Turbeville et al. 1989 C221 ER ID # 21587

Journal of Volcanology and Geothermal Research, 36 (1989) 267–291
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

LAVA-DOME GROWTH AND EXPLOSIVE VOLCANISM IN THE JEMEZ MOUNTAINS, NEW MEXICO: EVIDENCE FROM THE PLIO-PLEISTOCENE PUYE ALLUVIAL FAN

B.N. TURBEVILLE*, DAMON B. WARESBACK and STEPHEN SELF

Department of Geology, University of Texas at Arlington, Arlington, TX 76019, U.S.A.

(Received March 25, 1988; revised and accepted June 1, 1988)

Abstract

Turbeville, B.N., Waresback, D.B. and Self, S., 1989. Lava-dome growth and explosive volcanism in the Jemez Mountains, New Mexico: Evidence from the Plio-Pleistocene Puye alluvial fan. *J. Volcanol. Geotherm. Res.*, 36: 267–291.

The Plio-Pleistocene Puye Formation, north-central New Mexico, is a 200 km² volcanogenic alluvial fan shed eastward from the Tschicoma volcanic center, part of the Jemez Mountains volcanic field. The fan contains > 15 km³ of volcaniclastic material derived from closely spaced lava domes in the northeastern portion of the Tschicoma center. Interbedded in the fan sediments are at least 25 primary pyroclastic units from explosive eruptions of dacitic and rhyolitic lava domes. Tephra occur mainly as pumice falls but include several pumiceous ignimbrites and two thick proximal block-and-ash pyroclastic flows. The upper part of the fan also contains rhyolitic plinian deposits erupted from sources in the central portion of the Jemez field and basaltic ash derived from the central Rio Grande rift.

Fanglomeratic (pyroclastic and epiclastic) facies exhibit considerable lateral variation. Primary tephra deposits, however, provide a stratigraphic framework for reconstruction of the growth of individual lava domes. While only volcanic domes and lava flows are exposed in the Tschicoma center, Puye tephra layers show that vulcanian, subplinian and plinian activity, and block-and-ash pyroclastic flows accompanied many dome-forming events. Degradation of these lava domes produced coarse-grained debris flows dominated by lava and dome carapace clasts. From these epiclasts it is possible to identify lithologies of lavas that are either currently buried or have been obliterated by erosion or by collapse of the Valles calderas.

The preservation of Puye deposits reflects very high rates of aggradation and gradual down-faulting in the Española basin of the central Rio Grande rift. This record of pyroclastic and epiclastic deposition allows detailed interpretation of the evolution of a volcanic center from its pyroclastic and erosion products, and is the first example of a volcanogenic alluvial fan in an intracontinental rift setting to be described in detail. This study emphasizes that interpretation of any ancient volcanic terrain based solely upon data derived from mapping, radiometric dating, and chemical analysis of lavas or existing denuded edifices is likely to greatly underestimate both the role of explosive volcanism in the build-up of volcanic centers and subsequent estimates of the volumes of material produced.

Introduction

Explosive volcanism occurred throughout the 13.5-million year development of the Jemez Mountains volcanic field (JMVF; Fig. 1) of north-central New Mexico. Most work in this area has concentrated primarily on either the voluminous Quaternary rhyolitic ignimbrites (Smith and Bailey, 1966; Izett et al., 1981) and related calderas (Smith and Bailey, 1968), or on the petrology and age relationships of long-

*Current address: Department of Geological Sciences, University of Texas at Austin, Austin, TX 78713-7909, U.S.A.

0377-0273/89/$03.50 © 1989 Elsevier Science Publishers B.V.

JUL 22 1993
YCG
7463

lived episodes of lava effusion and dome growth (Gardner et al., 1986; Singer and Kudo, 1986; Loeffler et al., 1988), particularly in the Paliza Canyon and Tschicoma Formation sequences (Fig. 2). A neglected area has been study of the extensive volcaniclastic sequences that relate eruptive activity and erosion of individual Jemez volcanic centers to Rio Grande rift-controlled sedimentation. Detailed documentation of these sequences is crucial to understanding the volcanological evolution of this field, as they contain abundant pyroclastic deposits interstratified with epiclastic debris. These relationships are rarely evident in the central Jemez field but are particularly well displayed in the Puye Formation, a large volcaniclastic fan shed from the Tschicoma volcanic center in the northeastern part of the field (Fig. 1). The Puye Formation is ideal for study because of its excellent exposure and close spatial, temporal, and lithologic association with the Tschicoma center. Pyroclastic and epiclastic deposits in the Puye fan, therefore, provide valuable insight into the history of Plio-Pleistocene explosive eruptions and lava dome development in the northeastern JMVF.

Tschicoma volcanic center

The Jemez Mountains are situated on the western margin of the Rio Grande rift at its intersection with the Jemez Lineament (Fig. 1). Erupted products have been divided into three stratigraphic groups representing three successive periods of magmatic evolution and eruption (Bailey et al., 1969; Smith et al., 1970). The proposed divisions are the Keres (including the Paliza Canyon Formation), Polvadera (including the Tschicoma Formation), and Tewa (primarily Bandelier Tuff and post-caldera lava domes) Groups, in age sequence (Fig. 2). These volcanic and volcaniclastic deposits span the period 13.5 to 0.1 Ma (Gardner et al., 1986).

The Tschicoma volcanic center (7.40–2.9 Ma; Gardner et al., 1986; Singer and Kudo, 1986; Baldridge et al., 1987) contains >500 km^3 of dacitic lava flows and domes in the northern and eastern Jemez Mountains with subordinate amounts of 2-pyroxene andesite, rhyodacite, and low-silica rhyolite (Baldridge and Vaniman, 1986; David Broxton, unpubl. data). Andesitic lavas generally underlie the dacitic and rhyodacitic lavas and domes. Much of the southwestern part of the Tschicoma center has been obliterated, initially by formation of the Toledo Embayment (Fig. 1), and later by collapse of the Valles I (or Toledo; Smith, 1979) and II calderas at 1.4 and 1.1 Ma, respectively (Baldridge and Vaniman, 1986; Self et al., 1986). Surviving volcanic features of this center suggest a strong tectonic control on magmatism with the early development of basaltic and andesitic stratovolcanoes in the northwestern JMVF and later growth of dacitic and rhyodacitic dome complexes farther eastward (Singer and Kudo, 1986; Baldridge et al., 1987).

Magmatic activity in the northeastern JMVF began to wane between 4 and 2 Ma as several small, isolated lava domes (i.e. pumiceous flank domes) were emplaced onto Tschicoma Formation deposits (Fig. 1). These domes form the El Rechuelos Rhyolite and Cerro Rubio Quartz Latite (Fig. 2; Bailey et al., 1969), the latter sequence more recently recognized as part of the Tschicoma Formation (Gardner et al., 1986). The youngest El Rechuelos Rhyolite lavas are distinguished mineralogically and chemically from the "older (Tschicoma) rhyolites" of Loeffler et al. (1988), but are mineralogically similar to several tephra deposits in the upper Puye Formation. Epiclastic material from this center, however, is poorly represented in Puye deposits due to topographic barriers existing at the time of eruption of these domes.

The youngest eruptives hitherto reported from the Tschicoma volcanic center are 2.9 Ma (Baldridge et al., 1987), although this study emphasizes that portions of the center remained active up to 2 Ma (or less; Turbeville, 1986), and that evidence for younger dacite and rhyodacite lava domes (since destroyed by ero-

hern
ordi-
oda-
and
ata).
citic
f the
r has
f the
col-
979)
ively
t al.,
cen-
mag-
saltic
orth-
c and
ward
987).
MVF
flank
For-
m the
Quartz
ter se-
of the
1986).
as are
nically
es" of
gically
upper
m this
Puye
ting at

d from
.9 Ma
study
er re-
peville,
it and
o-

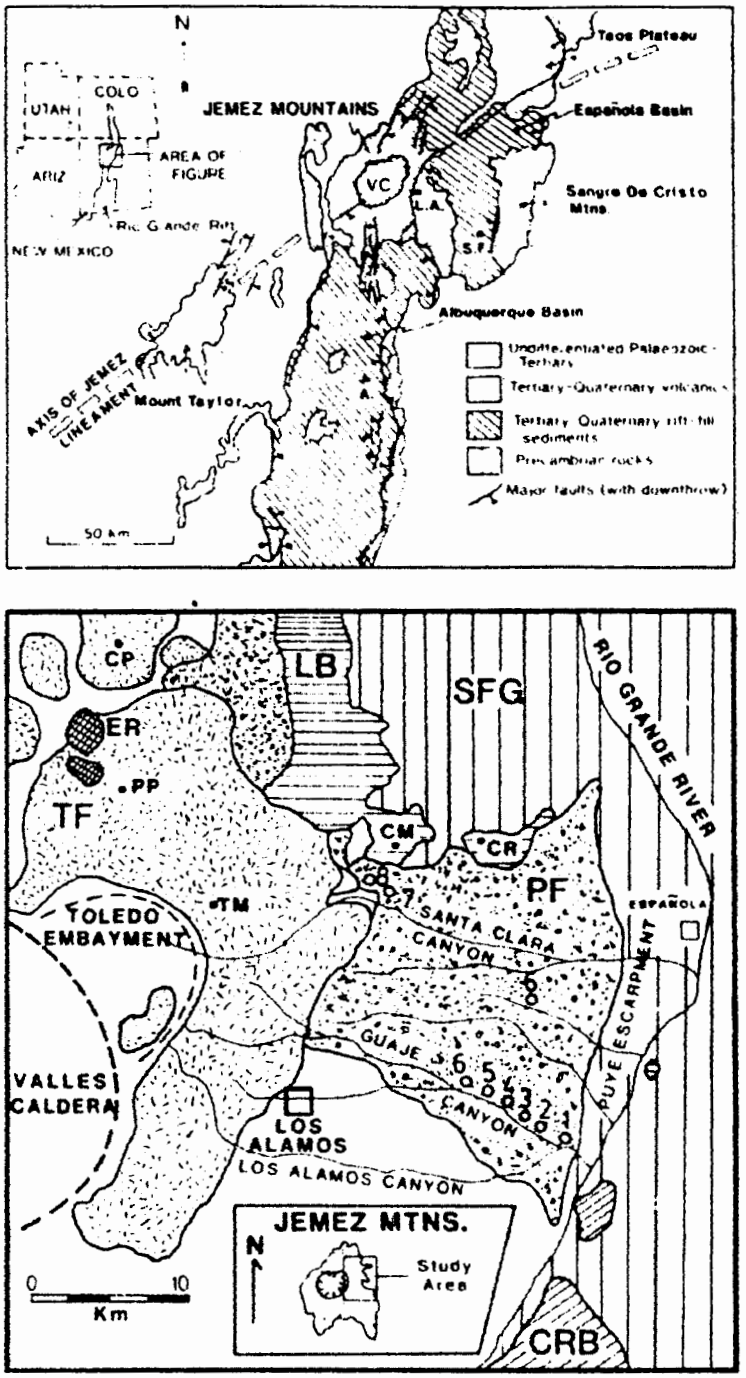


Fig. 1. Location map of the Jemez Mountains and Valles Calderas (*VC*), New Mexico (above), and the study area, eastern Pajarito Plateau (partly after Smith et al., 1970). Shown are surface extent of the Tschicoma Formation (*TF*), El Rechuelos Rhyolite domes (*ER*), the Puye Formation (*PF*), Loboto Basalt (*LB*), Cerros del Rio basalt field (*CRB*), and Santa Fe Group deposits (*SFG*). Also included are prominent local topographic features, Cerro Pelon (*CP*), Polvadera Peak (*PP*), Tschicoma (also Chicoma) Mtn. (*TM*), Cerros Mtn. (*CM*) and Clara Peak (*CR*); location numbers refer to composite sections in Fig. 5.

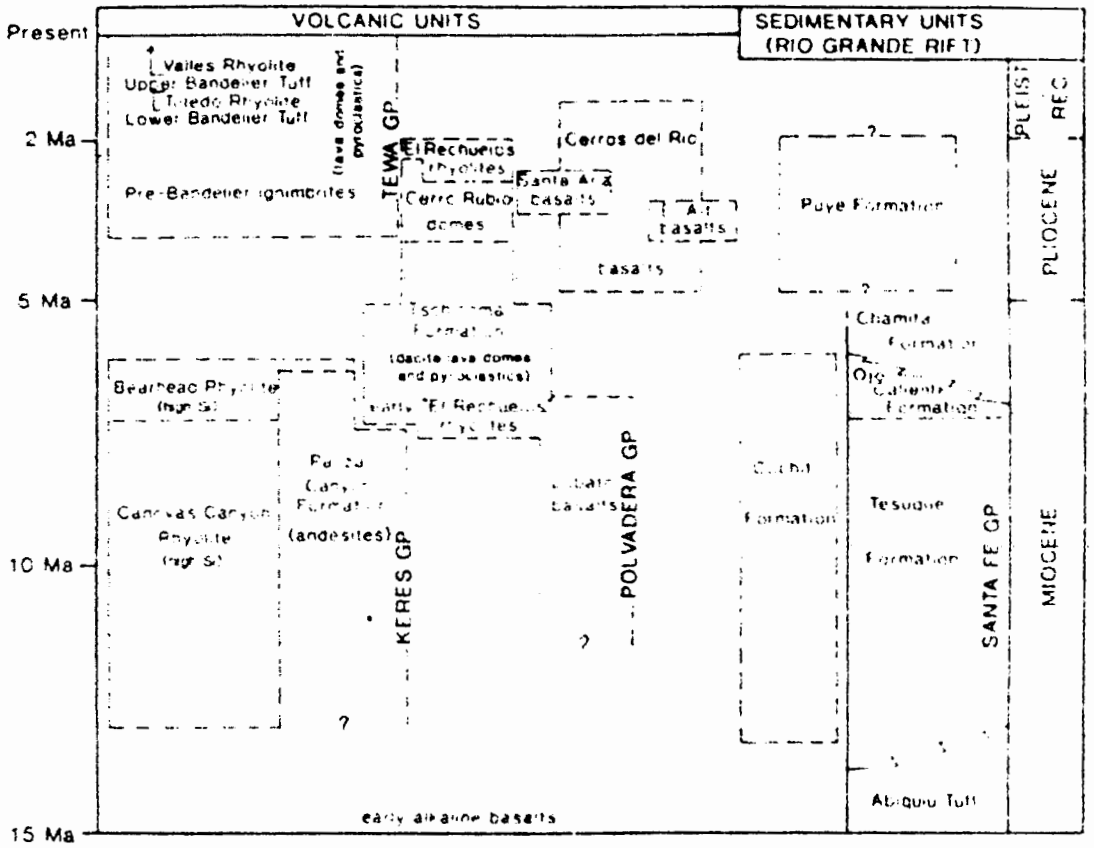


Fig. 2. Stratigraphy of major volcanic units of the Jemez Mountains volcanic field and associated sedimentary sequences of the Española basin, central Rio Grande rift (after Self et al., 1986)

