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Erosion, transport and segregation of pumice and lithic clasts in pyroclastic flows inferred from ignimbrite at Lascar Volcano, Chile

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Abstract

Investigations have been made on the distribution of pumice and lithic clasts in the lithic rich Soncor ignimbrite (26.5 ka) and the 1993 pumice flow deposits of Lascar Volcano, Chile. The Soncor ignimbrite shows three main lithofacies which grade into one another. Coarse lithic breccias range from matrix poor stratified varieties, irregular shaped sheets and elongate hummocks in proximal environments, to breccia lenses with pumiceous ignimbrite matrix. Massive, lithic rich facies comprise the bulk of the ignimbrite. Pumice rich facies are bimodal with abundant large pumice clasts (often with reverse grading), rare lithic clasts and occur distally and on high ground adjacent to deep proximal valleys. In the 1993 pyroclastic flow deposits lithic rich facies are deposited on slopes up to 14° whereas pumice rich facies are deposited only on slopes <4°. Lithic rich parts show a thin pumice rich corrugated surface which can be traced into the pumice rich facies. The high lithic content in the Soncor ignimbrite is attributed to the destruction of a pre-existing dome complex, deep explosive cratering into the interior of the volcano and erosion during pyroclastic flow emplacement. Lithic clasts incorporated into the flows during erosion of the basement substrate have been distinguished from those derived from the vent. Categorisation of these lithics and knowledge of the local geology allows these clasts to be used as tracers to interpret former flow dynamics. Lithic populations demonstrate local flow paths and show that lithics are picked up preferentially where flows move around or over obstacles, or through constrictions. Eroded lithics can be anomalously large, particularly close to the location of erosion. Observations of both the Soncor ignimbrite and the 1993 deposits show that lithic rich parts of flows were much more erosive than pumice rich parts. Both the Soncor and 1993 deposits are interpreted as resulting from predominantly high concentration granular suspensions where particle–particle interactions played a major role. The concentrated flows segregated from more expanded and turbulent suspension currents within a few kilometres of the source. During emplacement some degree of internal mixing is inferred to have occurred enabling entrained lithics to migrate into flow interiors. The facies variations and distributions and the strong negative correlation between maximum pumice and lithic clast size are interpreted as the consequence of efficient density segregation within the concentrated flows. The frictional resistance of the lithic rich part is greater so that it deposits on steeper slopes and generally closer to the source. The lower density and more mobile pumice rich upper portions continued to flow and sequentially detached from the lithic rich base of the flow. Pumice rich portions moved to the margins and distal parts of the flow so that distal deposits are lithic poor and non-erosive. The flows are therefore envisaged as going though several important transformations. Proximally, dense, granular flow, undercurrents are formed by rapid sedimentation of suspension currents. Medially to distally the undercurrents evolve to flows with significantly different rheology and mobility characteristics as lithic clasts are sedimented out and distal flows become dominated by pumice.

Keywords: pumice and lithic clasts; pyroclastic flows; ignimbrite

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1. Introduction

The physical nature of pyroclastic flows and the mechanisms of sediment transport and deposition are still not fully understood. Different conceptual models have been developed, ranging from dense concentration suspensions dominated by particle interactions and fluidisation effects (Sparks, 1976; Wilson, 1985) to dilute turbulent suspensions (Dade and Huppert, 1996; Bursik and Woods, 1996). Processes of sediment sorting and sedimentation within flows have also been discussed. Variations in grain size and composition with height in vertical sections have been interpreted as recording processes in the moving flows (Sparks, 1976) and progressive aggradation from the basal part of a flow that deposits different grain sizes or composition with time (Branney and Kokelaar, 1992). These different interpretations raise the issue of the extent to which the properties of the flows can be deduced from the features of the deposits.

Erosion by pyroclastic flows has long been recognised (Fisher, 1977; Kieffer and Sturtevant, 1988; Sparks et al., 1997; Cole et al., 1998). Lithic fragments can be eroded from the substrate and incorporated into the flow (Druitt and Bacon, 1986; Suzuki-Kamata, 1988; Buesch, 1992; Bryan et al., 1998). Transport and segregation of entrained 'tracer' lithic clasts can help constrain pyroclastic flow mechanisms. If the geology of a volcano is sufficiently well known then lithics derived directly from the vent and the conduit walls can be distinguished from those that are eroded from the ground (Druitt and Bacon 1986; Hildreth and Mahood, 1986). Furthermore, the sources of accidental lithics can be identified and the contrasted behaviour of the low-density pumice and the dense lithics can constrain segregation processes within flows. Lascar volcano in northern Chile provides an opportunity for such a study. The volcano has a diverse basement geology (Gardeweg et al., 1998) so that entrained lithics can be readily distinguished. Two of the major explosive eruptions, the Soncor eruption, at 26.5 ka and the 18–20 April 1993 eruption produced coarse grained, lithic rich, ignimbrites.

