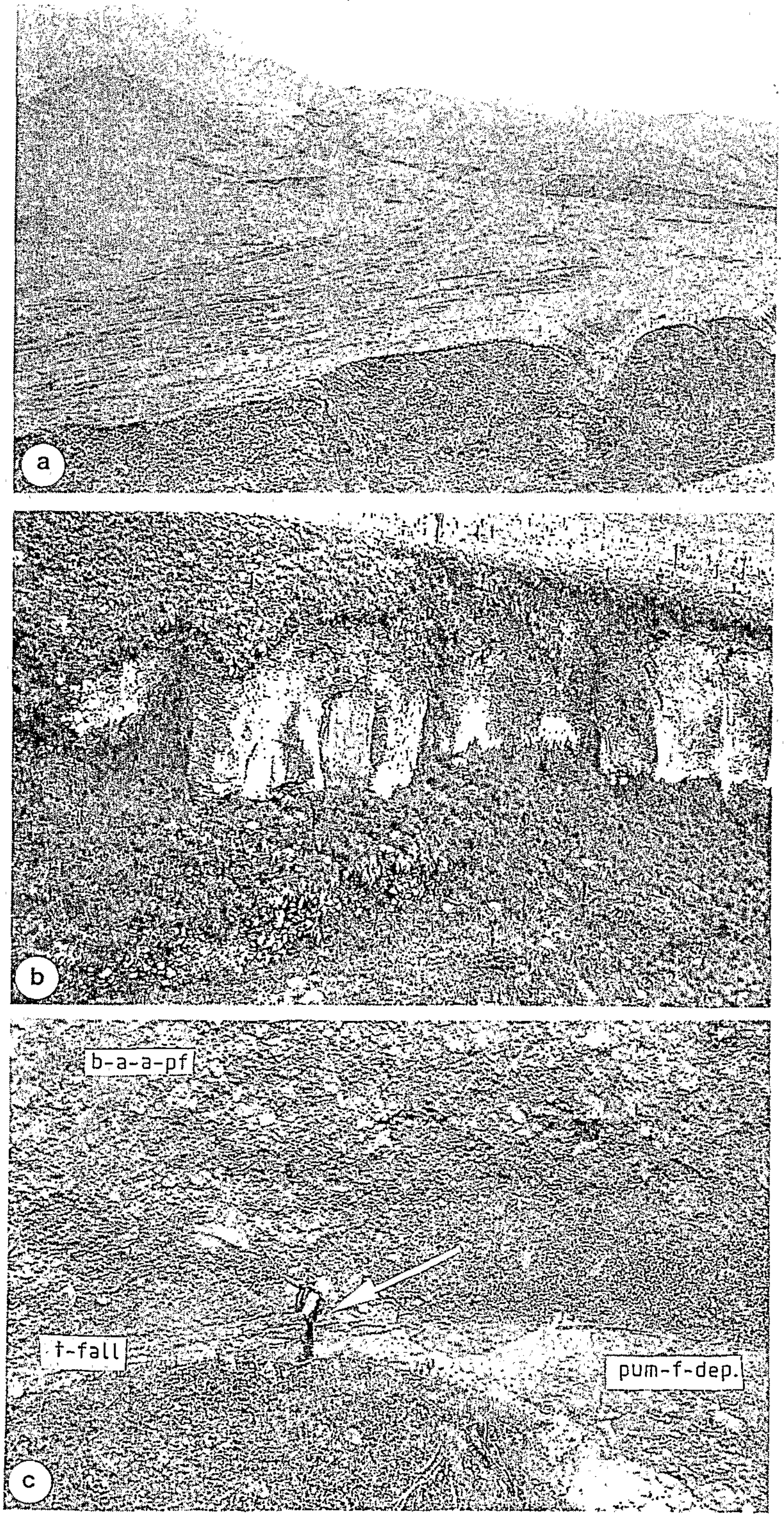
In addition, pumice-rich pyroclastic flows flowed in paleovalleys within stratigraphically similar scoria-flow deposits which overlie the upper Rio Combeima ignimbrite at El Rancho (Figs. 3, 5). The age of ca. 11,500–10,800 yr B.P. to ca. 10,000–9750 yr B.P. for all these deposits is based on the measured stratigraphic position of tephra layers and on correlation with a 50–70-cm-thick, plinian, pumice lapilli-fall layer (unit V, Figs. 6, 7). Charcoal in a thin soil directly above this layer was dated at 9750±370 yr B.P. ('Romerales cárcava' section, Figs. 6, 8; Table 3).

5.4. *Present Tolima volcano*

Lava domes were extruded high on the south flank (Figs. 2b, 3) during Holocene time (<10,000 yr B.P.), because they are neither dissected nor heavily overprinted by glaciers. Short lava flows, 1–3 km long and <0.5 km wide, of that time are piled on the upper part of the southern, young-Tolima-age flows (Fig. 3). Recent vent activity has apparently taken place toward the east and the south summit (Figs. 5, 9), where the present funnel-shaped crater and fumaroles break through the ice.

A series of large explosive eruptions repeatedly eroded the previous domes of the young Tolima volcano and again opened a wide vent during the Mesetas eruptive stage after ca. 7200 yr B.P. They are recorded by scoria-and-ash flow and pumice-and-ash flow deposits which are about 2.5 km long, 1.5 km wide and 10 m thick toward the north and northeast in Quebrada Canalones, and the east and southeast in Quebrada Mesetas (unit III, Fig. 6). These deposits flowed between moraines of late-glacial age and date from ca. 7200–6200 yr B.P. to 4720±170 yr B.P. (Fig. 6, Table