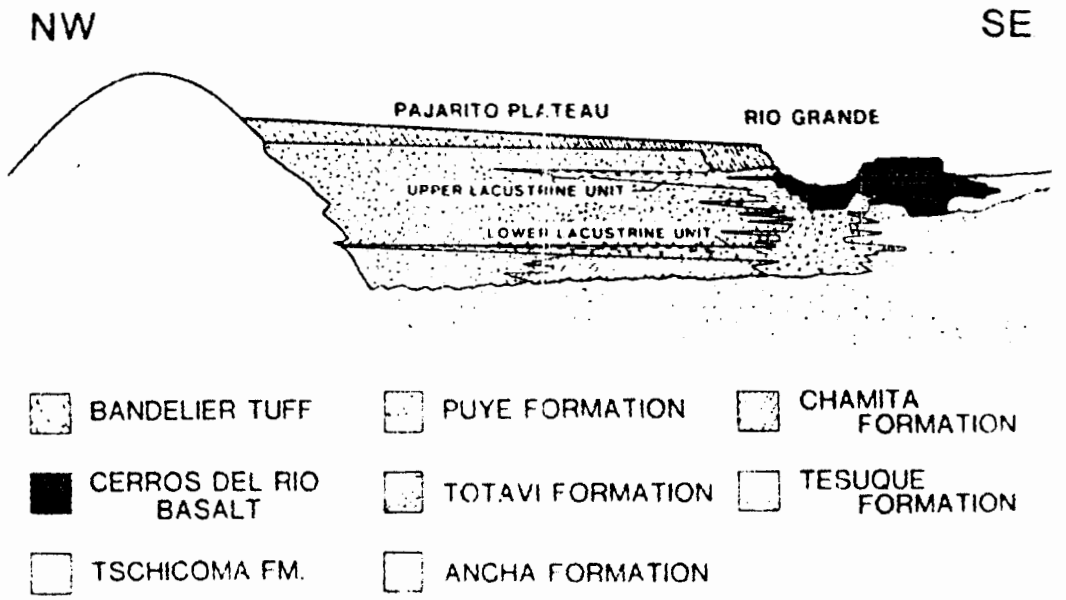


Fig. 3. Schematic cross section of the Pajarito Plateau, eastern Jemez Mountains, showing relationships between the Puye alluvial fan, the Tschicoma Formation volcanic pile (to the west) and Santa Fe Group sediments and Cerros del Rio basalts (to the east and southeast); note especially the interfingering between Puye fanglomerate deposits and lacustrine fluvial sediments of the Totavi Formation (ancestral Rio Grande) deposits. (After Waresback, 1986.)

TABLE 1

Whole-rock compositions of representative Puye Formation pumices and a Tschicoma Formation dacite lava flow

	Lower Group		Middle Group	Upper Rhyolite	Tschicoma Dacite*
	P2	P4	Puye Ignimb.	G22	(5 Ma)
Major elements (wt %)					
SiO_2	66.48	66.35	65.61	72.95	67.21
TiO_2	0.43	0.44	0.44	0.09	0.51
Al_2O_3	15.14	15.36	15.69	11.73	15.28
Fe_2O_3*	3.49	3.51	3.45	1.55	3.68
MnO	0.06	0.06	0.05	0.06	0.06
MgO	1.61	1.71	1.48	0.26	1.69
CaO	3.35	3.42	3.40	0.33	3.40
Na_2O	4.01	3.45	4.20	3.14	3.90
K_2O	3.72	3.90	3.80	5.24	3.18
P_2O_5	0.16	0.16	0.17	0.01	0.14
L.O.I	1.60	1.50	1.70	4.62	1.46
Total	100.05	99.96	99.99	99.77	100.51
Trace elements (in ppm)					
Sc	6.9	6.46	5.5	2.2	5.1
Cr	36	31	34	0.6	22
Rb	60	66	90	153	79
Cs	0.86	0.94	2.32	3.68	1.4
Ba	1200	1200	995	100	1180
La	33.3	33.5	36.4	48.8	44.1
Ce	64.2	65.3	62.1	95.4	54
Sm	4.4	4.5	3.45	7.06	4.4
Eu	1.1	1.1	0.91	0.13	1.0
Th	0.46	0.50	0.42	1.17	—
Yb	1.34	1.37	1.32	4.16	1.5
Lu	0.20	0.20	0.22	0.64	—
Hf	4.5	4.7	4.0	7.6	3.5
Ta	0.74	0.77	1.21	4.62	—
Th	4.37	4.58	8.22	18.70	7.5

Major elements by XRF, trace elements by INAA; see Turbeville (1986) for analytical methods and quality of data.
*Total iron as Fe_2O_3 from analysis.
*Chemical data from Gardner et al. (1986)

sion and caldera collapse) survives exclusively in the Puye Formation.

The Puye Formation

The Puye Formation (Griggs, 1964; Manley, 1976, 1979; Waresback and Turbeville, in press) is the exposed upper part of a thick volcaniclastic sequence emplaced contemporaneously with the Pliocene development of the Tschicoma volcanic center. The Puye Formation contains > 15 km^3 of Plio-Pleistocene alluvial sediments derived mainly from lava domes in the north-

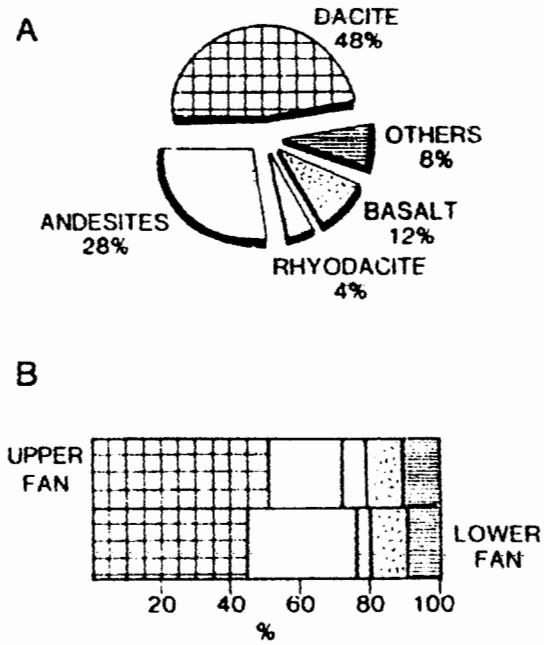


Fig 4. A. Approximate volume percentages of rock types found as epiclasts (see Table 2) in Puye fanglomerates (values derived from representative counts of clasts > 10 mm; $n = 200$ per deposit.
B. Variations in the percentage of these clast types between the lower and upper portions of the medial fan facies of the Puye Formation (see Figs. 5, 6).

eastern part of the Tschicoma center (Figs. 1, 3). This alluvial fan records a history of explosive activity that produced abundant dacitic to rhyodacitic tephra (Table 1) during the later development of the Tschicoma center (3.5–1.9 Ma; Gardner et al., 1986; Turbeville, 1986). The well-exposed parts of the fan show medial to distal volcanogenic fanglomeratic facies with abundant epiclastic material emplaced as subaerial mass flows and hyperconcentrated flood flows (c.f., Smith, 1986), stream channel deposits, and sheetflood conglomerates. These sediments are interbedded with primary and redeposited pyroclastic deposits and, to a lesser extent, areally extensive mafic lava flows and associated breccias. In addition, lacustrine deposits (including abundant water-lain felsic and basaltic tephra) are volumetrically significant in distal parts of the fan.

Explosive eruptions that accompanied the

TABLE 2

Puye Formation epiclastic rock types (classification based on modal mineralogies)

Epiclast	Lithic type	Salient features
I	Porph. gray dacite	Large plag. glomerocrysts and qtz with hb-bi-cpx-opx in an interstitial matrix of subparallel plag. microlites in dark gray glass.
II	Porph. red dacite	Similar to type I except much larger phenocrysts and distinctly lineated fabric; qtz. rare, hbl replaced by Fe oxides.
III	Porph. light gray dacite	Equigranular pl-qtz-cpx-opx-hb-bi-phen. in a matrix of stubby, randomly oriented plag. laths (orthophyric); glomerocrysts rare.
IV	Flow banded andesite	Alternating bands of glassy, microlite-poor and -denser, microlitic-seriate lava; plag. and Fe oxides in parallel fabric; equant cpx within cpx crystals.
V	Porph. pink dacite	Strongly embayed plag. megacrysts (up to 6 mm) in dense groundmass of fragmental microlites and glass; abund. bi-hb-px-mt macrolites; nonstriate matrix.
VI	Sl. porph. gray rhyodacite	Plag. megacrysts (up to 6 mm) with qtz in very dense matrix of lath-shaped plag., altered cpx and Fe oxides; groundmass strongly spherulitic.
VII	Gray to black porph. basalt	Plag. megacrysts (up to 14 mm) with equant cpx-olivine microphen. in matrix of stubby pl-cpx-opx-mt microlites in glass; pl-plag. intergrowths common.
VIII	Gray perlitic 2-px andesite	Fibrous-flowbanded (pyroclastic-like) texture; spherulitically devitrified groundmass; lacks plag.; abund. "andesite" laths and large (< 2 mm) isolated Fe oxide phenocrysts.
IX	Light gray hbl. andesite	Unusual orthophyric texture with stumpy plag. laths and by-bi-hbl in spherulitically devitrified (microbrecciated) groundmass; large green biotite crystals are conspicuous.
X	Red banded dacite	Similar to types I and II except for distinctive color banding and occurrence of large biotite crystals in dark red-brown groundmass.
XI	Porph. gray dacite	Pyroclastic-like groundmass; wavy shard-like features outline a weak flow banding; tan-brown devitrified matrix exhibits "stretched skin" appearance.
XII	Volcanic breccia	Individual basaltic clasts (< 30 cm diam.) in hydrothermally altered and banded gray-brown groundmass; unusual skeletal aggregates of bladed augite.
XIII	Fine-grained basalt	Distinctive flow texture in parted by plag. microlites; plag. phenocrysts strongly embayed; of px-mt macrolites in brown, glassy groundmass; high crystal-glass ratio.
XIV	Gray 2-px andesite	Large plag. glomerocrysts and subophitic augite in gray-brown glassy groundmass with few plag. microlites.
XV	Tan-brown hbl-bi dacite	Large plag. glomerocrysts in dense, oriented interstitial microlite groundmass; large (< 1 cm) hbl crystals and qtz macrophenocrysts.
XVI	Gray hbl-bi andesite	Large plag. phenocrysts with by-bi-hbl in randomly oriented microlitic matrix; mt-px-qt microphen. in radiating or dendritic clusters.
XVII	Black porphyry	Latite-rhyodacite with plag. phen. rimmed by perthitic or granophyric overgrowths in weakly flow-banded, dark gray groundmass; K-feldspar anomalously abundant as large tabular crystals.
XVIII	Agglomerate	Flow-banded lava clasts in distinctly pumiceous, microbrecciated matrix; crystal and lithic fragments common.

growth of Tschicoma lava domes were probably instrumental in remobilizing large portions of talus-covered dome surfaces (c.f., Rose, 1987; Scott, 1987). Steep topography and sporadic (possibly episodic) flood frequency and runoff in this semi-arid region (Kelley, 1979; Dethier and Demsey, 1984) contributed to the apparently high erosion rates associated with the denudation of these domes, providing abundant epiclastic material to the growing fan. For this reason, we believe that the Puye alluvial fan adequately represents an inverted stratigraphic succession of Plio-Pleistocene lava dome development and erosion in the northeastern part of the Tschicoma center.

Puye Formation epiclastic deposits contain a highly variable suite of lava lithologies (Table 2; Fig. 4); this is in sharp contrast to the exposed rock types of the Tschicoma eruptives (Baldridge and Vanman, 1986). Unfortu-

nately, direct correlation of fan deposits with the currently denuded volcanic center is greatly inhibited by limited exposure in the area where lava flows and fan sediments intertinger. Similarity between available mineralogical and geochemical characteristics of Puye tephra and Tschicoma lavas, however, strongly supports the contemporaneity of these rocks (see below).

The Puye fan also contains basaltic ash derived from phreatomagmatic eruptions in the Cerros del Rio volcanic field of the central Rio Grande rift (Figs. 1, 2; Aubele, 1979; Fisher et al., 1984). The combined influences of contemporaneous volcanism from these two adjacent volcanic centers are reflected in the fan by the development of distinctive cyclical depositional sequences. In essence, the Tschicoma center steadily supplied large quantities of volcaniclastic material to the prograding fan, whereas volcanism in the Cerros field strongly influenced sedimentation from the eastern basin margin, by lake development and variations in local fluvial base levels.

Pyroclastic stratigraphy

Analysis and correlation of primary pyroclastic deposits in the Puye Formation (see below) suggest that several explosive eruptions from the Tschicoma center produced widespread tall blankets across the growing Puye fan. Localized preservation of these deposits depended on the rapid accumulation of a protective cover of epiclastic debris or additional pyroclastic material. The absence of coeval pyroclastic deposits beyond the limits of this alluvial system suggests that the surrounding environments were therefore not suitable for the preservation of tephra. Any tephra emplaced to the southwest of the Tschicoma center was obliterated, along with Tschicoma lava flows and domes, by later episodes of caldera collapse and infilling by intracaldera Bandelier ignimbrite (Nielson and Hulen, 1984).

Explosive eruptions and closely associated epiclastic sedimentation produced cyclical sequences of one or more pumice falls, often underlain by thin mudflow deposits and overlain by either ignimbrite or thick pumiceous mudflows (Fig. 5). These sequences reflect individual eruptive events and are separated by intereruptive debris flow and hyperconcentrated flood flow deposits (including volcanic mudflows), fluvial sediments (i.e. braided stream conglomerates), and deposits of sheetflood activity. The latter reflect high rates of aggrada-

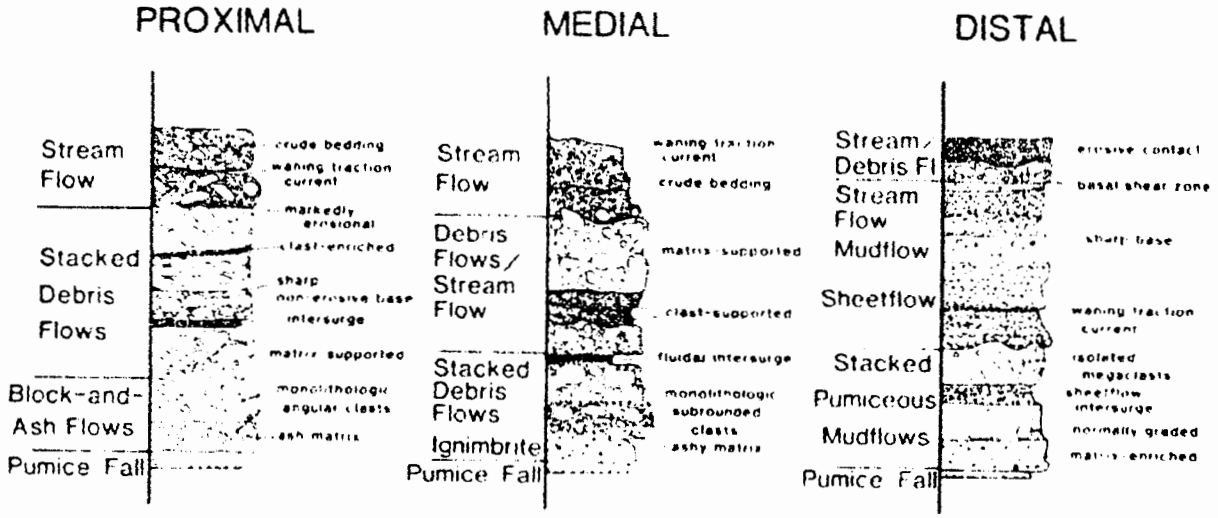


Fig. 5. Generalized depositional sequences related to individual explosive eruptions and inter-eruptional phases of sedimentation in proximal, medial, and distal Puye Formation exposures (see text for details).