This paper presents a study of the facies variations in the Lascar ignimbrites with emphasis on interpreting the erosion, transport and deposition of accidental lithic clasts. It develops concepts introduced in Sparks et al. (1997) inferred from erosion features produced by the 1993 pyroclastic flows. We interpret the data as indicating that these pyroclastic flows segregated into concentrated flows close to the source and that efficient sorting of particles according to their size and density occurred due to grain to grain interactions in highly concentrated suspensions. The data show that erosion was greatest proximally but strong erosion (in terms of mass transported) also occurred distally due to flow acceleration where local slopes increase, through constrictions and around bends. This study indicates that for these pyroclastic flows dilute, turbulent emplacement is not tenable.

2. The geology of Lascar

Lascar volcano (5592 m; 23° 22′ S, 67° 44′ W) is located in the Central Andean Volcanic Zone (Fig. 1) in a physiographic domain known as the Cordillera de los Andes, bordered to the west by the Salar de Atacama and to the east by the Andean plateau (the Altiplano). We describe the main substrate lithologies over which the pyroclastic flows moved with emphasis on those lithologies which are readily identified. Entrained lithics are divisible into two groups: rocks from Lascar volcano and regional basement rocks including neighbouring volcanoes (Table 1).

The basement is composed of Palaeozoic and Tertiary volcanic and sedimentary rocks. Pre-Cenozoic rocks outcrop as fault-bound inliers surrounded by Tertiary cover rocks. The Lila formation consists of marine Devonian to early Carboniferous siliciclastic rocks, quartzite being distinctive. The Cas Formation comprises Permian volcanic rocks and granites (Cerro Opla) typically containing epidote and chlorite with bright red and orange colours. Palaeozoic outcrops are confined to elevations below 3700 m and distances of more than 15 km from Lascar and provide good tracer lithologies in distal facies of the Soncor ignimbrite. Tertiary continental sedimentary rocks (arkosic sandstones) of the Quepe strata form a few isolated outcrops.

The volcanic centres of the western Altiplano and Cordillera (Late Tertiary–Quaternary) range from andesitic stratocones to dacitic dome complexes and large calderas with associated voluminous ignimbrite