Fig. 6. Composite stratigraphic sections of tephra, soils and glacial deposits that record the young and present Tolima eruptive periods. I. Composite stratigraphic sections of: (A) tephra-fall deposits, glacial sediments and soils in ash; (B) pyroclastic-flow, -surge and debris-flow deposits, and block-lava flows. (C) Composite stratigraphic and chronological section of the late glacial and Holocene volcanic and glacial sediments in the Ruiz–Tolima volcanic massif. **Tephra-fall deposits:** 1 = Ash-fall deposits. 2 = Pumice, lithic lapilli-fall, and ash-fall deposits. 3 = Plinian pumice and lithic lapilli-fall deposits. **Pyroclastic-flow and -surge deposits, and block-lava flows:** 4 = Pumice- or scoria-rich pyroclastic-flow deposits. 5 = Pyroclastic-surge deposits. 6 = Block-and-ash pyroclastic-flow deposits. 7 = Welded or poorly welded scoria-rich pyroclastic-flow deposits. 8 = Block-lava flows. **Sediments of volcanic and glacial sources:** 9 = Debris-flow deposits. 10 = Deposits of pyroclastic flows reworked after probable magma–ice interactions. 11 = Fluvioglacial and moraine deposits. 12 = Peat that has been deposited over the past interstadials. 13 = Soils in weathered ash (= Andepts or Andisols).


a
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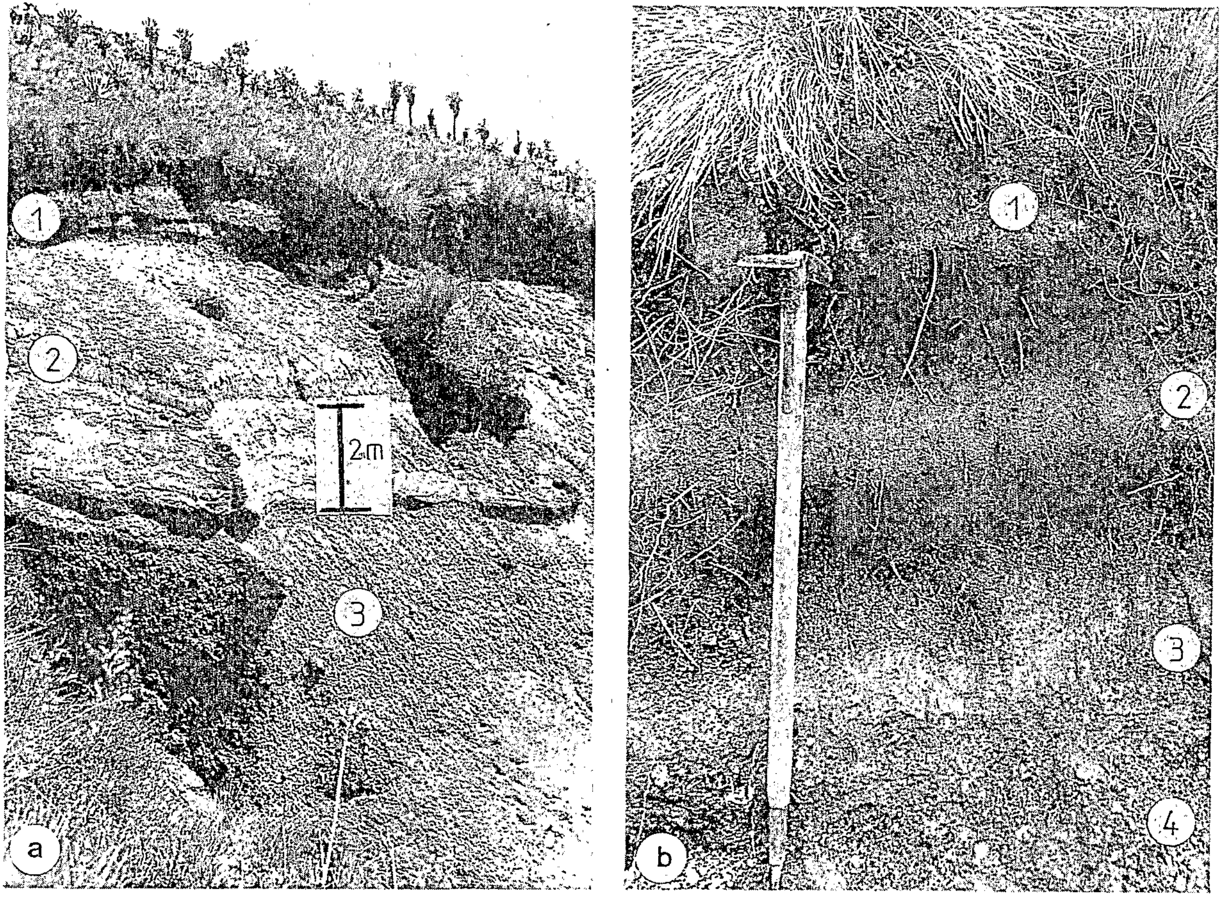


Fig. 8. (A) Thick measured stratigraphic sequence of Romerales carcava (4000 m, Fig. 3): 10-m-thick pumice-rich pyroclastic-flow deposit at the base (Romerales eruptive stage, no. 3), tephra-fall and pyroclastic-surge deposits and intercalated soil in ash (Canalones eruptive stage; charcoal dated at ca. 9750 yr B.P. within the black soil shown as no. 2, see Table 2B); tephra-fall and pyroclastic-surge deposits at the top (Mesetas eruptive stage, no. 1); the uppermost sequence is shown on photo B. (B) Uppermost sequence of tephra-fall deposits and black soils in ash (Andepts) that suggests a declining eruptive activity of Tolima volcano during the Encanto and Las Nieves eruptive stages. The location of dated charcoals is shown as follows: no. 1 ca. 820 yr B.P.?; no. 2 ca. 1725 yr B.P.; no. 3 in between 2100–2500 yr B.P.; no. 4 ca. 3600 yr B.P. (see Table 2B).

3). Pumice and scoria often show banded layers of andesitic and dacitic composition and biotite dacite bombs. Plinian and subplinian pumice-and-ash-fall preceded or accompanied pyroclastic flows and surges (unit III, Fig. 6). It appears that small-volume rock avalanches may have destroyed part of the northeastern

Fig. 7. (A) North flank of the Nevado del Tolima volcano showing thick apron of block-and-ash, pumice- or scoria-rich pyroclastic-flow and debris-flow deposits of young-Tolima-age (< 16,200 yr B.P.) overlying the El Placer ignimbrite (foreground). These deposits have filled a pattern of 'barrancos', the valleys between lava flows and pyroclastic-flow deposits of older Tolima volcano. The photo shows a slightly inverted topography and eroded scarps toward the young-Tolima-age summit (extreme left corner). (B) Crude columnar joints of a welded pumice flow that records the Romerales eruptive stage (ca. 13,000–12,300 yr B.P.) on the northwest flank of young Tolima (4 000 m). Recent, inset debris-flow deposits in the 'barranco'. (C) Stratigraphic section within the Quebrada Canalones, from the top to the base: 6-m-thick block-and-ash pyroclastic-flow deposits (b-a-a-pf) that record the Canalones eruptive stage (ca. 11,500 to 9750 yr B.P.), 0.8-m-thick tephra-fall and pyroclastic-surge deposits (t-fall), and 3-m-thick pumice-rich pyroclastic-flow deposit (pum-f-dep.). See a person for scale to the left of the arrow.