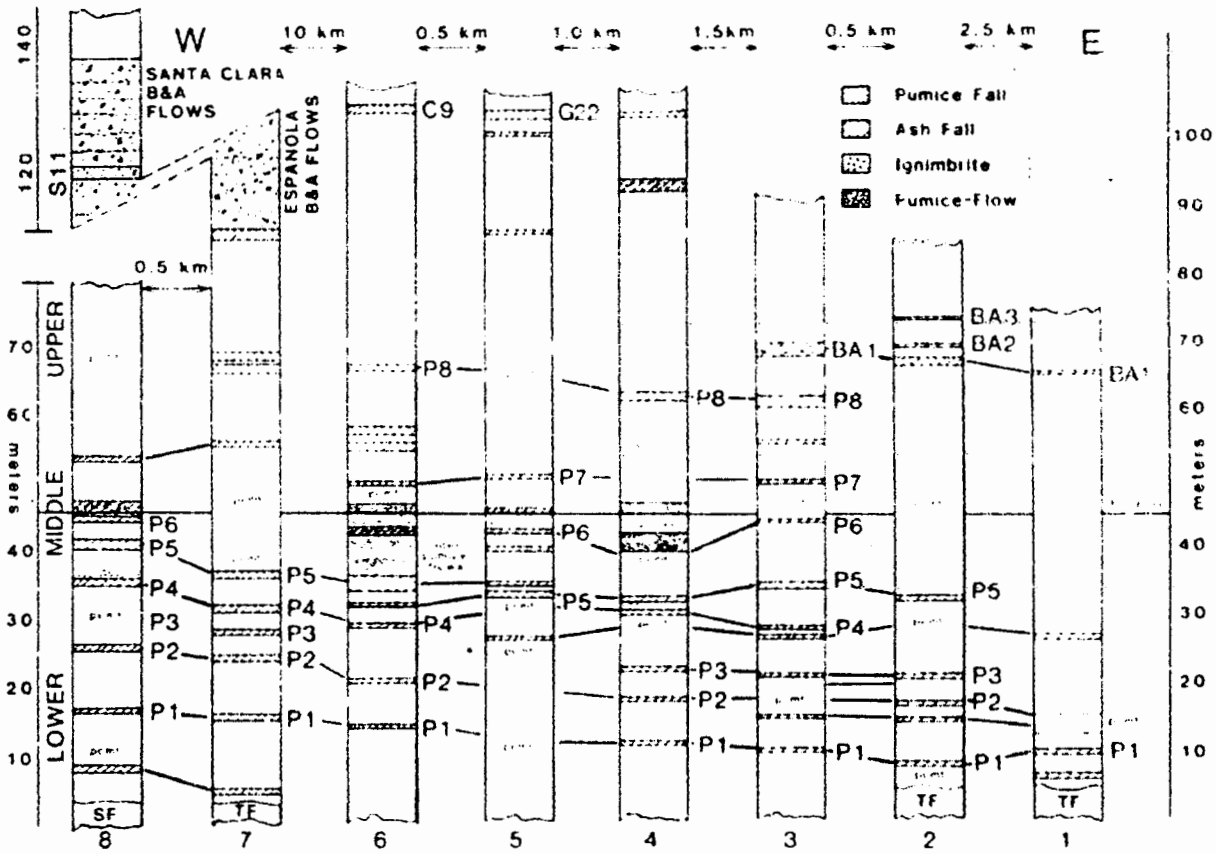


Fig. 6. Composite tephrostratigraphy of the Puye Formation showing lower, middle and upper tephra group deposits, prefix "P" indicates a fan-wide correlation (see text), other units are localized exposures confined to specific parts of the Puye fan (see Fig. 1 for section locations). Other designations are *G22* and *C9* = upper group rhyolite plinian deposits (see text), *BA* = basaltic ash deposits, pcmf = pumiceous mudflow deposits, *SF* = Santa Fe Group sediments, *TF* = Totavi Formation gravels. The Puye ignimbrite (2.53 ± 0.1 Ma) at approximately 45 m is a key stratigraphic marker horizon in the fan.

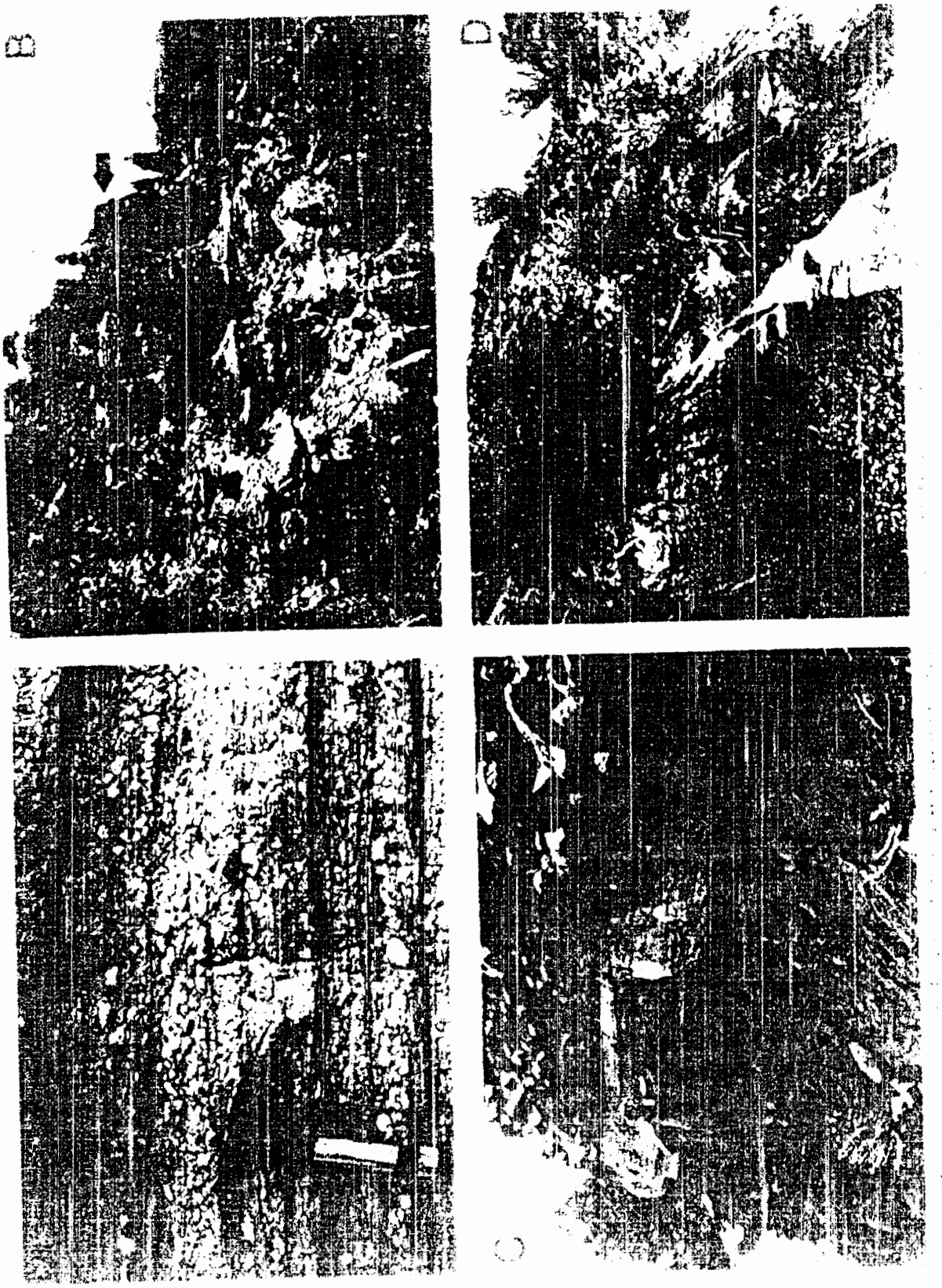
tion that did not permit significant incision by fan drainage and were commonly associated with the formation of shallow but widespread lakes.

Tephra deposits in the Puye Formation are informally divided into three stratigraphic groups according to distinctive changes in the dominant juvenile clast type, the environment of deposition, and suspected sources (Fig. 6).

The lower tephra group contains several widespread pumice fall deposits and thin ignimbrites, in addition to abundant redeposited tephra (Figs. 7A,B). These deposits contain light colored, fibrous, hornblende- and biotite-bearing rhyodacite pumice and lesser amounts of dark gray or banded two-pyroxene dacite pumice (Table 1).

A middle tephra group consists of a lithic-rich ignimbrite (informally called the "Puye ignimbrite", dated at 2.53 ± 0.1 Ma by K/Ar analysis of feldspar separates; Turbeville and Self, 1988) and coarse-grained pumice-flow deposits with large two-pyroxene dacite pumice blocks that lack biotite and hornblende. Associated with the ignimbrite sequence are several coarse, lithic-rich pumice falls and fine-grained capping ash falls (Fig. 8).

The upper tephra group contains several



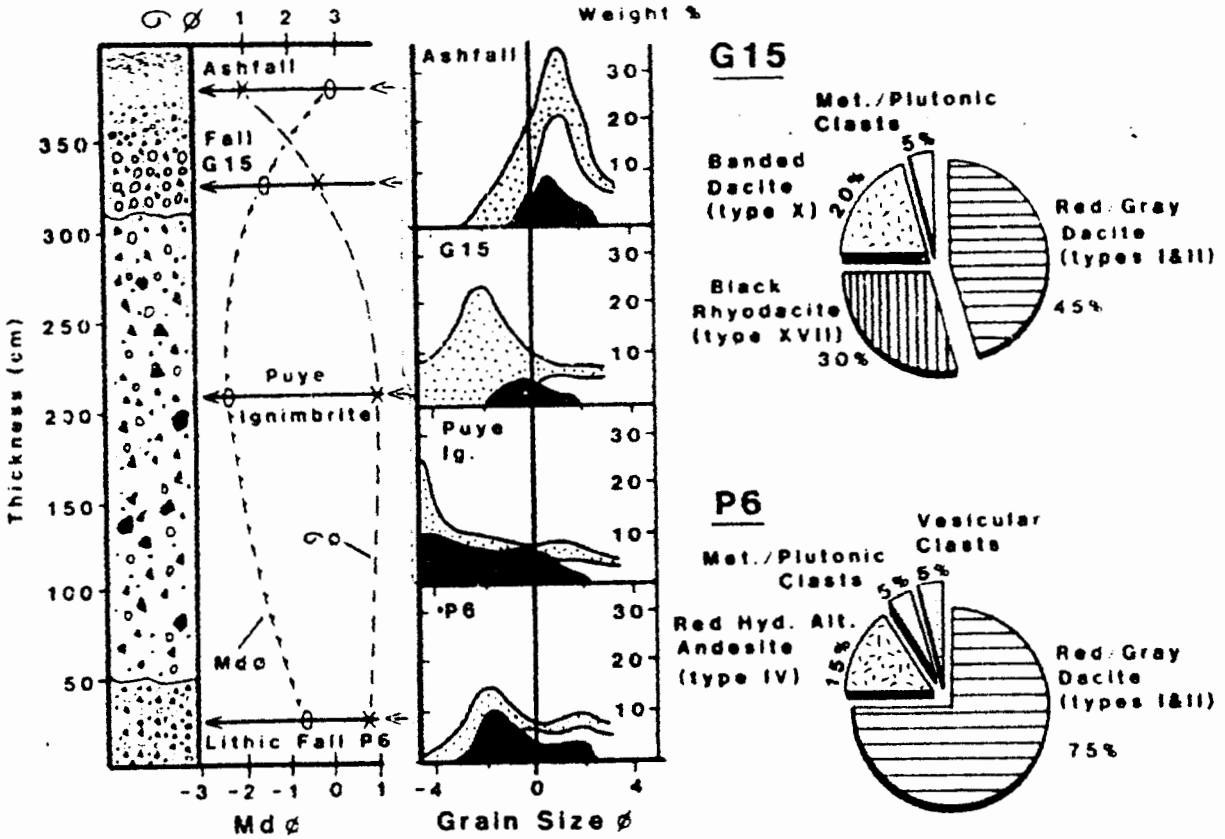


Fig. 8. Profile through the "Puye ignimbrite" and associated pumice and ash falls (Fig. 6) showing changes in median grain size (Mdø) and sorting of deposits (σø: values derived from cumulative frequency curves in the grain size range −4ø to 4ø), and frequency variation curves of individual component populations (pumice = stippled, lithics = shaded, crystals = unshaded). Samples taken from homogeneous (ungraded, massively bedded) portions of each unit. Shown at right are estimated percentages of accessory lithic types observed in pumice falls, P6 and G15 (lithic types refer to Table 2).

thick rhyodacitic pumice falls, abundant lake-deposited pumice and ash (Fig. 7C), and thick sequences of water-lain basaltic ash. Exposures of individual units are considerably more restricted than lower group deposits and differ markedly in mineralogy, lithic types, and grain-size characteristics. In addition, two rhyolite pumice falls in the upper part of the Puye fan (units G22 and C9, Figs. 6, 7D) differ significantly from other Puye tephra units in composition (Table 1), and are conjectured to have been derived from source vents currently buried beneath Valles II Caldera (Fig. 1). Only one exposure of each unit has been found, although it is apparent from deposit characteristics (see below) that they were once widespread plinian deposits.

Correlation of tephra units and deposit dispersal

Key stratigraphic tephra horizons were correlated (Turbeville, 1986) using a combination of mineralogical characteristics, distinctive lithic clasts, and trace element compositions of large pumice clasts. Correlation was impeded in many cases by a highly variable assemblage of juvenile clast types in individual deposits and by the often erratic lateral variability of individual tephra units due to localized reworking. The results of tephra unit correlation are presented schematically in Fig. 6.