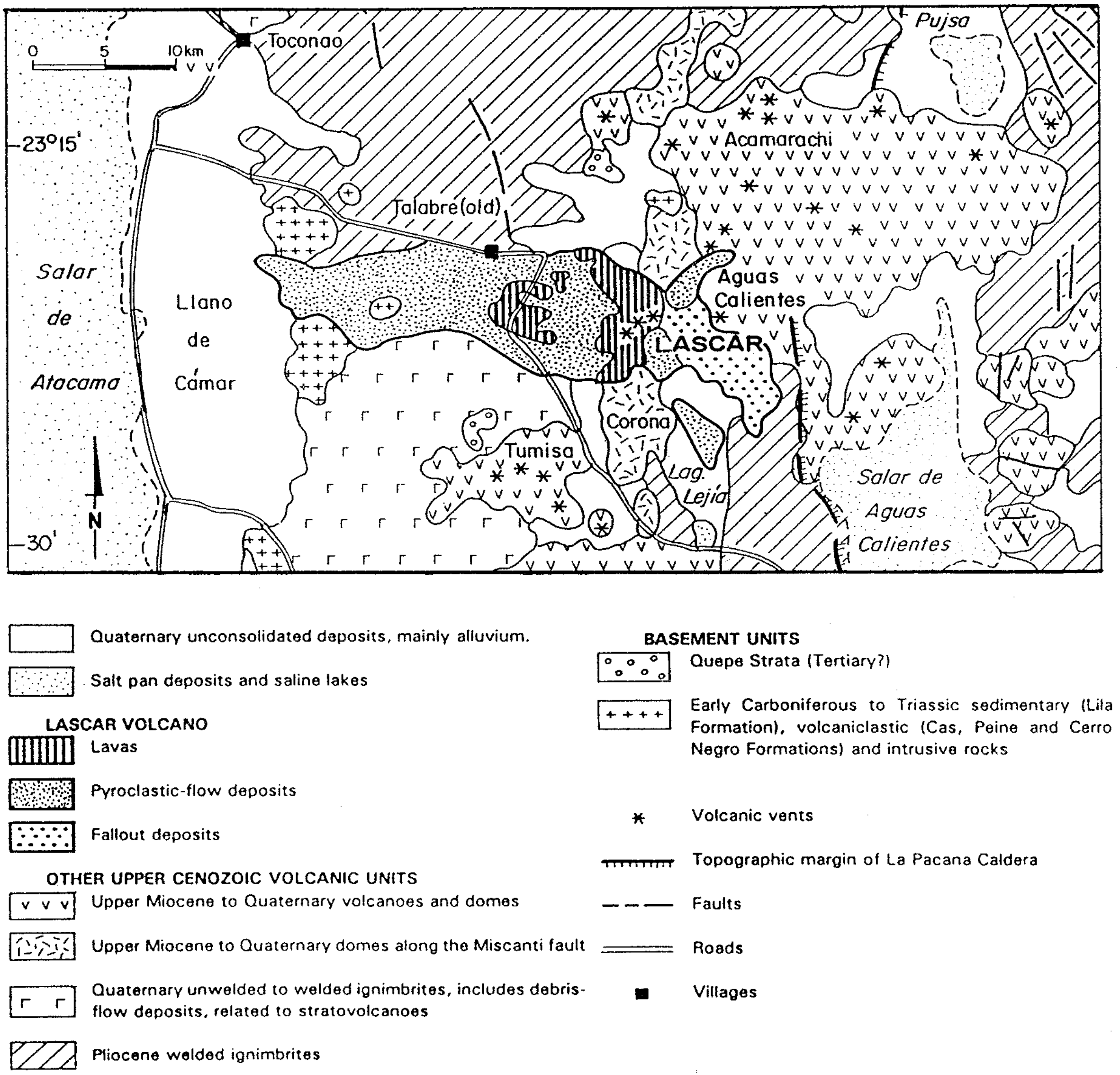


Fig. 1. Geological map of part of the Tocanao sheet, Antofagasta region, Chile after Ramirez and Gardeweg (1982). The map shows the location and the extent of the Lascar deposits (outlined in bold), the principal geological units of the Palaeozoic and Tertiary basement and the neighbouring Miocene–Quaternary volcanic centres (*).

sheets. The immediate substrate in the Lascar area is the Atana ignimbrite, dated at 4.5–3.7 Ma. It comprises a ($\sim$900 km^3) fine-grained, rhyodacitic crystal rich composite sheet sourced from the large, 4 Ma La Pacana caldera, 50 km to the east of Lascar (Gardeweg and Ramirez, 1987). Lascar itself is constructed on a ridge of dacite domes called the Cerro Corona and Cerro de Saltar dome complex. To the north, overlying the Tertiary ignimbrites, are successions of thin monomict debris flow units of very distinctive "pink quartz" rhyodacite, which extend from the Cerro Corona domes down to the Salar. Overlying the Tertiary ignimbrites to the south-west is Cerro Tumisa, a dacite dome complex of 2.5–0.4 Ma (Gardeweg, 1991). Pyroclastic deposits from the Tumisa complex have been dated at 1.5–0.5 Ma

Table 1
Summary descriptions and distinguishing features of the main rock types which comprise substrate-derived lithics; the Lascar volcanics group and pre-Lascar basement lithologies