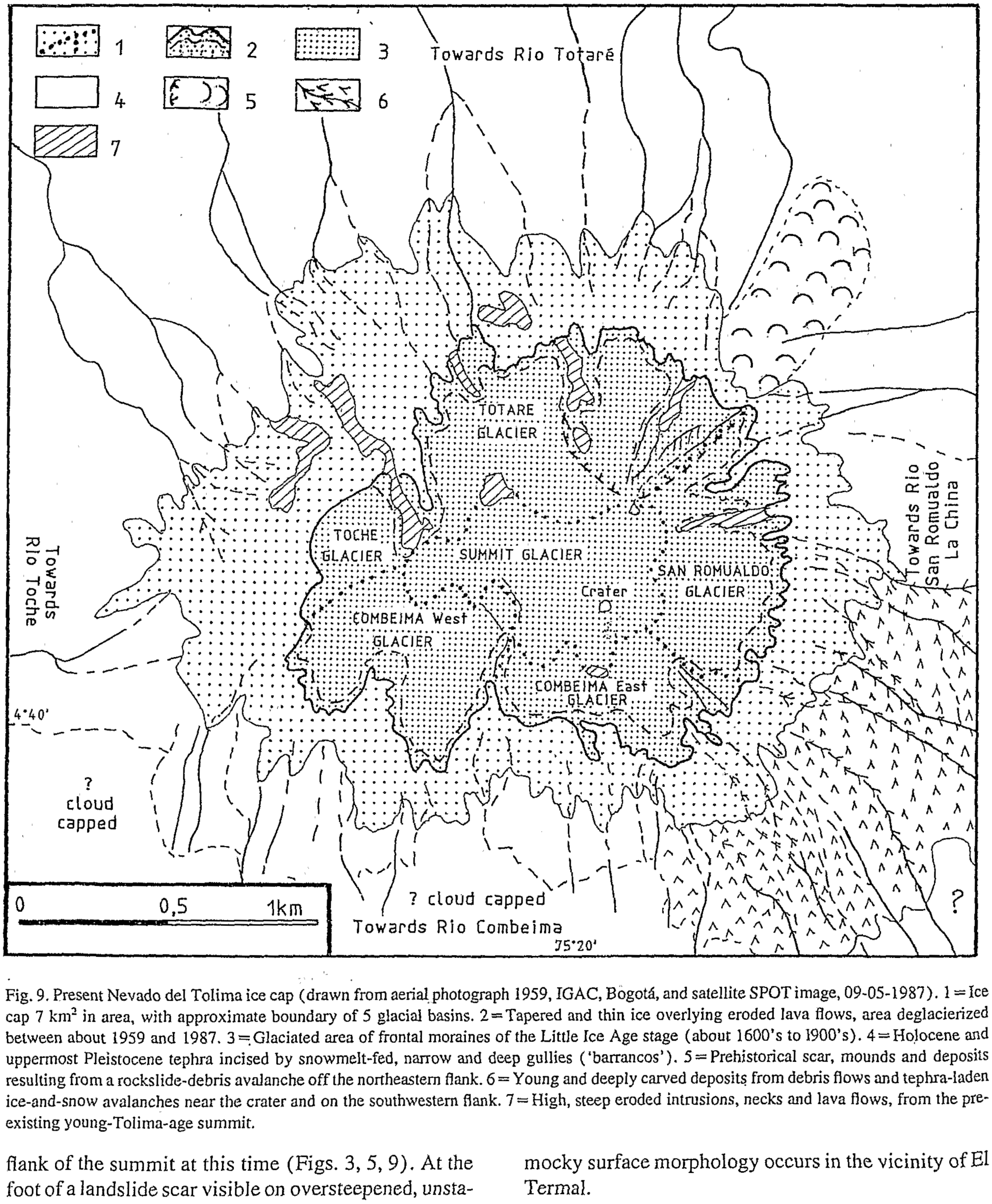


Fig. 9. Present Nevado del Tolima ice cap (drawn from aerial photograph 1959, IGAC, Bogotá, and satellite SPOT image, 09-05-1987). 1 = Ice cap 7 km^2 in area, with approximate boundary of 5 glacial basins. 2 = Tapered and thin ice overlying eroded lava flows, area deglacierized between about 1959 and 1987. 3 = Glaciated area of frontal moraines of the Little Ice Age stage (about 1600's to 1900's). 4 = Holocene and uppermost Pleistocene tephra incised by snowmelt-fed, narrow and deep gullies ('barrancos'). 5 = Prehistorical scar, mounds and deposits resulting from a rockslide-debris avalanche off the northeastern flank. 6 = Young and deeply carved deposits from debris flows and tephra-laden ice-and-snow avalanches near the crater and on the southwestern flank. 7 = High, steep eroded intrusions, necks and lava flows, from the pre-existing young-Tolima-age summit.

flank of the summit at this time (Figs. 3, 5, 9). At the foot of a landslide scar visible on oversteepened, unstable and hydrothermally altered breccia pipes, a hummocky surface morphology occurs in the vicinity of El Termal.

Tephra-fall deposits ca. 7200 to 3600 yr B.P. in age were dispersed mostly to the west, northeast and north, as indicated by measured stratigraphic sections. A plinian eruption at 3620±70 yr B.P. formed a pumice lapilli-fall layer (unit II, Fig. 6, Table 3). Isopaches for this single plinian tephra-fall deposits show a 50-cm thickness 5 km from the vent, and a 3-cm thickness at 30 km along the northeastern dispersal axis (Fig. 10). Volume is estimated at about 0.5 km^3 DRE. The ca. 13,000-yr B.P. and ca. 11,500–10,800-yr B.P. single plinian pumice-fall layers were somewhat larger (1 km^3 DRE each), with the 1-cm isopach present as far as 60 km, and with dispersal lobes conspicuous toward the northeast for the first and toward the west-northwest for the second layer (Fig. 10).