Of the 25 primary felsic pyroclastic deposits exposed in the Puye Formation, eight pumice falls and two ignimbrites are recognized fan-

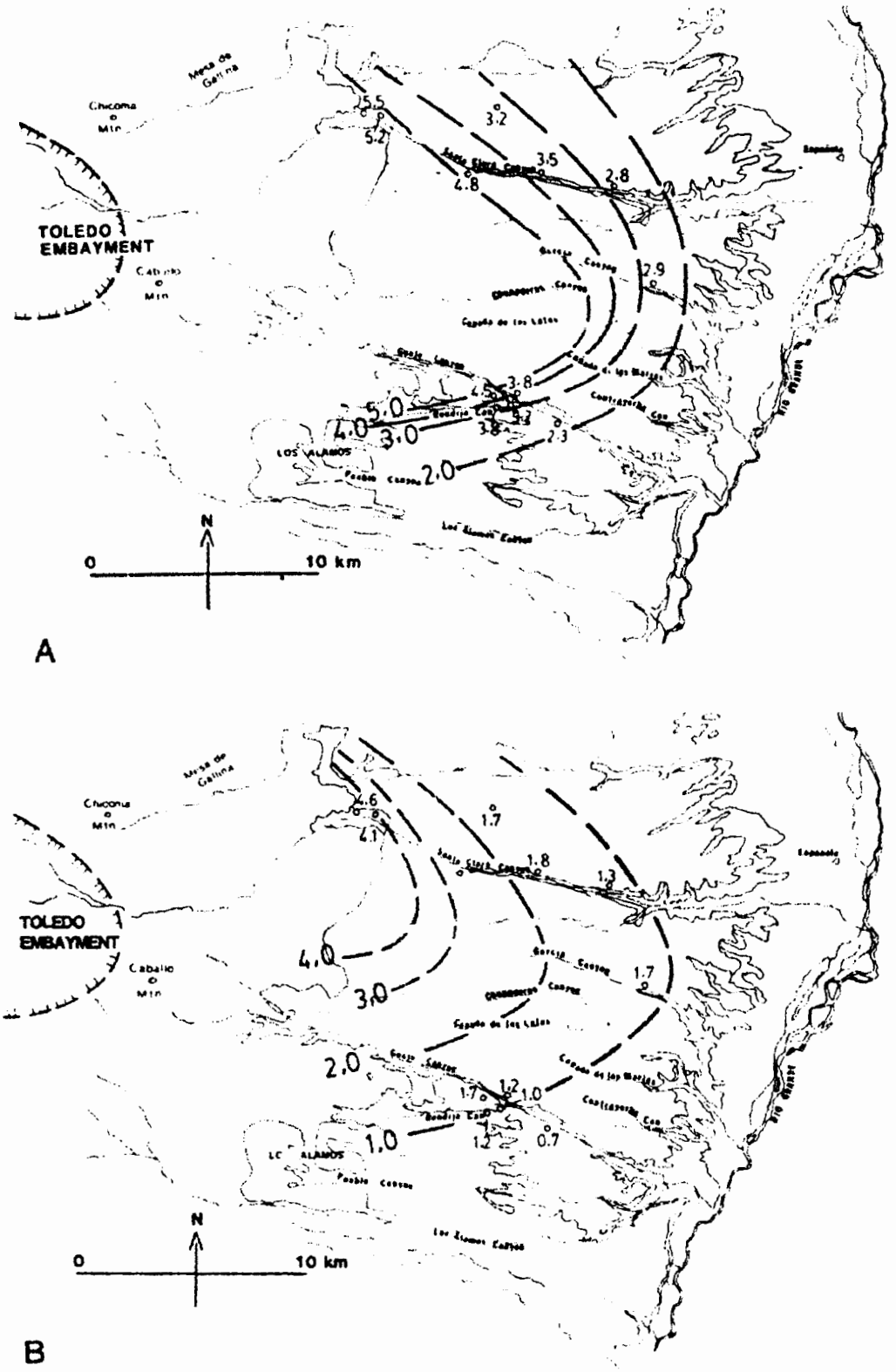


Fig. 9. Isopleth maps showing dispersal patterns of pumice fall P4 based on the maximum diameters (in cm) of pumice (A) and lithic (B) clasts; values shown are averages of the five largest clasts (long dimension) measured in outcrop.

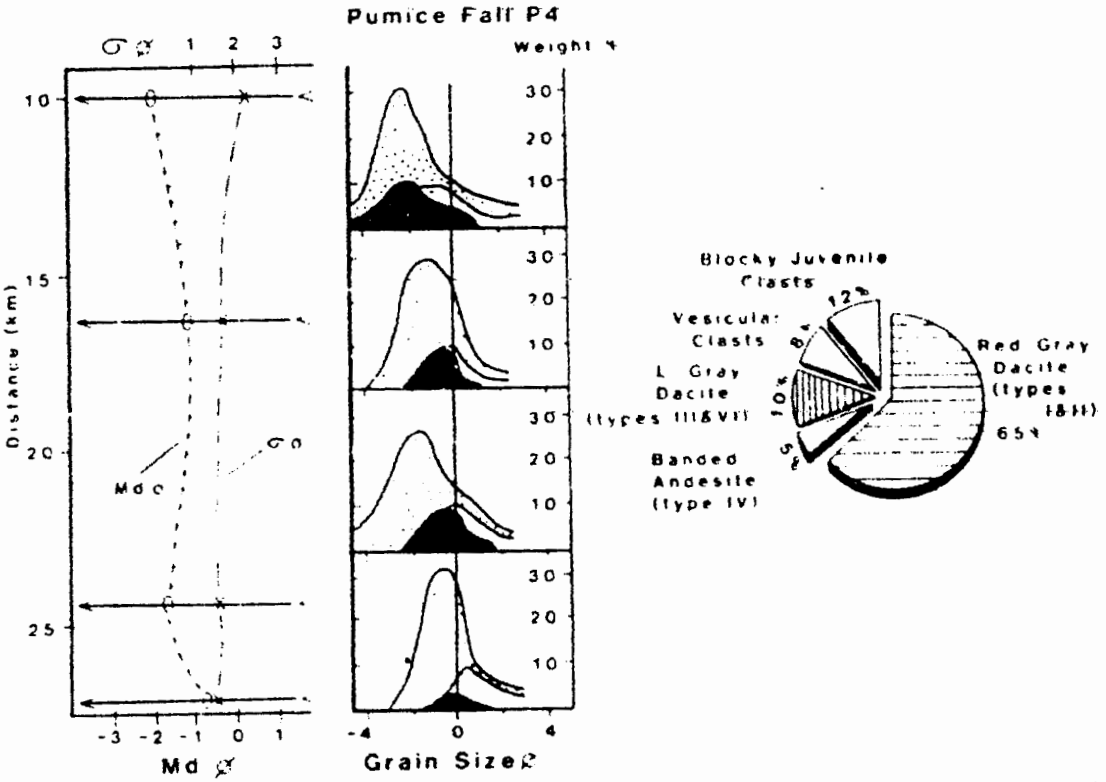


Fig. 10. Variation in grain size characteristics of pumice fall P4 (see Fig. 1) with distance from Tschicoma (Tschicoma Mountain arbitrarily selected, see Figs. 1, 9); shown are changes in median grain size (Md φ) and sorting (σφ) of deposits and frequency distributions of component populations (symbols as in Fig. 8). Diagram at right shows percentage of clast types (Table 2) observed as accessory lithics in unit P4.

wide. At least thirteen units that cannot be laterally correlated are exposed in the southern portion of the Puye fan (Fig. 1), two more in the eastern fan segments, and yet another two in the northern and proximal exposures (excluding two block-and-ash pyroclastic flow sequences; see below). In addition, pumice and ash constitute a significant proportion of many epiclastic deposits and lacustrine sediments (Fig. 7).

The limited exposure only permits approximations of deposit dispersals based on the distribution of maximum clast diameters (Fig. 9). The highly irregular thickness variations of most fall deposits altogether limit the usefulness of isopach maps. The contours for unit P4 (Figs. 6, 10) and other Puye falls display crude but consistent trends. There is a systematic east and southeast dispersal, also common to post-Puye JMVF tephra deposits (Wright et al., 1984b), consistent with probable source vents in the northeastern Tschicoma dome complex. Abundant accessory lithic clasts in these pumice falls (Table 2; Figs. 8, 10) closely resemble Tschicoma lavas exposed to the northwest (see below), whereas the Tschicoma deposits southwest of the fan (Fig. 1) are sufficiently different compositionally from Puye tephras (David Broxton, pers. commun., 1985) to exclude them as probable sources. Tephra dispersal patterns are also consistent with possible sources in the region of the Toledo Embayment. This depression, however, whether a caldera or landslide scar (Fraser Goff, pers. commun., 1985; Self et al., 1986), formed not later than 3.6 Ma (Gardner et al., 1986), at least 0.5 m.y. earlier than any currently dated, exposed Puye tephra.

The northwestern Puye fan exposures (Figs.

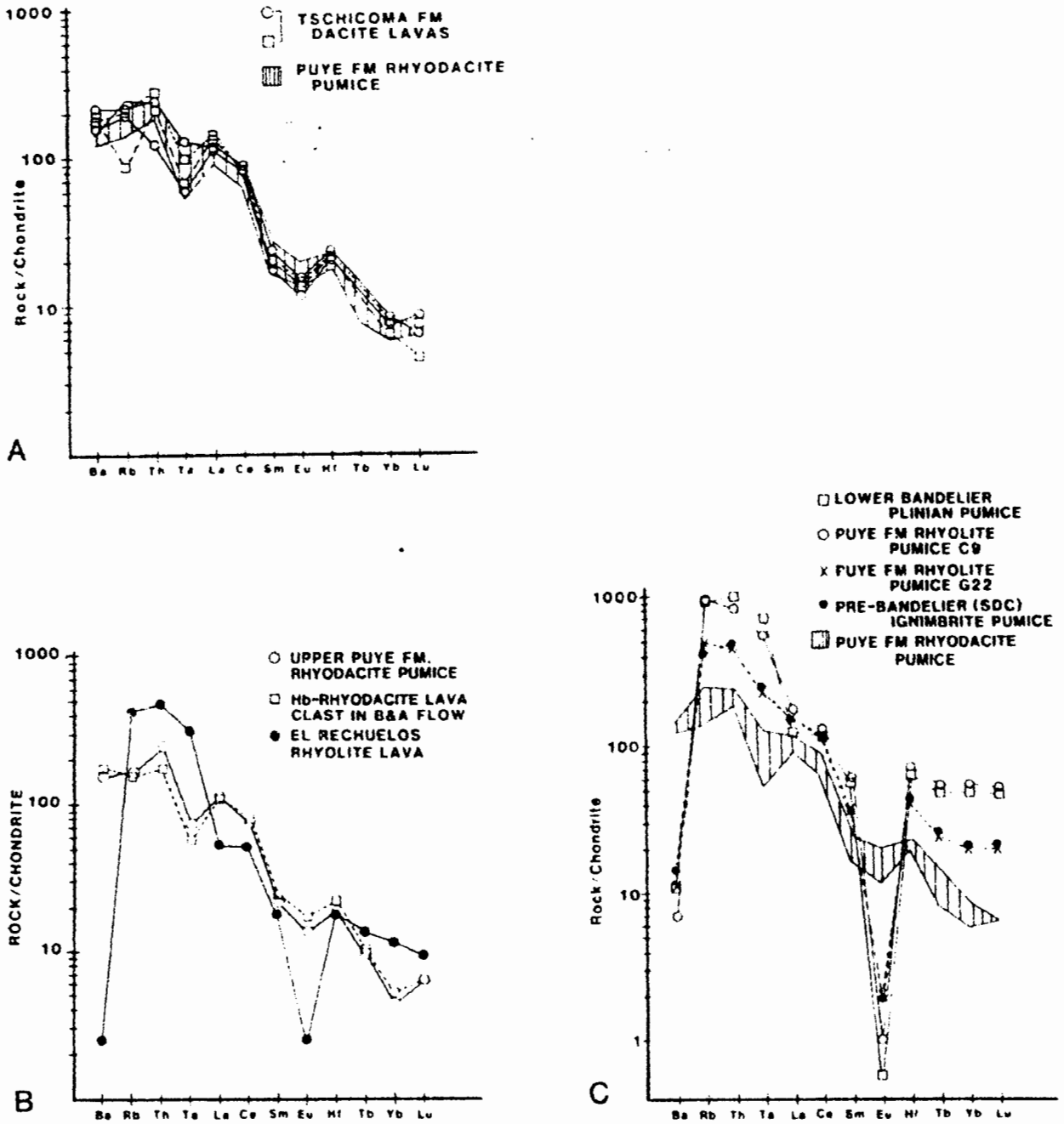


Fig. 11. Chondrite-normalized (Haskin et al., 1968; Thompson, 1982) trace-element diagrams comparing (A) Puye Formation rhyodacite pumices and Tschicoma Formation dacite lavas; (B) Puye Formation upper group rhyodacite pumice, rhyodacite lava blocks in proximal block-and-ash flows (see text), and El Rechuelos Rhyolite dome lava; and (C) Puye Formation rhyolite pumices (G22, C9; Fig. 6), Lower Bandelier plinian pumice, pumice from pre Bandelier (San Diego Canyon) ignimbrites, and range of Puye Formation rhyodacite pumices. Tschicoma and El Rechuelos Rhyolite data from Loeffler (1984) and Gardner et al. (1986).

1, 6) are clearly proximal. This is supported by the presence of (1) greater thicknesses and overall coarseness of pumice fall deposits, (2) thick accumulations of coarse, lithic-dominated pumiceous ignimbrites and ash-rich debris flow deposits, (3) a sequence of nearly monolithologic block-and-ash flow deposits in the upper part of the section, and (4) an overall paucity of sheetflood deposits that dominate inter-eruption sequences along the eastern and southern portions of the fan (Fig. 5; Waresback and Turbeville, in press). Puye deposits in this area also interfinger to some extent with surface exposures of Polvadera Group lavas and talus breccias, relationships elsewhere only detected in the subsurface (Griggs, 1964).

Andesite lavas in the Tschicoma center exhibit a felted plagioclase-pyroxene groundmass and phenocrysts of plagioclase, augite, hypersthene, and magnetite (Gardner et al., 1986). Dacite and rhyodacite lavas, on the other hand, are typically vitrophyric and contain the assemblage bi-hbl-qtz-cpx-opx-mt, minor apatite and zircon, and complexly zoned plagioclase glomerocrysts with pronounced disequilibrium (sieve) textures (Loeffler, 1984). Puye Formation rhyodacite pumice deposits exhibit petrographic features similar both to the older andesites and to the younger, more evolved Tschicoma lavas (Manley, 1976; Turbeville, 1986).