Lascar Volcanics			
Stage		Unit	Distinguishing features of lithology
IV	1848–present	Historic pyroclastic flow deposits (1993) Lava domes and vulcanian ejecta	White andesite and grey mafic pumice with diverse lithic clasts, mainly andesite dome fragments
	<7.1 ka	Summit craters ejecta blankets	
	~7.1 ka	Tumbres–Talabre lava flow	Glassy porphyritic andesite with phenocrysts of pyroxene and hornblende
III	~9.3 ka	Tumbres plinian and pyroclastic flow deposits	Dark grey/red scoria and cream andesitic pumice
	<22.3 ka	Western stratocone lavas	Porphyritic silicic andesite to dacitic lava
	20.8–19.2 ka	Post-Soncor fluvioglacial fan	Rich in Soncor pumice
	22.3 ka	Debris-avalanche deposit	Large blocks mostly of Stage I lavas
II	26.5 ka	Soncor plinian deposit and ignimbrite	Pale grey/dacitic pumices with minor banded and grey andesite pumice and diverse lithics
	>26.5 ka	Piedras Grandes block and ash flow and glacier burst deposits	Pale grey/pink poorly vesicular porphyritc silicic hornblende andesite
I	>26.5 ka	Saltar pyroclastic flow deposits	Coarse dense andesite bombs: brick red moderately vesicular and porphyritic, euhedral augite phenocrysts~1 cm
		Chaile pyroclastic flow deposits	Coarse dense cauliflower andesite bomb deposits, micro-porphyritic, plagioclase-phyric
	<43 ka	Stage I lavas	Mafic andesite lavas (55–65 wt% SiO_2) microporphyritic, plagioclase-phyric

Pre-Lascar Basement	
Tumisa Volcano deposits (2.5–0.4 Ma) lavas, pyroclastics and debris flow deposits	White porphyritic dacite with megacrysts of hornblende and plagioclase
Pliocene welded, large volume ignimbrites (4.5–1 Ma)	Fine grained rhyolitic, moderately welded massive tuffs
Upper Miocene to Pliocene domes (5 Ma — Quaternary) Cerro Corona, Cerro de Saltar and block and ash flow deposits	Dark glassy porphyritic rhyodacite with distinctive pink quartz
Tertiary continental siliclastic sedimentary rocks (Quepe Strata)	Medium to coarse arkosic sandstones
Devonian to Triassic sedimentary (Lila fm), volcaniclastics (Cas fm, Peine Strata, Cerro Negro fm) and intrusive rocks	Quartizites, porphyries, volcaniclastic sediments, orange granites and micrograntes with hypabyssal textures

and comprise white porphyritic dacite pumice flow and block-and-ash flow deposits. Directly to the east of Lascar lies the Quaternary Aguas Caliente stratocone volcano consisting of hornblende andesite and dacite lavas.

Lascar volcano is elongate with an ENE–WSW trend. The active centre has migrated westward from the eastern side, before switching back to the east side at ~7 ka, so that the active craters are now situated on the site of the original stratocone. The volcano's evolution has been divided into four stages (Gardeweg et al., 1998). Stage I began <43 ka ago with blocky two-pyroxene andesite (55–65 wt% SiO_2) lavas that outcrop to the north and west of Lascar and extend to 16 km from the vent (Fig. 1) This stage culminated in the emplacement of three, small volume, coarse grained andesitic pyroclastic flow deposits: the Saltar unit and Upper and Lower Chaile units. These comprise dense to poorly vesicular cauliform and breadcrust bomb deposits in poorly sorted unconsolidated scoriaceous ash matrix. The Saltar deposits outcrop on the northern, north-eastern, and southern flanks while the Chaile deposits (Upper and Lower units) extend ~6 km down the south-western flanks.

Stage II activity involved silicic andesite and dacite products and a migration of the active vent to the west. A fan of dome collapse block-and-ash flow deposits, the Piedras Grandes unit, extends 4 km down the western flanks and flood deposits derived from this unit extend a further 8 km. This unit comprises large, prismatically jointed blocks of silicic andesite with hornblende phenocrysts set in an unconsolidated to welded pink ashy matrix. Overlying the Piedras Grandes unit is the compositionally zoned (67–56 wt% SiO_2) Soncor plinian deposit and ignimbrite on which this study is based. The main fan of the Soncor ignimbrite, the most extensive of the Lascar deposits, extends 27 km west from the volcano. The Soncor deposits have been dated at 26.45 ± 0.5 ka by AMS radio carbon geochronology (Gardeweg et al., 1998). Stage III involved the building of the western stratocone over the Soncor eruption vent. Much of the edifice is built of thick porphyritic silicic andesite to dacite lavas and small andesite scoria flow deposits. Stage IV began with the 9.2 ka Tumbres andesitic pumice fall and scoria flow eruption, this deposit is exposed on the north-west and west of the volcano and consists of moderately vesicular andesitic to basaltic andesite scoria clasts and red breadcrust bombs with red welded agglutinate close to the vent. Stage IV activity then shifted back to the eastern stratocone, and the eruption of the Tumbres–Talabre lava (7.1 ka), an andesitic blocky lava flow extending 8 km to the north-west. Historical activity since the 1840s has been dominated by a nearly continuous steam and SO_2 column, typically 1 km high, with intermittent short-lived vulcanian explosions. Four discrete cycles of dome growth have been identified since 1984 (Matthews et al., 1997), with the last major explosive eruption occurring on 18–20 April 1993. This eruption generated a column of 5–23 km and pyroclastic flows reaching up to 9 km from the vent on the north-western flanks (Guarinos and Guarinos, 1993; Gardeweg and Medina, 1994).