The volume of all pyroclastic deposits that resulted from Holocene activity is estimated to be roughly 2.5 km^3. Because the present Tolima-age landforms and deposits are not much eroded by glaciers, we know that the summit is not older than early to middle Holocene. In contrast, the pre-Holocene young Tolima-age pyroclastic deposits are two times as voluminous (4–5 km^3 DRE) and accumulated in glacially shaped valleys of late-glacial age.

Historical Las Nieves eruptive stage

Pumice lapilli- and ash-fall deposits up to 50 cm thick blankets all Tolima's flanks, especially to the west where they are 10 cm thick at a distance of 20 km. These deposits attest to a series of moderate eruptions probably occurring throughout pre-historical time. However, recent eruptions were of small magnitude, as indicated by the thin lithic ash and pumice lapilli-fall layers 2510±120 yr B.P., 2125±35 yr B.P. and 1725±25 yr B.P. in age (Table 3). These deposits are only 5–10 cm thick in young soils, within about 5 km distance from the vent (Fig. 6). Minor lithic-rich tephra fell during the historical period to the mid-1800's.

Tolima was apparently active on March 1822, March 1825, March 2, 1826 (explosive activity, VEI 2: Hantke and Parodi, 1966), and again on May–June 1918 and March 1943 (VEI 2: Simkin et al., 1981). Unfortunately, this remote volcano is seldom visible, a factor contributing to the paucity of historical accounts (Caldas, 1910; Krueger, 1927; Kraus, 1944) that precludes a detailed understanding of these events. Only weak seismic activity is reported since 1989 (INGEOMINAS, unpublished monthly reports).

Interactions of hot eruptive products with the ice cap probably triggered debris flows which spilled down the valleys of Rio Combeima and Totare. Debris flows likely formed the Holocene terraces of the volcaniclastic fan of Ibagué, as far as 50–70 km down the valleys of Rio Combeima and Coello. Similar terraces are also found in the Holocene and historical volcaniclastic fans of Venadillo, as far as 50–70 km down the valley of Rio Totare (Fig. 1). Immediately downslope of the present Nevado del Tolima ice cap (Fig. 9), historical moraines and pyroclastic debris have been reworked by glacial meltwaters and debris flows. They have formed thick fans, especially toward the north-northeast and the south-southeast (Fig. 7a). On the southeastern flank of the steepest summit, channelized deposits that are unsorted and loose may represent debris transported by recent tephra-laden snow-and-ice avalanches (Fig. 9).

5.5. Holocene eruptive history of Cerro Machin

The 3600-yr B.P. plinian event at Nevado del Tolima was the most recent, but only one of several large explosive events within the Ruiz–Tolima massif in Holocene time. It was almost contemporaneous with the end of activity of the 3-km-wide caldera of Cerro Machin, which opened on the metamorphic basement of the Central Cordillera and contains twin active, fumarolic, dacitic domes (Fig. 1). Explosive products of Cerro Machin consist of multiple units of nonwelded, quartz-dacitic pumice-and-ash flow deposits that partly filled the surrounding valleys (Rios Toche and Coello; Fig. 1), between 4980±25 yr B.P. and 3675±35 yr B.P. (Table 3). These high-aspect-ratio nonwelded ignimbrites are up to 400 m thick, up to 40 km long (the maximum distance flowed by ignimbrite in the Ruiz–Tolima massif), and are made of essentially quartz-dacite pumice (50%), lithics (30%, mostly metamorphic xenoliths) and ash. The ignimbrite sequence suggests a very large bulk volume (ca. 5 km^3), explosive event perhaps responsible for collapse of the caldera. The Cerro Machin domes have been explosive during the late Holocene, producing extensive tephra falls and several block-and-ash pyroclastic flows toward the west and south that breached the south rim of the caldera. The last pumice-fall shown in stratigraphic section on the west rim of the caldera was deposited 820 ± 100 yr B.P. ago (calendar age 1030–1325 A.D., Table 3).

6. Hazard-zone mapping and model

Hazard-zone mapping at Nevado del Tolima has been carried out using hazard appraisal methods used previously at Nevado del Ruiz (Parra et al., 1986; Thouret, 1987, 1988; Cepeda et al., 1988). The eruptive history of Nevado del Tolima over the past 16,000 yr B.P. suggests that pyroclastic flows and debris flows are the most probable hazards, especially on the south, north and northeast flanks. Debris flows have extended as far as 70 km in the past. In addition, the recurrent plinian or subplinian style that has characterized the explosive behaviour of Nevado del Tolima, and collapse of high eruptive columns, have generated pyroclastic flows, surges, and ballistic ejecta on the volcano flanks, as far as 11 km. Widespread tephra fall has been dispersed as far as 60 km toward the west and the east-northeast. Hazard also exists from the oversteepened south flank of the summit and west rim of the presumed caldera; the hydrothermally altered extrusions of the north flank have already been partially removed by recent, small-volume rockslides. On oversteepened flanks like those of the Tolima summit cone, landslides present a hazard even when explosive events are small or short-lived. On the other hand, we cannot preclude the potential occurrence of a lateral blast, as suggested by the composition of magma, the frequent dome extrusions, and a thin layer of unsorted juvenile deposits discovered on the south flank by M. Rosi (pers. commun., 1992).