Figure 11 compares whole-rock trace-element compositions of several Puye Formation tephras with rock types common as Puye fall lithics (Table 2; Fig. 10) and with other JMVF eruptives of similar age. Puye Formation rhyodacite pumices (Fig. 11A) have similar compositions to Tschicoma dacite and rhyodacite lavas described by Loeffler (1984) and by Baldridge and Vaniman (1986). Hornblende-rhyodacite lava blocks in proximal block-and-ash flow deposits (see below) are similar, compositionally, to tephras of the upper group (Fig. 11B). Figure 11C shows close similarities between upper Puye Formation rhyolite pumice falls (622 and C9 (Fig. 6)) with pumice in Late Pliocene (pre-Bandelier) ignimbrites exposed southwest of Valles II Caldera (Turbeville and Self, 1988) and Lower Bandelier plinian pumice, respectively.

In summary, the Puye alluvial fan probably represents only a small proportion of the material that may conceivably have been erupted explosively from the Tschicoma and El Rechuelos domes, or from vents that were obliterated by collapse of the Valles calderas. It is difficult to estimate the volume of juvenile pyroclastic material preserved in the fan or the percentages of these tephras derived from individual lava domes. However, the primary deposits and recognizable eruption sequences suggest that a minimum of fifteen small (0.1–1.0 km³) explosive eruptions accompanied the growth of lava domes in the northeastern part of the Tschicoma volcanic center, in addition to two significant episodes of vulcanian activity probably associated with gravitational lava dome collapse. Also, at least three explosive eruptions possibly associated with the younger El Rechuelos Rhyolite domes (Loeffler et al., 1988) are represented, as well as two plinian deposits from sources now buried beneath Valles II Caldera. All of this activity occurred between about 3.5 and 1.9 Ma (Manley, 1976, 1979; Turbeville, 1986).

Characteristics of pyroclastic and associated deposits

Rhyolitic pumice falls and related deposits

Pumice fall deposits in the Puye fan vary from lithic-poor pumice and ash falls (Fig. 10) to crystal and lithic-dominated fall deposits with only subordinate amounts of pumice (e.g., Fig. 8, fall unit P6). These features are distinctive of falls produced by sub-plinian and vulcanian eruptions, respectively (e.g., Newhall and Melson, 1983; Heiken and Wohletz, 1985), and suggest that both types of eruption commonly accompanied the growth of Tschicoma lava domes. In addition, most Puye falls contain a

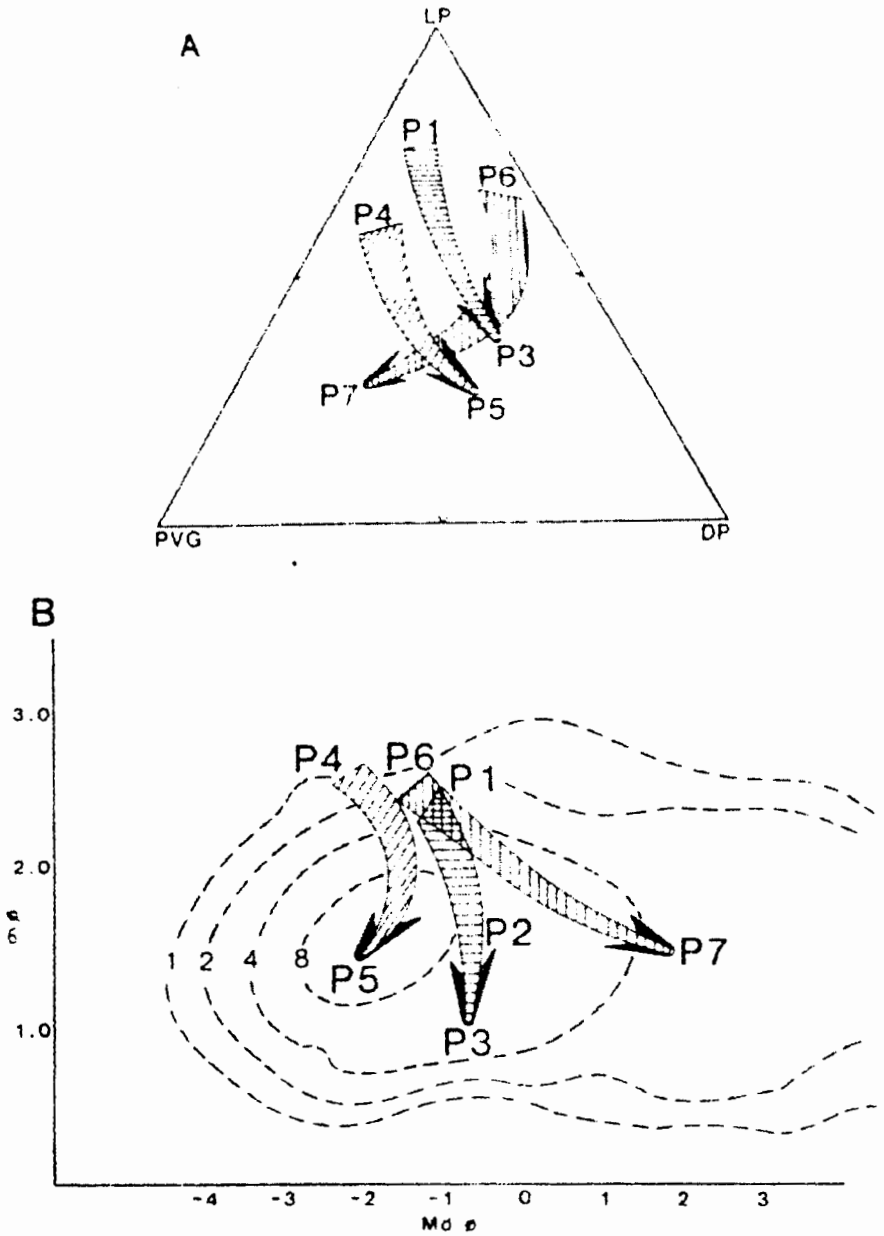
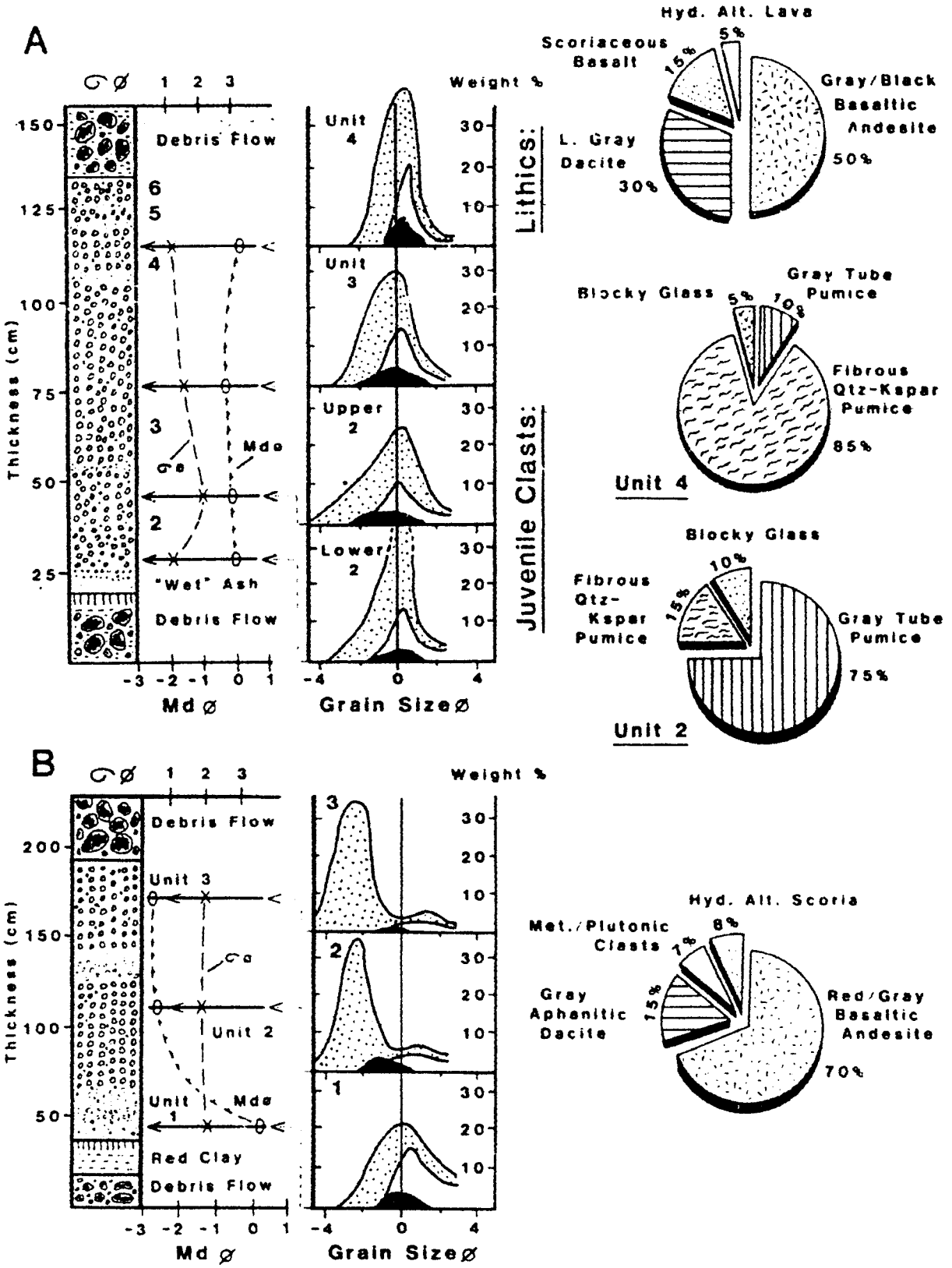


Fig. 12. A. Ternary proportions of light colored hornblende pumice (LP), dark gray 2 pyroxene pumice (DP), and aphyric, poorly vesicular (blocky) juvenile clasts (PVG) in eruption sequences P1–P3, P4–P5, and P6–P7 (see Fig. 6 and text for details); hatched fields include all samples analyzed from each sequence (n = 24).
B. Median grain size (Md φ) plotted against Inman's (1952) sorting parameter (σ φ) for the same tephra sequences as in A; contoured fields are Walker's (1971) percentages of pyroclastic fall deposits studied worldwide.

wide assortment of distinctive juvenile and accessory clast types (Table 2), and an overall trend is apparent stratigraphically. At least three consecutive sequences in the lower group contain pumice falls (P1, P4, P6; Fig. 6) overlain by ignimbrite. Each sequence exhibits either an upward increase in the proportion of dark gray or banded pumice in successive fall deposits or changes in the proportions of poorly vesicular juvenile material and pumiceous accessory clasts (Fig. 12A). The apparent cyclicity is also reflected by grain size data from ho


A
σØ
1 2 3
Debris Flow
6
5
4
3
2
"Wet" Ash
Debris Flow
Mdø
σø
Thickness (cm)
150
125
100
75
50
25
-3 -2 -1 0 1
Md ø
Weight %
Unit 4
Unit 3
Upper 2
Lower 2
30
20
10
-4 0 4
Grain Size ø
Lithics:
Juvenile Clasts:
Hyd. Alt. Lava
Scoriaceous Basalt
5%
15%
Gray/Black Basaltic Andesite
50%
L. Gray Dacite
30%
Blocky Glass
5%
Gray Tube Pumice
10%
Fibrous Qtz-Kspar Pumice
85%
Unit 4
Blocky Glass
10%
Fibrous Qtz-Kspar Pumice
15%
Gray Tube Pumice
75%
Unit 2
B
σØ
1 2 3
Debris Flow
Unit 3
σø
Unit 2
Unit 1
Mdø
Red Clay
Debris Flow
Thickness (cm)
200
150
100
50
-3 -2 -1 0 1
Md ø
Weight %
3
2
1
30
20
10
-4 0 4
Grain Size ø
Hyd. Alt. Scoria
Met./Plutonic Clasts
8%
1%
Gray Aphanitic Dacite
15%
Red/Gray Basaltic Andesite
70%

mogeneous (i.e. ungraded, massively bedded) parts of each fall unit (Fig. 12B). Pumice falls at the base of each sequence appear to be moderately well sorted and rich in crystals and highly vesicular hbl-bi-bearing pumice. Overlying units are progressively better sorted, especially P7 that also becomes much finer-grained and richer in non-vesicular glass.

These trends suggest successively higher water contents in eruption columns, that could have initiated premature deposition of finer-grained material and would have dramatically lowered eruption column heights (Walker, 1981; B. Houghton, pers. commun., 1988). Common transitions between phreatomagmatic and predominantly magmatic activity have been documented from dome eruptions elsewhere (Heiken and Wohletz, 1987). These data, however, do not support the suggestion that phreatomagmatic activity need always be precursory to magmatic eruptions from growing domes. In addition, if subsequent eruptions had tapped deeper, more volatile-poor magma, the resulting eruption plumes would also have been lower and less effective in dispersing coarse clasts (Carey and Sparks, 1986). Consequent column collapse or ash fountaining (Sparks and Wilson, 1976; Sparks et al., 1978; Horn, 1986) might be expected to have produced thin but widespread pyroclastic flows also rich in poorly vesicular juvenile glass and lava lithics.

Pumice deposits are more closely spaced toward the top of the lower tephra group, suggesting that explosive activity may have been accelerated during this period, culminating with emplacement of the Puye ignimbrite (Fig. 6). This possible increase in the frequency of eruptions is also reflected by associated epiclastic deposits: thick inter-eruption sequences of mudflows occur and sheetflood deposits, abundant in sequences below, become less apparent upward. Also, debris flow deposits become thicker upward in the fan and predominate over clast-poor mudflows. These trends reflect increases in source area relief and proximal fan slope and suggest an increase in the amount of coarse volcaniclastic material available to these flows. As blocky talus slopes are virtually ubiquitous features of volcanic domes (Williams, 1932; Rose, 1987), an increase in the frequency of explosive eruptions from Tschicoma domes must have greatly accelerated the movement of large volumes of poorly consolidated material, proximally represented by very coarse grained debris avalanches and block-and-ash pyroclastic flows, and distally by stacked, clast-supported debris flow deposits (Fig. 5).