3. The Soncor eruption and its products

The products of the Soncor eruption comprise a compositionally zoned plinian pumice fall deposit and an associated unconsolidated lithic rich ignimbrite. The juvenile component is predominantly white dacite pumice (62–67 wt% SiO_2) containing 28–44 vol% phenocrysts (on a vesicle free basis) of plagioclase, orthopyroxene, clinopyroxene, oxide and minor biotite (Matthews et al., 1999). There are also lesser amounts of denser pumices containing abundant hornblende and compositionally banded pumice with mafic andesite scoria (61 wt% SiO_2) containing 32–39 vol% phenocrysts. The ignimbrite is compositionally zoned with more mafic andesite pumice and scoria (56 wt% SiO_2) characterising the later erupted flow units. Isopach maps for the pumice fall deposit give a thickness half distance of ~2.5 km, and a minimum in situ volume of 2.3 km^3 (Gardeweg et al., 1998). Fallout pumice densities are in the range 400–800 kg m^{-3} with a mean of 580 kg m^{-3}. Maximum lithic size data give a minimum cross wind range of 11 km with a column height estimation of 25–30 km.

The Soncor ignimbrite forms an extensive fan on the western flank which extends 27 km towards the Salar de Atacama (Fig. 2). The deposits are concentrated in canyons (*quebradas*) which run from the foot of Lascar down towards the Salar, dissecting the Tertiary ignimbrite plateau. The three largest quebradas, Quebrada de Talabre, Quebrada de Soncor and Quebrada de Chaile, acted as the major channels for the Soncor pyroclastic flows. They extend approximately 17, 17 and 9 km, respectively, and are between 80 and 500 m wide and 30–80 m deep. Numerous other minor quebradas and small valleys on the western flanks also contain Soncor ignimbrite. Smaller fans of ignimbrite also occur to the north-east and south-east of Lascar. The south-eastern deposits, in the Pampa Lejia area, can be traced up to 11 km from the vent and comprise a 3 km wide fan of between 5 and 20 m in thickness. In the north-east, a fan ~800 m wide and 2–6 m thick extends 6 km down the Quebrada de Morro Blanco.

Deposit thickness measurements for 60 localities within the major quebradas provide the basis for a volume estimate of 1.1 km^3 for the channelled portions of the deposits. The total volume of the ignimbrite is estimated at 4.7 km^3, and the fallout at 2.3 km^3. The volume of the lost co-ignimbrite ash has been estimated using the pumice crystal content (36%) and crystal concentration data on fractions <2 mm (61.5 wt% crystals) by the Sparks and Walker (1977) method. These data indicate an average of at