6.1. Volcanic hazard zones and types

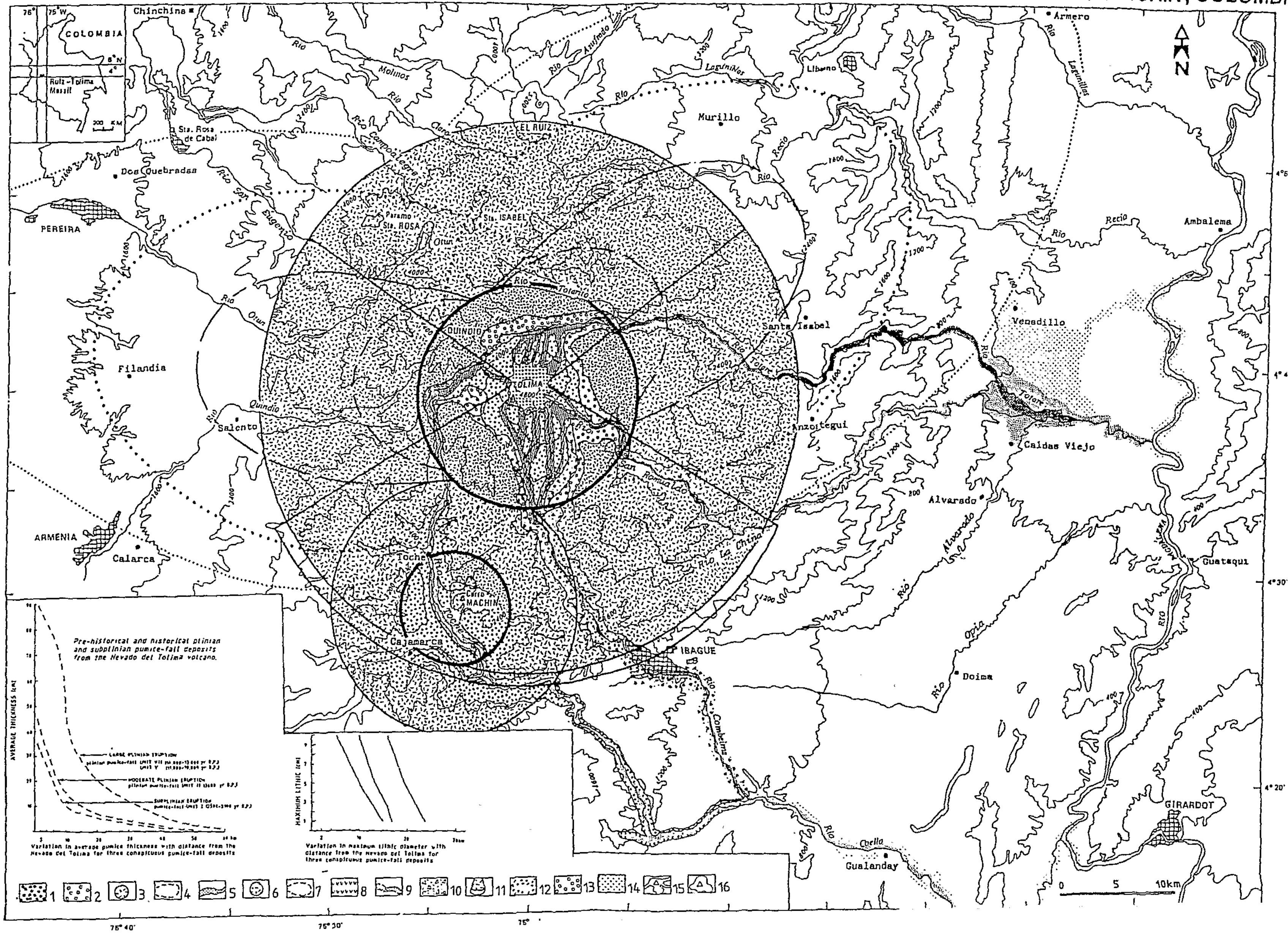
A general hazard map shows the areas likely to be affected by all hazards including pyroclastic flow and ash-cloud surge, tephra fall, blast, rockslide avalanche, and lava flow, with special attention given to debris flows (Fig. 10, Tables 4, 5 and 6). Three hazard scenarios were constructed based on three potential magnitudes. Three known events, the moderate (VEI 3) ca. 3600-yr B.P. event, the moderate (VEI 3–4) 11,500–10,800-yr B.P. episode and the large (VEI 4–5) ca. 13,000-yr B.P. episode, were selected as typical eruptions for Nevado del Tolima (inset plot in Fig. 10). The hazard types are described in detail below.

Pyroclastic flows, surges and companion ash clouds are the probable hazards for the Rio Combeima, Rio Totare and Rio San Romualdo valleys, and headwaters of Rio Toche valleys. Pyroclastic surges and ash-cloud surges could devastate valley sides up to about 100–300 m above and about 1 km away from the channels. Small areas drawn at about 10 km around Nevado del Tolima and 5 km around Cerro Machin volcanoes (see no. 1, Fig. 10) point out to the approximate limit of topography encompassed within the 'energy line' of potential pyroclastic flows (computed as θ_f = arctan height/distance), using the method of Hsü (1975), Malin and Sheridan (1982), and Sheridan and Malin (1983).

Tephra-fall deposits and ballistic ejecta would likely be shed by a plinian, subplinian, or phreatomagmatic eruption. Three possible tephra-fall areas and volumes are considered based on past events, mentioned above (inset plot, Fig. 10). The small circles drawn around Nevado del Tolima and Cerro Machin (see no. 6, Fig.

Fig. 10. Potential areas of volcanic hazards from future eruptions at Tolima and Cerro Machin volcanoes, Colombia (inset plot: pre-historical and historical plinian and subplinian pumice-fall deposits from Tolima volcano). **I. Areas of potential hazards from a moderate eruption (VEI < 3)** 1 = Areas likely to be affected by scoria flows or block-and-ash pyroclastic flows. 2 = Areas likely to be affected by ash clouds accompanying Unit 1 pyroclastic flows and pyroclastic surges. 3 = Areas likely to be affected by ballistic ejecta and tephra fall. 4 = Areas likely to be affected by dispersal tephra fall (10 cm isopach) toward northeast and west. 5 = Areas likely to be affected by debris flows (mostly triggered by magma–ice interactions). **II. Areas of potential hazards from a major eruption (VEI > 3)** 6 = Areas likely to be affected by ballistic ejecta and tephra fall from a blast or a plinian event. 7 = Areas likely to be affected by dispersal tephra fall (10 cm isopach) toward the northeast and west. 8 = Areas likely to be affected by mixed avalanches and flows that may generate debris flows. 9 = Areas likely to be affected by large or distal debris flows. 10 = Areas likely to be affected by large pyroclastic flows or debris avalanches, and subsequent debris flows. 11 = Areas likely to be affected by a blast or laterally directed explosion toward south or north. **III. Areas of potential hazards from a cataclysmal eruption (VEI > 5)** 12 = Areas likely to be affected by dispersal tephra fall (10 and 1 cm isopach) toward northeast and west. 13 = Areas likely to be affected by a large high-aspect-ratio pyroclastic flow (similar to the Cerro Machin ignimbrite). 14 = Areas likely to be affected by floods, if the Rio Magdalena were to be dammed at the Rios Totare and Coello confluences by debris flows. 15 = Areas likely to be affected by non-extensive block-lava flows from lava domes. 16 = Present Nevado del Tolima ice cap.