Upper tephra group pumice falls are comparatively thick where preserved (1–2 m) in exposures up to 20 km from source. Deposits are frequently water-lain and reworked in distal exposures (Fig. 7C), suggesting an increase in fluvial activity and lake development along the fan toe as the Puye fan matured (Fig. 3). These falls contain a variety of cognate and accessory lithic types not observed in the lower group — obsidian, apatite-bearing banded pumice, and a wide assortment of highly porphyritic rhyodacitic clasts — and accompany an apparent upward increase in the proportions of quartz- and sanidine-phyric lava clasts in epiclastic sequences (Fig. 4B). Pumice lapilli in the airfalls also tend to be more aphyric, and the percentage of dark gray 2-pyroxene pumice evident in lower group deposits diminishes upward through the upper groups, as does the propor-

Fig. 13. A. Grain size-sorting profile through upper Puye Formation rhyolite pumice fall G2? (see Fig. 6); numbers at right of column refer to individual fall units (symbols as in Fig. 8). Diagrams at right give percentages of juvenile clast types in lower and upper fall units, and the overall proportions of accessory lithic types; note that there are no corresponding lithic clast types (i.e. Table 2) in Puye Formation tanglomeratic deposits.
B. Profile through upper Puye Formation rhyolite pumice fall C9 (Figs. 6, 7D) and percentages of clast types observed as accessory lithics. Lithic clast types from both G2? and C9 are similar to lava lithologies reported from the Paliza Canyon Formation exposed south and west of Valle-II Caldera (Gardner et al., 1986).

tion of blocky, glassy material. In addition, the deposits are generally lithic-poor and comparatively enriched in free crystals relative to units below. These features suggest marked changes in the nature of explosive eruptions, that probably accompanied changes in magma composition (and rheology) in the Tschicoma volcanic center (Baldridge and Vaniman, 1986), coincident with extrusion of the El Rechuelos Rhyolite domes (Loeffler et al., 1988). Silicic tephra deposits in the Puye Formation persist upward to the Pleistocene erosion surface (Fig. 3), considered by Waresback (1986) to represent only minor escarpment retreat prior to emplacement of the Lower Bandelier Tuff approximately 1.45 Ma.

Several basaltic phreatomagmatic eruptions occurred during the deposition of an upper Puye lacustrine sequence (Figs. 3, 6; also "Culebra" lake clay of Kelley, 1956). These units interfinger with Puye fluvial gravels and lake sediments in the southern portion of the fan, and reflect the close association of Tschicoma-Puye sedimentation and phreatomagmatic activity in the Cerros del Rio volcanic field (Fisher et al., 1984). Coarse debris flow deposits dominate the upper Puye Formation in medial and distal fan segments and are everywhere associated with pumiceous fluvial and lacustrine deposits (Waresback and Turbeville, in press), again suggesting the importance of mass flow processes (along with Cerros del Rio basaltic eruptions) in influencing local drainage patterns. Many of the mudflows and debris flows were emplaced subaqueously (Waresback, 1986) and can be traced upfan to laterally equivalent proximal block-and-ash sequences.

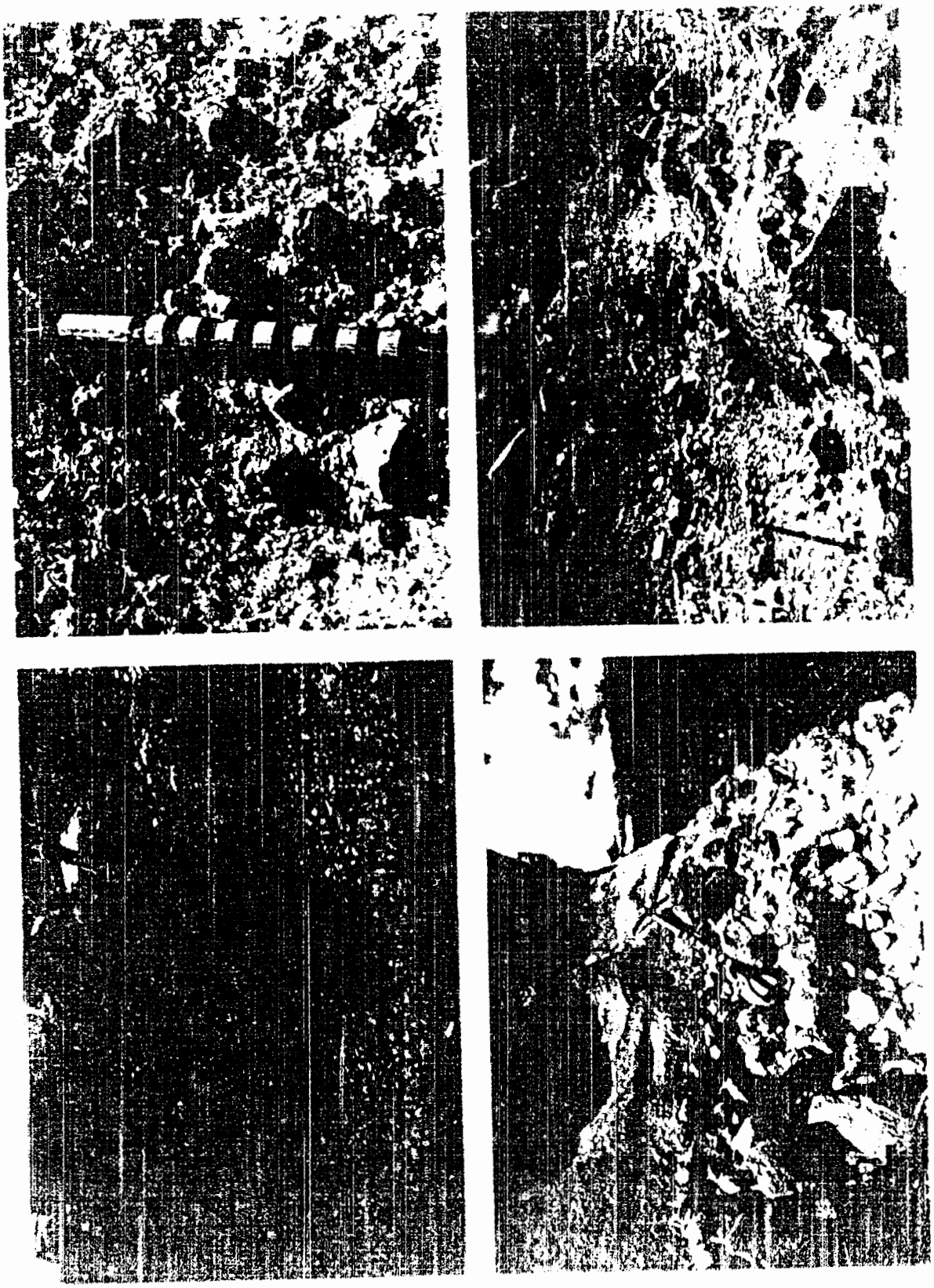
Rhyolite pumice falls

Rhyolite pumice falls occur in two areas at the top of the Puye fan and are both overlain by 2-4 m of epiclastic material (units G22 and C9, Fig. 6). These are distinct from other Puye tephras, although the limited exposure of each renders their correlation difficult. Unit G22 is 120 cm thick and consists of six fall units, each separated by 0.5-3.0 cm of very fine, crystal-rich ash (Fig. 13A). This deposit contains distinctive aphyric tube (capillary) pumice with vesicles of aspect ratio > 100:1. This juvenile clast type has only been observed elsewhere in the pre-Bandelier San Diego Canyon ignimbrites on the southwestern margin of Valles II Caldera (Turbeville and Self, in press).

Capping the Puye Formation in the central portion of the fan is a second unit (C9, Figs. 6, 7D), a 250-cm-thick rhyolite pumice fall resting on a distinctive reddish clay horizon. Silky white, sanidine-phyric pumice in this deposit is chemically and morphologically indistinguishable from pumice of the Lower Bandelier (Guaje) plinian deposits (Fig. 11C) that overlie the Puye Formation in this area. Unit C9 is distinguished from the Guaje pumice fall by a high matrix clay content, absence of associated ignimbrite, overall finer grain size and better sorting, and an anomalously crystal-enriched lower fall unit (Fig. 13B). The absence of tube pumice and chemical dissimilarities distinguish the unit from pumice fall G22 (Fig. 11C), although both units suggest contemporaneity between eruptions from the Tschicoma/El Rechuelos domes and rhyolitic ignimbrite-forming events in the central JMVF (Turbeville and Self, 1988).

Ignimbrites and block and ash flow deposits

Two thin ignimbrites (Fig. 6) in the lower tephra group occur between coarse-grained, lithic rich pumice falls and are composed predominantly of gray 2-pyroxene pumice. The ignimbrites each consist of a relatively homogeneous main flow unit and several finely stratified, fine- to coarse-grained pumiceous layers that vary from lithic-rich to lithic-poor and exhibit slight pinch-and-swell features, often with thin intervening ash layers (Fig. 14A). These ignimbrites are similar to deposits attributed to pyroclastic flows traveling in highly fluidized or



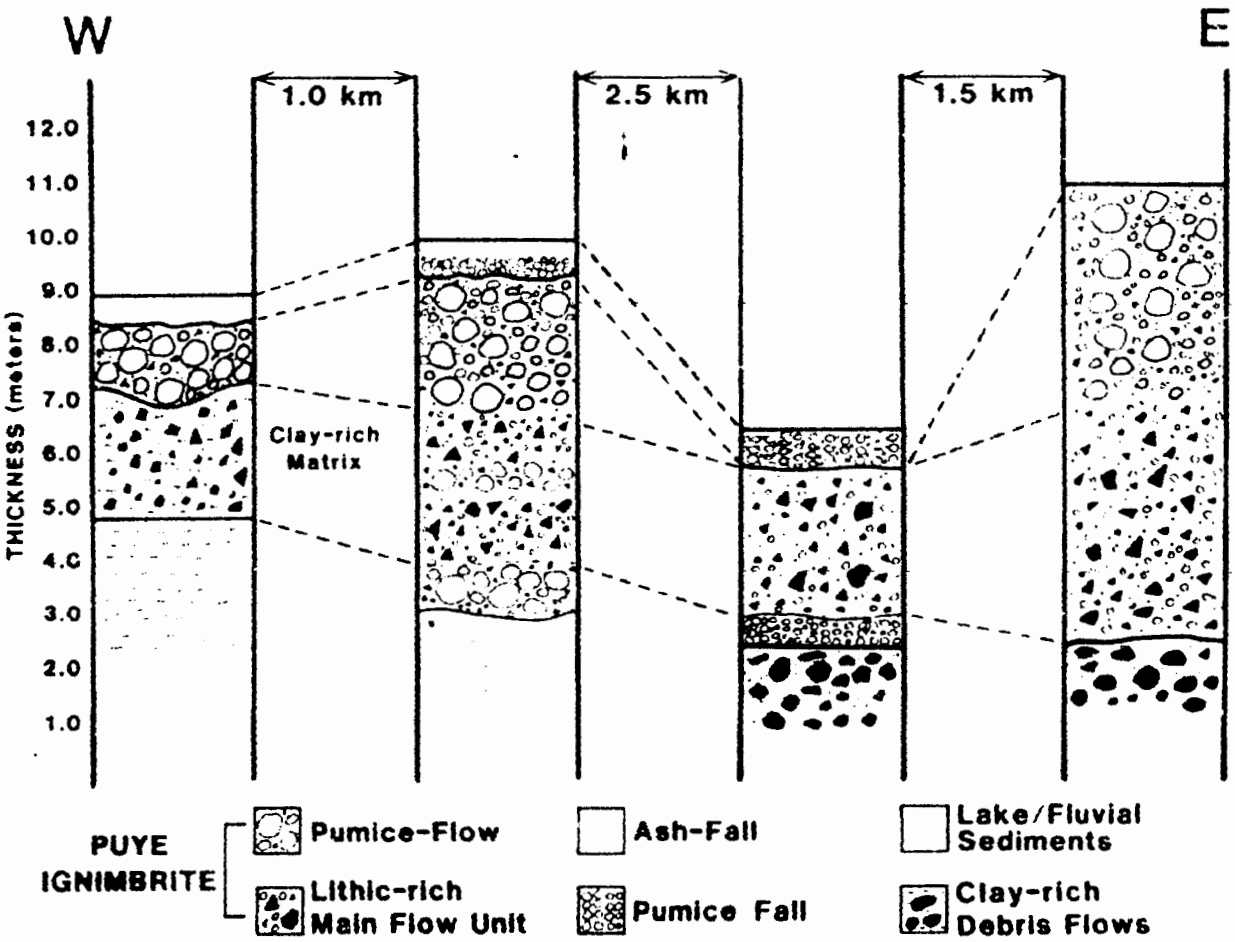


Fig. 15. Facies variations of the Puye ignimbrite (see also Fig. 8), note especially the lateral variability of associated pumice flows and fall deposits, and westward transition of main flow unit due to subaqueous emplacement. Clast sizes not to scale.

highly energetic flow regimes ("low-aspect ratio ignimbrites" of Walker et al., 1980; Walker, 1983; Wilson, 1984). Both units exhibit considerable lateral variability within relatively short distances, and in proximal exposures are much coarser-grained, massively bedded, and more lithic-rich than distal equivalents.

The Puye ignimbrite of the middle group also exhibits considerable lateral variability yet is consistently represented in different exposures by a 2–5-m-thick, very lithic-rich main flow unit (Fig. 15). Underlying deposits vary from coarse, lithic-rich basal pumice falls (Fig. 8) to very coarse, clast-supported pumice-flow deposits. The main flow unit is non-welded and contains a variety of large (>40 cm diam.), angular to sub-angular lithic clasts of Tschicoma Formation andesite and dacite lavas (Fig. 14B) with small rounded pumices in a matrix of pink ash. This unit has a sharp basal contact with underlying pumice deposits, but a gradational upper contact with the overlying pumice flows. The entire sequence attains a maximum thickness of about 10 m in channels (Fig. 15). The Puye pumice flows, and a thick sequence of largely reworked, coarse-grained pumiceous deposits immediately below the ignimbrite ("older pumice-flows", Fig. 6), vary from matrix-supported to pumiceous clast-supported and contain large (up to 70 cm diam.), well-rounded, breadcrust-like pumice blocks (Fig. 14C) in exposures 15–20 km from source.

Two thick block-and-ash flow sequences occur in the proximal upper Puye Formation (Figs. 5, 6). These sequences are informally designated the Española and Santa Clara block-and-ash deposits. They differ in appearance and deposit characteristics. The Española sequence is >15 m thick and consists of at least six flow units distinguished by symmetrical and reverse grading of large, subangular lava clasts. All units are non-welded, but strongly lithified, and grade laterally and vertically to very coarse, polylithologic debris flow deposits with predominantly red and gray porphyritic dacite boulders (some >3 m diam.) in an indurated pink ash matrix.

The overlying Santa Clara sequence contains 13.5 m of white, almost monolithologic block-and-ash deposits with six units separated by thin layers of fluvially reworked ash. These deposits are distinguished from the underlying Española sequence by the poorly consolidated nature of the former, the overall white color, a monolithologic hornblende rhyodacite boulder assemblage (see Fig. 11B), and a comparatively high ratio of matrix ash to subrounded blocks (Fig. 14D). The fluvially reworked ash layers do not contain abundant detrital material, suggesting fairly rapid emplacement of successive flow units.