POTENTIAL AREAS OF VOLCANIC HAZARDS FROM FUTURE ERUPTIONS AT NEVADO DEL TOLIMA AND CERRO MACHIN, COLOMBIA



10) encompass areas likely to be affected by subplinian ballistic ejecta, whereas larger circles encompass areas likely to be seriously affected by plinian tephra-fall. We made estimates of eruption characteristics based on the maximum diameter of pumice and lithic fragments in 13 measured stratigraphic sections using methods of Carey and Sparks (1986) and Wilson and Walker (1987). We assumed, for past eruptions, erupted magma volumes of 0.5 to 1 km^3, heights of eruptive columns from 10 to 20 km, magma rates from 40 to 75×10^6 kg/s, durations of the eruption from $\leqslant 30$ minutes to $\geqslant 2$ hours, VEI 2 to 5, and wind directions to the west and east-northeast.

The location of tephra-fall dispersal lobes is dictated by the direction of the seasonal prevailing winds (Fig. 10). Winds are from the southeast in 'dry' seasons (i.e. December–March and July–September) and from the west-southwest during the rest of the year, similar to the situation at Nevado del Ruiz. In addition, subplinian eruption columns (< 15 km) could produce tephra fall toward the west, whereas the highest eruption columns could shed tephra toward the northeast, because of a change in wind direction above the tropopause. A major tephra-producing event would likely resemble the ca. 13,000-yr B.P. eruption and could send lapilli-size ballistic ejecta as far as 10 km. The area 10 km in diameter around the vent would be especially hazardous because of falling tephra and ballistic ejecta.

Rock or debris avalanches could be triggered by earthquake or intrusion. An earthquake could shake hydrothermally altered lavas on the north flank or the presumed caldera rim on the southwest. Intrusion into the steep south-southeastern summit could decrease slope stability even without an eruption. Debris avalanche could be channeled along the deep Rio Combeima gorge and probably transform into debris flows that might devastate the Combeima valley as far as Ibagué and the Rio Coello confluence (Fig. 10).

Table 3
Estimated volume of liquid water available from Nevado del Tolima ice cap and areas likely to be impacted by tephra
(A) Surface area and volume of the ice cap and glacial basins (Fig. 9)

Glacial basin	Calculated surface area (km^2)	Rough estimate thickness	Slope angle average (degrees)	Rough estimate ice* volume (km^3)	
Summit	1.1	≥ 50 m	5-10°	0.05	* ice density ≈ 0,9
Combeima W					
E	2.5	40 m	30°	0.09	
Totare	1.95	30 m	35°	0.054	average total volume
San Romualdo	1.05	40 m	30°	0.038	0.25-0.31km³
Toche	0.35	40 m	30°	0.013	
Total	**6.95**			**0.245**	

(B) Areas likely to be impacted by energetic pyroclastic flows, surges, and by tephra fall or lava flows, and estimate of potential liquid water from snow and firn

Glacial basin	Calculated surface area (km^2)	Estimate volume (km3) of		Estimate total volume of liquid water (km^3)	
		snow (1)	firn (2)		
Summit	1.1	0.0022	0.0044	0.0029	(1) assuming density
Combeima W					0.35 for snow ; 0.5 for firn
E	2.5	0.005	0.01	0.0085	(2) assuming thickness 2
Totare	1.95	0.004	0.008	0.0018	m for snow and 4 m for
San Romualdo	1.05	0.002	0.004	0.0027	firn
Toche	0.35	0.0007	0.0014	0.00027	
Total	**6.95**	**0.0139**	**0.0278**	**0.0162** (3)	

If 10% of the whole ice cap were to be impacted (minor eruption) = 0.0016 km^3 of liquid water available (3). If 30% of the whole ice cap were to be impacted (moderate eruption) = 0.0048 km^3 of liquid water available. If 60% of the whole ice cap were to be impacted (large eruption) = 0.0096 km^3 of liquid water available. If 90% of the whole ice cap were to be impacted (catastrophic eruption) = 0.014 km^3 of liquid water available. Thus, 1–6 to 14×10^6 m^3 of liquid water (from snow and firn melt) are available for debris flow generation (see Table 5). For comparison, some 0.044 km^3 of liquid water was available at Nevado del Ruiz, and 10% of the ice cap was impacted by the November 13, 1985, eruption.

Lava flows are the least hazardous phenomenon likely to occur, because extrusive activity has been short-lived and is likely to produce block-lava flows such as those of young-Tolima age. Highly viscous and slow-moving block-lava flows could reach only 5–6 km when channeled, and likely move to the southeast or south. However, the very steep south flank would enable lava flows to travel more than 6 km if the chemical composition, physical properties, and hence viscosity of erupted magma changed.

6.2. *Debris flow initiation and magma–ice interactions*

Debris flows are likely to occur on all the steep flanks during a violent eruption (VEI > 3) and are most likely to form on the south and north flanks. In the event of a large magmatic eruption similar to the caldera-forming Combeima eruptive stage, debris flows could also spill down the Rio Toche to Cerro Machin (west and southwest), and the Rio San Romualdo and La China (east) to the Magdalena basin as far away as the town of Venadillo (Fig. 10).