Discussion: eruptions from lava domes and evolution of the Puye Fan

Most Puye Formation eruption sequences suggest transitions between phreatomagmatic and predominantly magmatic (subplinian and plinian) activity, similar to lava dome eruptions documented elsewhere (Heiken and Wohletz, 1987). Pumice falls of the lower group rarely exceed 2 m thickness (even in proximal exposures), and commonly exhibit highly erratic variability in grain size, sorting and deposit grading, suggesting fallout from low, rapidly fluctuating eruption columns rather than from sustained plumes. Fall deposits are generally poorly sorted particularly in basal fall units, attesting to the premature flushing of ash from water-rich columns. These units also contain abundant poorly vesicular juvenile material possibly formed by quenching of magmas prior to vesiculation. Phenocrysts typically display evidence of incomplete disaggregation from host pumice glass, and liberated crystals often have a large percentage of glass adhering to their surfaces, suggesting inefficient magmatic fragmentation and possibly less explosive eruptions (Meyer, 1972). Highly porphyritic cognate lithics, varying from dense to moderately vesicular, are abundant in most Puye falls (Table 2) and resemble "carapace"-like material described from volcanic domes and obsidian lava flows (Fink and Manley, 1987; Heiken and Wohletz, 1987). Similar clasts are also abundant in ignimbrites produced by these eruptions.

The coarse-grained Puye Formation pumice-flows, dense block-and-ash pyroclastic flows, and relatively thin, lithic rich and well stratified ignimbrites (Fig. 14) further suggest that vulcanian and subplinian eruptions were precursory to and accompanied the growth and possible episodic collapse of portions of Tschicoma lava domes or oversteepened lava flows (c.f., Rose et al., 1976; Nairn and Self, 1978; Wright et al., 1984a). However, several of the upper tephra group deposits may have been produced by more violently explosive eruptions, approaching the dispersal characteristics of plinian activity (Walker, 1981), and the upper group rhyolite pumice falls (C9 and G22) are almost certainly of plinian type. The presence of multiple fall units of even thickness and the paucity of poorly vesicular juvenile clasts in these thicker rhyolitic fall deposits attest to this probability. Unfortunately the limited exposure of these units and the highly unsystematic variations in thickness of most Puye tephra deposits do not permit a precise estimate of either the dispersal area (D) or fragmentation index (F) of Walker (1973).

The earliest explosive activity represented in the Puye fan is shown by several coarse grained rhyodacite pumice falls and thin pumiceous

mudflow deposits. These debris-laden mudflows apparently dammed the axial drainage at the fan toe, forming a widespread lake (Fig. 3) into which abundant tephra accumulated (Fig. 7a). Stacked pumiceous mudflows form a prominent 2–5 m thick apron around the perimeter of the Puye fan at this horizon (Fig. 6) and are correlative upfan with thick sequences of interbedded pumiceous sheetflood and braided stream conglomerates. Several explosive eruptions are recorded in the lower 45–50 m of the fan, each sequence consisting of two or more pumice falls, thin ignimbrites, and highly pumiceous mudflow deposits that represent laterally remobilized portions of primary tephra units. These sequences are separated by several meters of sands, gravels, and conglomerates deposited by channelized streams, sheetfloods, and mass flows (Fig. 5).

Explosive eruptions continued as the fan prograded eastward into the Española basin and were accompanied by increases in the proportions of coarse debris flows and coarse pumiceflows, many of which were rapidly reworked upon emplacement. This period culminated with eruption and emplacement of the lithic-rich Puye ignimbrite and accompanying pumice and ash deposits. Following this event, coarse debris flows characterized much of Puye fan deposition, as abundant material was being supplied from proximal dome breccias. Fluvial activity was apparently accelerated, probably due to cycles of increasingly efficient incision across the growing fan surface, and lacustrine systems again began to predominate along the fan toe as drainage patterns were disrupted by episodic sediment accumulations. The well preserved nature of most deposits in the Puye fan (especially mudflows) and the lack of evidence for abundant vegetation in this semi-arid region (Kelley, 1979; Manley, 1979; Dethier and Demsey, 1984) suggest that climatic fluctuations were not significant during this period, hence most sedimentary processes in the fan are more feasibly attributed to changes in volcanological and tectonic regimes. Continued silicic eruptions from the Tschicoma/El Rechuelos centers, and simultaneous basaltic activity from the Cerros del Rio volcanic center, resulted in the coeval subaqueous emplacement of abundant felsic and basaltic tephra.

The proximal block-and-ash flow sequences attest to at least two episodes of vulcanian activity, probably associated with the gravitational collapse of unstable portions of a lithologically distinctive hornblende-rhyodacite lava dome that has not yet been identified in the Tschicoma volcanic center. These episodes are also reflected distally in the fan by coarse-grained, near monolithologic stacked debris flow sequences that dominate the upper parts of the Puye Formation (Figs. 5, 7C; Waresback and Turbeville, in press).

Volcanogenic alluvial sequences like the Puye Formation preserve excellent records from volcanic terrains. An estimated 15–16 km^3 of largely Tschicoma-derived volcaniclastic material currently resides in the Puye fan and an undetermined, but undoudbtedly significant, amount of sediment exists in the subsurface beneath the eastern edge of the Tschicoma massif (Fig. 1; Griggs, 1964). The large variety of rock types found as Puye epiclasts (Table 2), compared to the much more restricted suite observed as Puye airfall lithics (e.g., Figs. 8, 11) or among Tschicoma lava flows, strongly implies the former existence of a lithologically highly variable northeastern Tschicoma dome complex that was rapidly denuded following cessation of volcanism. Topographic constraints suggest that much of the material shed from this complex was transported by eastward-flowing drainage en route to the ancestral Rio Grande. However, the fairly high rates of aggradation evident from the Puye fan, due to the sporadic availability of water in this semi-arid region and gradual down-faulting in the associated depocenter (Española basin of the central Rio Grande rift), greatly enhanced the incorporation of much of this material into the Puye Formation.

Conclusions

From this study of pyroclastic units in the Puye Formation, north-central New Mexico, we can make the following conclusions concerning the Late Pliocene-Early Pleistocene evolution of the Jemez Mountains volcanic field.

(1) The Puye alluvial system contains >15 km^3 of volcaniclastic material derived almost exclusively from the northeastern part of the Tschicoma volcanic center and records explosive volcanism and epiclastic sedimentation directly related to the growth of large lava domes. These dacitic and rhyodacitic domes supplied abundant material to the fan in the form of coarse epiclasts derived from proximal talus slopes and pyroclastic material emplaced as pumice falls and pyroclastic flows. At least 15 small-magnitude (0.1-1.0 km^3) explosive eruptions from the northeastern Tschicoma lava domes are recorded, as well as two episodes of vulcanian block-and-ash flow, possibly associated with gravitational lava dome collapse. In addition, the fan contains rhyolitic and basaltic tephra derived from sources outside of the Tschicoma center.

(2) The recognition of cyclical Puye depositional sequences greatly simplifies an interpretation of eruptive events from this dome complex. The Puye Formation represents a distinctive depositional megasequence that reflects contemporaneous volcanism from two adjacent volcanic centers, the Tschicoma dome complex to the west and the Cerros del Rio basaltic field to the south. The Tschicoma center steadily supplied large quantities of volcaniclastic material to the prograding fan system, whereas volcanism in the Cerros field strongly influenced sedimentation from the basin margins. Preservation reflects the combined influences of a continuous volcaniclastic sediment supply in a semi-arid region and post-4 Ma tectonic activity (down-faulting) in the Española basin of the central Rio Grande rift. In this respect, the fan is also an integral stratigraphic feature of this major intracontinental depression and is essentially contemporaneous with other alluvial systems exposed along the rift.

(3) Volcanogenic alluvial facies as completely preserved as the Puye Formation are uncommon in the stratigraphic record, suggesting that such sequences generally have very low preservation potential and that the Puye alluvial fan is therefore somewhat unusual. Relationships between volcaniclastic sequences and their sources, however, are rarely as clear-cut as that of the Tschicoma-Puye system. Similar sequences are preserved in more complicated volcanic terrains (Hay, 1956; Christiansen and Blank, 1972; Fritz and Harrison, 1985; Smith, 1987; Smith et al., 1987) where several volcanogenic aprons overlap and coalesce, forming widespread volcaniclastic sequences >1000 m thick. In many older volcanic terrains only the distal to mid-portions of once extensive volcaniclastic facies are likely to be preserved, hence the sources of these sequences are rarely apparent. Distal volcanic facies may therefore provide the only clues for the interpretation of parent terrains, and it will be necessary to extract as much information as possible from isolated volcaniclastic deposits so that the recognition of distinctive eruption sequences (on any scale) can fully complement petrologic evaluations.

Acknowledgements

We gratefully acknowledge the New Mexico Bureau of Mines and Mineral Resources, Sigma Xi, and American Western Universities, Inc., in cooperation with colleagues in the Earth and Space Sciences Division of Los Alamos National Laboratories, for technical and financial support. We thank Phil Kyle, New Mexico Tech, for INAA data. We are also indebted to George Walker, Colin Wilson, Richard Fisher, Fraser Goff, Grant Heiken, David Vaniman, and David Broxton for providing useful insights into these complicated volcanic sequences. Early versions of this manuscript greatly benefited

from comments by Dan Barker, John Wolff, Bruce Houghton, and an anonymous reviewer.

References

Aubele, J.C., 1979. The Cerros del Rio volcanic field. N.M. Geol. Soc., 30th Annu. Field Conf. Guideb., Santa Fe Country, pp. 243-252.

Bailey, R.A., Smith, R.L. and Ross, C.S., 1969. Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico. U.S. Geol. Surv. Bull., 1274-P: 1-19.

Baldridge, W.S. and Vaniman, D.T., 1986. Spatial and temporal patterns of Neogene volcanism in the northeastern Jemez volcanic field, New Mexico. EOS (Trans. Am. Geophys. Union), 67: 1253.

Baldridge, W.S., Vaniman, D.T. and Shafiqullah, M., 1987. Late Miocene to Pliocene development of the Northern Jemez volcanic field, New Mexico. EOS (Trans. Am. Geophys. Union), 68: 1532.

Carey, S.N. and Sparks, R.S.J., 1986. Quantitative models of the fall-out and dispersal of tephra from volcanic eruption columns. Bull. Volcanol., 48: 109-125.

Christiansen, R.L. and Blank, H.R., Jr., 1972. Volcanic stratigraphy of the Quaternary Rhyolite Plateau in Yellowstone National Park. U.S. Geol. Surv., Prof. Pap., 729B: B1-B18.

Dethier, D.P. and Demsey, K.A., 1984. Erosional history and soil development on Quaternary surfaces, northwest Española Basin, New Mexico. N.M. Geol. Soc., 35th Annu. Field Conf. Guideb., pp. 227-235.

Fink, J.H. and Manley, C.R., 1987. Origin of pumiceous and glassy textures in rhyolite flows and domes. Geol. Soc. Am., Spec. Pap., 212: 77-88.

Fisher, R.V., Heiken, G.H., Purtyman, W.D. and Wohletz, K.H., 1984. Cerros del Rio, New Mexico, maars. EOS (Trans. Am. Geophys. Union), 65: 1145.

Fritz, W.J. and Harrison, S., 1985. Early Tertiary volcaniclastic deposits of the Northern Rocky Mountains. In: R.M. Flores and S.S. Kaplan (Editors), Cenozoic Paleogeography of West-central U.S. Rocky Mountain Section-SEPM, Denver, CO, pp. 383-402.

Gardner, J.N., Goff, F., Garcia, S. and Hagan, R.C., 1986. Stratigraphic relations and lithologic variations in the Jemez Mountains volcanic field, New Mexico. J. Geophys. Res., 91: 1763-1779.

Griggs, R.L., 1964. Geology and groundwater resources of the Los Alamos area, New Mexico. U.S. Geol. Surv., Water Supply Pap., 1753, 107 pp.

Haskin, L.A., Haskin, M.A., Frey, F.A. and Wilderman, T.R., 1968. Relative and absolute terrestrial abundance of the rare-earths. In: L. Ahrens (Editor), Origin and Distribution of the Elements, Pergamon, New York, NY, pp. 889-912.

Hay, R.L., 1956. Pitchfork Formation, detrital facies of early basic breccia, Absaroka Range, Wyoming. Bull., Am. Assoc. Pet. Geol., 40: 1863-1898.

Heiken, G. and Wohletz, K., 1987. Tephra deposits associated with silicic domes and lava flows. Geol. Soc. Am., Spec. Pap., 212: 55-76.

Horn, M., 1986. Physical models of pyroclastic clouds and fountains. M.S. thesis, Arizona State University, Tempe, AZ, 188 pp. (unpubl.).

Inman, D.L., 1952. Measures describing the size distribution of sediments. J. Sediment. Petrol., 22: 125-145.

Izett, G.A., Obradovich, J.D., Naeser, C.W. and Cebula, G.T., 1981. Potassium-argon and fission-track zircon ages of Cerro Toledo rhyolite tephra in the Jemez Mountains, New Mexico. U.S. Geol. Surv., Prof. Pap., 1099-D, 43 pp.

Kelley, V.C., 1956. The Rio Grande Depression from Taos to Santa Fe. N.M. Geol. Soc., 7th Field Conf. Guideb., pp. 109-114.

Kelley, V.C., 1979. Geomorphology of the Española basin. N.M. Geol. Soc., 30th Annu. Field Conf. Guideb., pp. 281-288.

Loeffler, B.M., 1984. Major- and trace-element and strontium- and oxygen-isotope geochemistry of the Polvadera Group, Jemez Mountains, New Mexico: implications for the petrogenesis of the Polvadera Group. Ph.D. thesis, University of Colorado, Boulder, CO, 259 pp. (unpubl.).

Loeffler, B.M., Vaniman, D.T., Baldridge, W.S. and Shafiqullah, M., 1988. Neogene rhyolites of the Northern Jemez volcanic field, New Mexico. J. Geophys. Res., 93: 6157-6168.

Manley, K., 1976. The late Cenozoic history of the Española basin, New Mexico. Ph.D. thesis, University of Colorado, Boulder, CO, 171 pp. (unpubl.).

Manley, K., 1979. Stratigraphy and structure of the Española basin, New Mexico. In: R.E. Riecker (Editor), Rio Grande Rift: Tectonics and Magmatism. Am. Geophys. Union, Washington, D.C., pp. 71-87.

Meyer, J.D., 1972. Glass crust on intratelluric phenocrysts in volcanic rocks as a measure of eruptive violence. Bull. Volcanol., 35: 359-368.

Nairn, I.A. and Self, S., 1978. Explosive eruptions and pyroclastic avalanches from Ngauruhoe in February, 1975. J. Volcanol. Geotherm. Res., 3: 39-60.

Newhall, C.G. and Melson, W.G., 1983. Explosive activity associated with the growth of volcanic domes. J. Volcanol. Geotherm. Res., 17: 111-131.

Nielson, D.L. and Hulen, J.B., 1984. Internal geology and evolution of the Redondo Dome, Valles Caldera, New Mexico. J. Geophys. Res., 89: 8695-8711.

Rose, W.I., 1987. Volcanic activity at Santiaguito Volcano, 1976-1984. Geol. Soc. Am., Spec. Pap., 212: 17-28.

Rose, W.I., Jr., Pearson, T. and Bonis, S., 1976. Nuee ardente eruption from the foot of a dacite lava flow, Santiaguito Volcano, Guatemala. Bull. Volcanol., 40: 23-38.