Because the summit of Nevado del Tolima is mantled by snow and ice, large debris flows may be triggered if pyroclastic flows, surges or lava flows scour and melt parts of the ice cap (as during recent eruptions at Nevado del Ruiz, 1985 and Mt. Redoubt, 1990). The ice cap covers 6.95 km^2 above 4800 m in elevation and encompasses 5 glacial basins (see details on Fig. 9 and Table 4). The ice volume is estimated to be 0.25–0.31 km^3 based on a computation of the ice surface area and a thickness of 30 to 50 m (Table 4). These estimates are inferred from equations developed by Nye (1952, 1965, *in* Thouret 1990). The extent of the ice cap decreased by one half and the ice margin retreated from 4550 to 4800 m over the past 50 years (Fig. 9). These estimates are based on altitude measurements (Caldas, 1910), aerial photos (1946, 1959, 1979), and one SPOT satellite image (1987, Fig. 9). The ice cap flowed down to 4400 m and had an approximate area of 10 km^2 during the Little Ice Age (1600's to 1800's). Between 14,000 and 10,000 yr B.P., the late-glacial ice cap was probably as large as 35 km^2 (Figs. 3, 6). Thus, there is a high probability that magma–ice interactions occurred during the young Tolima volcanic period. Those interactions were most likely less efficient during the Holocene, because the smaller area of ice meant that less meltwater was produced in a given eruption.

The characteristics of any debris flow generated on Tolima volcano are dependent upon valley morphology, slope gradient, and efficiency of incorporating sediments from channel slopes and bed (Tables 5, 6). It appears that tephra-laden snow-and-ice avalanches, and also water flows, can bulk into debris flows. On the south flank, flows could bulk quickly and transform downstream into rapid debris flows owing to abundant and potentially erodible sediments within a steep, deep, and short gorge. The closest village of Juntas is within 11 km of the ice cap margin and 3000 m below. The city of Ibagué (200,000 people) is only 27 km away and 3600 m below Tolima summit. If flows traveled 10–15 m/s in a manner similar to the 1985 Nevado del Ruiz debris flows in Rio Chinchina (Table 6; Pierson et al., 1990), potential debris flows within the steep Combeima drainage could reach Ibagué within 45 minutes to an hour. However, the expected velocity of potential debris flows could decrease to about 5–6 m/s, and deposition could occur near Ibagué city 27 km away, and again at the Rio Coello confluence 39 km away (Fig. 10). This situation is somewhat similar to the 1985 Rio Lagunillas debris flows in the distal part of the Armero fan (Pierson et al., 1990).

Debris flows could incorporate more sediments and bulk more quickly within the Rio Combeima than within the Rio Totare valley. Because of the narrow and meandering nature of the channel over a distance of 50 km to the town of Venadillo, the expected mean velocity of future debris flows within the Rio Totare drainage would probably not exceed 8–10 m/s. This situation is comparable to the 1985 debris flow at Armero (Table 6). However, debris-flow deposits are preserved as much as 6 m above channels now eroded into the Venadillo fan, indicating that present-Tolima-age debris flows were able to bulk up substantially 60 km away from the source. On the east flank of the volcano, the upper channels of the Rio Toche and San Romualdo–La China valleys have a very flat slope gradient, and debris flows here would slow and be influenced by deposition. On the west flanks of the volcano, potential water flows or debris flows would bulk greatly because of erosion of pumice and unwelded ash-flow deposits as thick as 400 m within the Rio Toche and upper Rio Coello valleys. The geologic record indicates that mid-Holocene debris-flow deposits as thick as 10

Table 4
Estimated volumes of liquid water available for debris flow generation, according to presumed, future eruption magnitudes
Case 1 - Moderate eruption

Tephra volume	Column height	Magma discharge	Eruption duration	VEI	Maximum distance ballistic ejecta	Prevailing winds
0,05 km^3	≥ 10 km	40-50 x 10^{6}kg/s	≥ 30 mn	2-3	≤ 6 km	toward W or NE

Impacted glacial basins	Surface area	Total volume of available liquid water		Volume of available liquid water if 10-20 % impacted area	
		from snow and firn	from ice	from snow and firn	from ice
a - Summit + Combeima + Toche	3.95 km^2	0.011 km^3	0.153 km^3	0.001-0.002	0.015-0.03
b - Summit + Totare	3.05 km^2	0.0047 km^3	0.104 km^3	0.0004-0.0008	0.01-0.02

Case 2 - Large eruption

Tephra volume	Column height	Magma discharge	Eruption duration	VEI	Maximum distance ballistic ejecta	Prevailing winds
1 km^3	20 km	75-100 x 10^{6}kg/s	120 mn	4	8 km	toward NE and SE

Impacted glacial basins	Surface area	Total volume of available liquid water		Volume of available liquid water if 30-60 % impacted area	
		from snow and firn	from ice	from snow and firn	from ice
a - Summit + Totare + San Romualdo	4.1 km^2	0.0074 km^3	0.142 km^3	0.002-0.004 km^3	0.042-0.084 km^3
b - Summit + Combeima + San Romualdo	4.65 km^2	0.0141 km^3	0.178 km^3	0.004-0.008 km^3	0.051-0.102 km^3

Case 3 - Catastrophic eruption

Tephra volume	Column height	Magma discharge	Eruption duration	VEI	Maximum distance ballistic ejecta	Prevailing winds
2-3 km^3	20-30 km	1 x 10^7- 10^8 kg/s	several hours	≥ 5	10 km	toward W and NE

Impacted glacial basins	Surface area	Total volume of available liquid water		Volume of available liquid water if 60-90 % impacted area	
		from snow and firn	from ice	from snow and firn	from ice
a - Summit + Combeima + Toche	3.95 km^2	0.011 km^3	0.153 km^3	0.006-0.012 km^3	0.09-0.135 km^3
b - Summit + Totare + San Romualdo	4.1 km^2	0.0074 km^3	0.142 km^3	0.004-0.008 km^3	0.102-0.153 km^3

m are preserved as far as Gualanday, 70 km from the source (Fig. 10).

The history of frequent explosive eruptions and the geomorphic instability of Nevado del Tolima and its glaciers render this volcano more hazardous than Nevado del Ruiz for debris-flows. Although the area of the Nevado del Tolima ice cap is only 30% of the Nevado del Ruiz ice cap, a comparison of magma–ice interaction processes at Nevado del Ruiz in 1985 (Thouret, 1990; Pierson et al., 1990), and at Redoubt Volcano, Alaska, in 1990 (Trabant et al., 1994) has taught several lessons. The surface area and thickness of snow and firn upon the ice cap are as critical as the volume of the ice itself. They may be even more critical if an eruption similar to the 1985 Nevado del Ruiz event were to produce much scouring and to occur when the snow and firn cover is thickest. Moreover, the greater the energy and duration of pyroclastic flowage on snow, the larger the resulting debris flow. Third, in spite of its small size, the crevassed Tolima ice cap would probably yield large avalanches of snow, ice and rock. Potential water flows would bulk rapidly on steep slope gradients on the north and south flanks, and even more with voluminous, extensive pyroclastic and loose glacial sediments along rivers.

Finally, Nevado del Tolima has been violent because of its magma chemistry. The dacite and andesite magmatic evolution that we observe within the Holocene products cannot preclude the possibility of catastrophic explosions, perhaps caldera forming. Moreover, there has been a long interval, about 1700 to 3600 years, since its last major eruption, while the average occurrence interval between major eruptive events is 2000 to 4000 years. A major eruption could produce large-volume tephra falls and pyroclastic flows, a directed blast (shown on Fig. 9), rockslide debris-avalanches, and huge lahars, especially toward the Combeima gorge, where the majority of debris would be channeled. Thus, Nevado del Tolima is considered rather hazardous for the 50,000 people living in the Com-

Table 5
Characteristics of potential eruption-triggered debris flows within the Rio Combeima and Totare drainages, compared to those of the 1985, eruption-induced Rio Chinchina and Azufrado debris flows at Nevado del Ruiz (1)

	Stream segment length (km)	Slope gradient (%)	Volume of initial available liquid water (m^3)	Bulking vate m^3/m	Volume m^3	Peak discharge m^3	Mean peak velocity m/s	Mean flow depth m	Time travel minute
1985 Lahar of Rio Molinos-Nereidas to Chinchina	11,2 33 47,4	} average 118 m/km }9-12 % 92 m/km }	3.7×10^6 -	350-670 680 210	11.2×10^6 26×10^6 29×10^6	19,900 11,700 7,300	7.8 8.7 6.4	14.9 11.9 7.4	to Chinchina 70
1985 Lahar of Rio Azufrado to Armero	9,6 49,7 69,3	} average } 8% 77 m/km }	$11\text{-}18 \times 10^6$ - -	160-140 460 500	11.4×10^6 30×10^6 39.8×10^6	48,000 30,200 27,100	14.6 17.0 13.5	19.8 16.8 13.5	to Armero 135

Stream segment length (km)	Slope gradient (%)		Volume of initial available liquid water $10^6 m^3$ (2)	Expected volume 10^6 m^3 (3)	Expected mean velocity m/s	Expected mean height m	Expected mean height m	Expected time travel mn	Expected time travel mn
Potential debris flow of Rio Combeima to Ibagué									
to Juntas 10-11	30	Case 1	1-2	4-5 to 7-8	8-10	at Juntas 8-10	at Ibagué 9-11	to Juntas 11-14	to Ibagué 40-41
to Ibagué 27	15	Case 2	4-8	7-11 to 10-14	10-12	9-12	10-14	14-16	45
		Case 3	6-12	9-12 to 12-18	12-15	12-13	14-18	16-21	56
Potential debris flow of Rio Totare to Venadillo									
to Venadillo		Case 1	0.4-0.8	8-8.5 to 22.23		at Venadillo		to Venadillo	
50	9.5	Case 2	2-4	10-12 to 24-26	8-10	4-6 m		83-104 mn	
		Case 3	4-8	12-16 to 26-30					

(1) According to data from Pierson et al. (1990).

(2) These figures do not include the volume of available liquid water from ice; however, a large part of liquid water could be released by ice melt and ice avalanching.

(3) Assuming a bulking rate for the Rio Combeima debris flow similar to that of the 1985 Rio Chinchina debris flow: 350–680 m^3/m (Pierson et al., 1990). Assuming a bulk rate for the Rio Totare debris flow similar to that of the 1985 Rio Azufrado debris flow: 160–460 m^3/m (Pierson et al., 1990).

beima valley. This volcano and Cerro Machin are indirectly hazardous for 300,000 more, the Cerro Machin domes are active and present a hazard from pyroclastic flows and plinian tephra falls.

7. Conclusion

The eruptive activity of Nevado del Tolima during the last 1.4 Ma is divided into four eruptive periods, termed pre-Tolima (> 1.3 Ma old), ancestral Tolima (1.3 to 0.7 Ma), older Tolima (about 0.7 to 0.14 Ma), and young Tolima (< 0.14 Ma to present time). Except for the oldest, each of these periods includes two long constructive phases, consisting of lava flows and dome growth, and separated by a shorter destructive phase, mostly explosive, that leads typically to a caldera collapse or to a wide crater opening.

The stratigraphic record of the most recent 16,000-year-long destructive phase of the young and present Tolima eruptive periods indicates that eruptive events were relatively large and prolonged. The historical record indicates only a series of small events, but this probably reflects a basically dormant stage (1000 to 1500 years in duration). Recurrent eruptive stages (< 2000 years in duration) and eruptive episodes (centuries to 1000 years in duration) produced plinian pumice flows and falls and scoria flows from a large crater. They alternated with block-and-ash pyroclastic flows, dome extrusion, and block-lava flows. Interactions between hot eruptive products and ice and snow are inferred to have triggered debris flows, which were valley-confined and reached major river confluences as far as 70 km downvalley. Except for mid-Pleistocene, the youthful stratigraphic record shows no compelling evidence for previous large rockslides-debris avalanches, although the steep-sided and hydrothermally altered flanks render the summit cone potentially unstable, especially on the south and north flanks.

Owing to the proximity of population centers to the volcano, there would be only a very short time required for debris flow to reach the uppermost villages of Las Juntas (only 11 km away) and 27 km further downstream, the city of Ibagué, where 50,000 people live. The velocity of such debris flow could be comparable to the 1985 debris flows at Nevado del Ruiz. The closest village could be devastated within about 10 to 20 minutes, and the suburbs of Ibague could be destroyed within about 45 minutes to an hour. Although debris flows in the Rio Totare and Toche valleys would be slower, floods could devastate not only the flat Venadillo fan, but also the inhabited alluvial lowlands, should the upper Rio Magdalena become temporarily obstructed (Fig. 10).

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