Scott, W.E., 1987. Holocene rhyodacite eruptions on the flanks of South Sister volcano, Oregon. Geol. Soc. Am., Spec. Pap., 212: 35-54.

Self, S., Goff, F., Gardner, J.N., Wright, J.V. and Kite, W.M., 1986. Explosive rhyolitic volcanism in the Jemez Mountains: vent locations, caldera development and relation to regional structure. J. Geophys. Res., 91: 1779–1799.

Singer, B.S. and Kudo, A.M., 1986. Assimilation-fractional crystallization of Polvadera Group rocks in the northeastern Jemez Mountains volcanic field, New Mexico. Contrib. Mineral. Petrol., 94: 374–386.

Smith, G.A., 1986. Coarse-grained non-marine volcaniclastic sediments: terminology and depositional processes. Geol. Soc. Am. Bull., 97: 1–10.

Smith, G.A., 1987. The influence of explosive volcanism on fluvial sedimentation: Deschutes Formation (Neogene) of central Oregon. J. Sediment. Petrol., 57: 613–629.

Smith, G.A., Snee, L.W. and Taylor, E.M., 1987. Stratigraphic, sedimentologic, and petrologic record of late Miocene subsidence of the central Oregon High Cascades. Geology, 15: 389–392.

Smith, R.L., 1979. Ash-flow magmatism. Geol. Soc. Am. Sp. Paper, 180: 5–27.

Smith, R.L. and Bailey, R.A., 1966. The Bandelier Tuff: a study of ash-flow eruption cycles from zoned magma chambers. Bull. Volcanol., 29: 83–104.

Smith, R.L. and Bailey, R.A., 1968. Resurgent cauldrons. Geol. Soc. Am. Mem., 116: 613–662.

Smith, R.L., Bailey, R.A. and Ross, C.S., 1970. Geologic map of the Jemez Mountains, New Mexico. U.S. Geol. Surv. Map, I-571.

Sparks, R.S.J. and Wilson, L., 1976. A model for the formation of ignimbrite by gravitational column collapse. J. Geol. Soc. London, 132: 441–451.

Sparks, R.S.J., Wilson, L. and Hulme, G., 1978. Theoretical modeling of the generation, movement, and emplacement of pyroclastic flows by column collapse. J. Geophys. Res., 83: 1727–1739.

Thompson, R.N., 1982. Magmatism of the British Tertiary volcanic province. Scott. J. Geol., 18: 49–107.

Turbeville, B.N., 1986. Mineralogy, facies analysis, and interpretation of felsic pyroclastic deposits of the Puye Formation, Jemez Mountains, New Mexico. M.S. thesis, University of Texas, Arlington, TX, 417 pp. (unpubl.).

Turbeville, B.N. and Self, S., 1988. San Diego Canyon ignimbrites: pre-Bandelier Tuff ignimbrite explosive rhyolitic volcanism in the Jemez Mountains, New Mexico. J. Geophys. Res., 93: 6148–6156.

Walker, G.P.L., 1973. Explosive volcanic eruptions – a new classification scheme. Geol. Rundsch., 62: 431–446.

Walker, G.P.L., 1981. Plinian eruptions and their products. Bull. Volcanol., 44: 223–240.

Walker, G.P.L., 1983. Ignimbrite types and ignimbrite problems. J. Volcanol. Geotherm. Res., 17: 65–88.

Walker, G.P.L., Heming, R.F. and Wilson, C.J.N., 1980. Low aspect ratio ignimbrites. Nature, 283: 286–287.

Waresback, D.B., 1986. The Puye Formation, New Mexico: Analysis of a continental rift-filling volcaniclastic alluvial fan sequence. M.S. thesis, University of Texas, Arlington, TX, 225 pp. (unpubl.).

Waresback, D.B. and Turbeville, B.N., in press. Evolution of a Plio-Pleistocene volcanogenic alluvial fan: the Puye Formation, Jemez Mountains, New Mexico. Geol. Soc. Am. Bull.

Williams, H., 1932. The history and character of volcanic domes. Univ. Calif. Publ. Geol. Sci., 21: 51–146.

Wilson, C.J.N., 1984. The role of fluidization in the emplacement of pyroclastic flows, II: experimental results and their interpretation. J. Geol. Soc. London, 139: 581–592.

Wright, J.V., Roobol, M.J., Smith, A.L., Sparks, R.S.J., Brazier, S.A., Rose, W.I., Jr. and Sigurdsson, H., 1984a. Late Quaternary explosive silicic volcanism on St. Lucia, West Indies. Geol. Mag., 121: 1–15.

Wright, J.V., Turbeville, B.N. and Self, S., 1984b. Plinian pumice deposits of the Jemez Mountains, New Mexico. EOS (Trans. Am. Geophys. Union), 65: 1134.

Journal of volcanology and geothermal research

Editor-in-Chief

A.R. McBirney
Center for Volcanology, University of Oregon, Eugene, OR 97403, U.S.A.

Editorial Board

P.E. Baker, Nottingham
R. Batiza, Evanston, IL
G. Bodvarsson, Corvallis, OR
Y. Bottinga, Paris
C.K. Brooks, Copenhagen
H. Craig, La Jolla, CA
R.R. Dibble, Wellington
D. Dzurisin, Vancouver, WA
A.J. Ellis, Wellington
R.V. Fisher, Santa Barbara, CA
J.G. Fitton, Edinburgh
M.O. Garcia, Honolulu, HI
P. Gasparini, Naples
T.M. Gerlach, Albuquerque, NM
A. Grunder, Corvallis, OR
M.L. Hall, Quito
B.F. Houghton, Rotorua
C.P. Jaupart, Paris
A.M. Jessop, Calgary, Alta
A.D. Johnston, Eugene, OR
J. Klerkx, Tervuren
I. Kushiro, Tokyo
F. Le Guern, Gif-sur-Yvette
J.F. Luhr, St. Louis, MO
S.D. Malone, Seattle, WA
B.D. Marsh, Baltimore, MD
E.A.K. Middlemost, Sydney, N.S.W.
K. Nakamura, Tokyo
H. Pichler, Tubingen
G.R. Robson, Thirsk
W.I. Rose Jr., Houghton, MI
L. Rybach, Zurich
R. Scandone, Naples
S. Self, Arlington, TX
D.A. Swanson, Vancouver, WA
R.I. Tilling, Menlo Park, CA
E. Tryggvason, Reykjavik
P.M. Vincent, Clermont-Ferrand
S.D. Weaver, Christchurch
C.J.N. Wilson, Cambridge

Scope of the journal

Papers covering the following aspects of volcanology and geothermal research will qualify for publication in the *Journal of Volcanology and Geothermal Research*: (1) geochemical aspects – geochemistry of volcanic rocks, geochemistry of volcanic gases and related products, isotope studies; (2) petrological aspects – magma genesis and magma evolution, petrology of volcanic rocks; (3) economic aspects – ore deposits related to volcanic rocks, geothermal energy; (4) geophysical aspects – physical properties of volcanic rocks and magmas, heat flow studies, physical volcanology, volcanic seismology, volcanic surveillance, geophysical exploration for geothermal resources; (5) tectonic aspects – relation of volcanism to global and regional tectonic processes; (6) environmental aspects – volcanic gases and their effect on the atmosphere.
Types of contribution to be published are: (1) research papers, (2) reviews, (3) short communications, (4) letters, (5) book reviews and (6) announcements.

Publication schedule and subscription information

The *Journal of Volcanology and Geothermal Research* will have four issues to the volume, four volumes per year. 1988 Subscription price: Dfl. 1000.00 plus Dfl. 104.00 (p.p.h.) = Dfl. 1104.00 (US$ 538.00). This covers volumes 35–38.
Personal subscriptions (rate available upon request) are only available if the personal subscriber's institution or company has a full-price subscription.

Please send your order to: Elsevier Science Publishers B.V., Journals Department, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel. 5803911, Telex 18582 ESPA NL.
Claims for missing issues will be honoured, free of charge, within three months after publication date of the issue.
All back volumes are available at Dfl. 250.00 plus Dfl. 18.00 (p.p.h.) = Dfl. 268.00 (US$ 131.00).
Our p.p.h. (postage, packing and handling) charge includes surface delivery of all issues, except to subscribers in Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Malaysia, Mexico, New Zealand, Pakistan, P.R. China, Singapore, South Africa, South Korea, Taiwan, Thailand, and U.S.A., who receive all issues by air delivery (S.A.L. = Surface mail, Air Lifted) at no extra cost. For Japan, air delivery requires 50% additional charge; for all other countries airmail and S.A.L. charges are available upon request.

Customers in the U.S.A. and Canada wishing information on this and other Elsevier journals, please contact Journal Information Center, Elsevier Science Publishing Co., Inc., 655 Avenue of the Americas, New York, NY 10017. Telephone: (212) 633 3750.

Publication of abstracts and contents
Abstracts or contents of this journal are published in: *A.G.I.'s Bibliography and Index of Geology*, *Chemical Abstracts*, *Current Contents*, *Geo Abstracts* and *Mineralogical Abstracts*.

JOURNAL OF VOLCANOLOGY AND GEOTHERMAL RESEARCH

VOLUME 36 (1989)

ıy of
:ts –
:anic
and

ɔook

1988

y has

, The

ntina.
South
ed) at
ıs are

orma-
(212)

Journal of volcanology and geothermal research

An international journal on the geophysical, geochemical, petrological, and economic aspects of geothermal and volcanological research

Editor-in Chief

A.R. McBirney, Eugene, OR

Editorial Board

P.E. Baker, Nottingham
R. Batiza, Evanston, IL
G. Bodvarsson, Corvallis, OR
Y. Bottinga, Paris
C.K. Brooks, Copenhagen
H. Craig, La Jolla, CA
R.R. Dibble, Wellington
D. Dzurisin, Vancouver, WA
A.J. Ellis, Wellington
R.V. Fisher, Santa Barbara, CA
J.G. Fitton, Edinburgh
M.O. Garcia, Honolulu, HI
P. Gasparini, Naples
T.M. Gerlach, Albuquerque, NM
A. Grunder, Corvallis, OR
M.L. Hall, Quito
B.F. Houghton, Rotorua
C.P. Jaupart, Paris
A.M. Jessop, Calgary, Alta.
A.D. Johnston, Eugene, OR
J. Klerkx, Tervuren
I. Kushiro, Tokyo
F. Le Guern, Gif-sur-Yvette
J.F. Luhr, St. Louis, MO
S.D. Malone, Seattle, WA
B.D. Marsh, Baltimore, MD
E.A.K. Middlemost, Sydney, N.S.W
K. Nakamura, Tokyo
H. Pichler, Tübingen
G.R. Robson, Thirsk
W.I. Rose Jr., Houghton, MI
L. Rybach, Zürich
R. Scandone, Naples
S. Self, Arlington, TX
D.A. Swanson, Vancouver, WA
R.I. Tilling, Menlo Park, CA
E. Tryggvason, Reykjavik
P.M. Vincent, Clermont-Ferrand
S.D. Weaver, Christchurch
C.J.N. Wilson, Cambridge

VOL. 36 (1989)

ELSEVIER, AMSTERDAM – OXFORD – NEW YORK – TOKYO

VOLUME 36 NO. 1-3 SPECIAL ISSUE

PITON DE LA FOURNAISE VOLCANO, RÉUNION ISLAND

A R. McBIRNEY (Editor)

Contents

Introduction vii
The off-shore continuation of an active basaltic volcano, Piton de la Fournaise (Réunion Island, Indian Ocean), structural and geomorphological interpretation from Sea Beam mapping
J.-F. Lénat and P. Vincent (Clermont-Ferrand, France), and P. Bachèlery (La Réunion, France) 1
Complete gravity study of Piton de la Fournaise volcano, Reunion Island
D. Rousset and A. Lesquer (Montpellier, France), A. Bonneville and J.-F. Lénat (Clermont-Ferrand, France) 37
Eruptive history of the Piton de la Fournaise volcano, Réunion Island, Indian Ocean
P.-Y. Gillot (Gif-sur-Yvette, France) and P. Nativel (Orsay, France) 53
A statistical and probabilistic study of the historic activity of Piton de la Fournaise, Réunion Island, Indian Ocean
L. Stieltjes and P. Moutou (La Réunion, France) 67
The December 4, 1983 to February 18, 1984 eruption of Piton de la Fournaise (La Réunion, Indian Ocean): description and interpretation
J.-F. Lénat (Clermont-Ferrand, France), P. Bachèlery (La Réunion, France), A. Bonneville and P. Tarits (Clermont-Ferrand, France), J.-L. Cheminée and H. Delorme (Paris, France) 87
The Grand Brûlé exploration drilling: new data on the deep framework of the Piton de la Fournaise volcano. Part 1: Lithostratigraphic units and volcanostructural implications
J.P. Rançon, P. Lerebour and T. Augé (Orleans, France) 113
The Grand Brûlé exploration drilling: new data on the deep framework of the Piton de la Fournaise volcano. Part 2: Secondary minerals
P. Lerebour, J.P. Rançon and T. Augé (Orleans, France) 129
The Grand Brûlé exploration drilling: new data on the deep framework of the Piton de la Fournaise volcano. Part 3: Mineral chemistry of the cumulate rocks
T. Augé, P. Lerebour and J.P. Rançon (Orleans, France) 139
Geothermal model of the Salazie Cirque (Réunion Island): volcanic and structural implications
J. Demange, P. Chovelon and P. Puvilland (Orleans, France) 153
The Salazie Cirque ignimbrite (Piton des Neiges volcano, Réunion Island): chronostratigraphy, description and significance of lithic fragments and eruptive mechanisms
P. Rocher (Paris, France) and D. Westercamp (Orleans, France) 177
Réunion hotspot activity through Tertiary time: Initial results from the Ocean Drilling Program, Leg 115
R.A. Duncan, J. Backman and L. Petersen 193
March 1986 eruptive episodes at Piton de la Fournaise volcano (Réunion Island)
H. Delorme (Paris and Plaine des Cafres, La Réunion, France), P. Bachèlery (La Réunion, France), P.A. Blum and J.L. Cheminée (Paris, France), J.F. Delarue and J.C. Delmond (La Réunion, France), A. Hirn and J.C. Lepine (Paris, France), P.M. Vincent (Clermont-Ferrand, France) and J. Zlotnicki (Paris, France) 199
The beginning of the 1985-1987 eruptive cycle at Piton de la Fournaise (La Réunion); new insights in the magmatic and volcano-tectonic systems
J.-F. Lénat (Clermont-Ferrand, France), P. Bachèlery (La Réunion, France), A. Bonneville (Clermont-Ferrand, France) and A. Hirn (Paris, France) 209

3/89/$03 50
; mechanical,
Amsterdam.
dest possible
ns for copying
1974 (S 351
of articles for
er-copy fee for
st page of each
ongress Street
e author(s). All
other kinds of
be obtained
e, or from
endorsement of