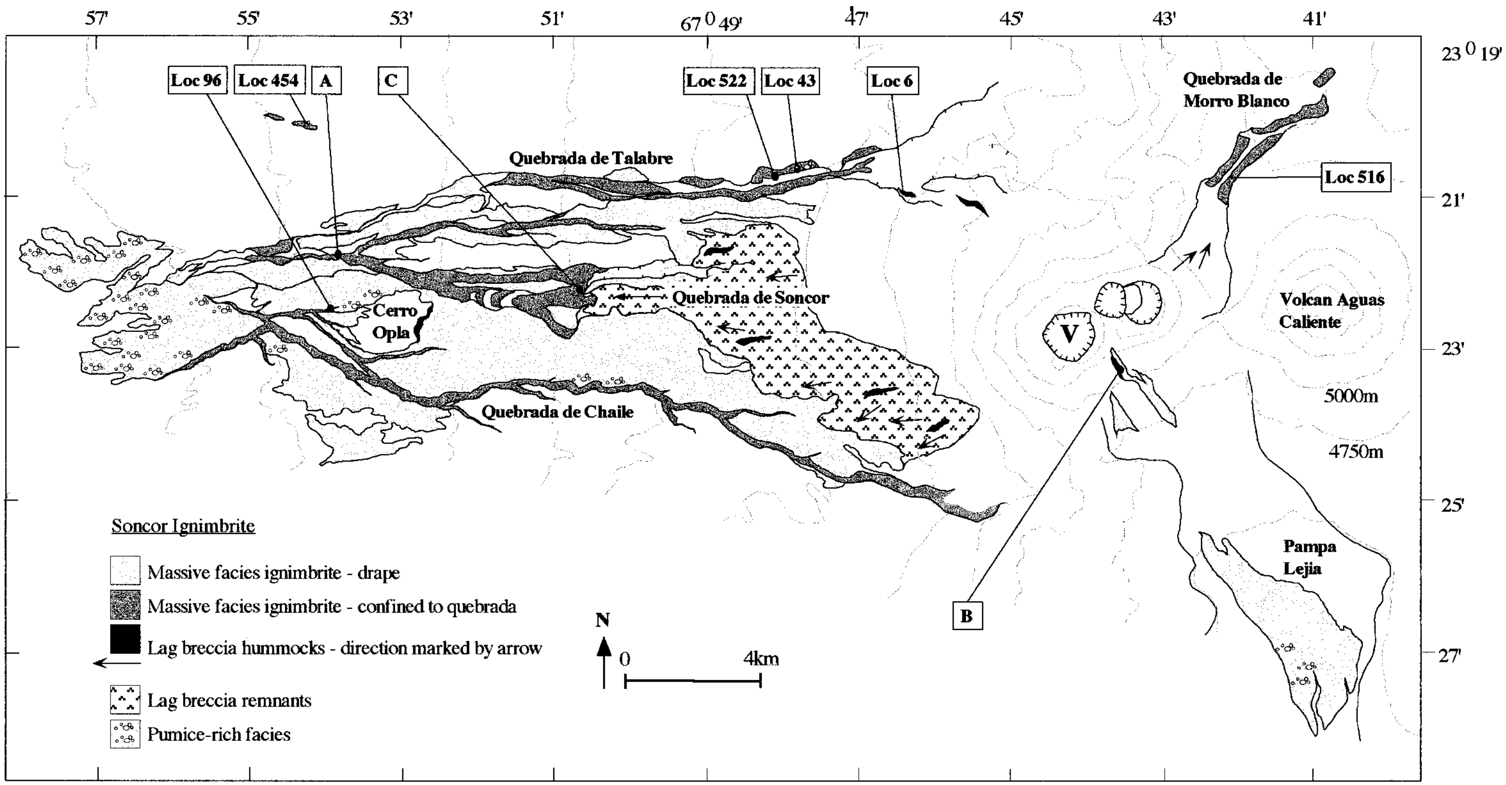


Fig. 2. Distribution of the Soncor ignimbrite showing the lithofacies variations, the major quebradas and the locations of the six stratigraphic sections illustrated in Figs. 6 and 7. Also shown is the location of: (A) a constriction in the Quebrada de Soncor, upstream of which ~0.064 km^3 of massive facies deposit has ponded; (B) the plinian section and stratified lithic breccia; and (C) the type locality of stratified sheet breccia.

least 20 wt% of the original juvenile material is lost, representing approximately 1.15 km^3. With an additional estimate for volume of lost eroded deposits, the minimum erupted volume is estimated as 10 km^3 in situ; this corresponds to 5.6 km^3 DRE of juvenile magma when the volume of lithic fragments is taken into account (see below).

Lithic content of ignimbrite samples have been analysed and vent-derived and substrate-derived lithics have been distinguished for specific height intervals throughout the deposit. On average the lithic content of the ignimbrite is 54 wt% with 20% of the lithics being substrate-derived. Entrained lithics are often larger than those that are derived from the vent and may comprise up to 25 wt% of the massive facies deposit. About 2 km^3 of the ejecta is estimated to consist of lithics derived from the pre-Soncor volcanic complex. Deep explosive cratering into the interior of the volcano is inferred to have occurred by the abundance of vent-derived, hypabyssal and plutonic clasts. Lithic studies have been limited to the western fan as it is notably richer in lithics and the substrate is better constrained.

Three main lithofacies are recognised. First, there is a lithic rich, massive ignimbrite comprising the bulk of the ignimbrite fan. Second there is a pumice rich facies with large pumices set in a fine ash, lithic poor matrix. Third there is a coarse lithic breccia facies which varies from matrix poor in proximal environments to those with an interstitial pumiceous matrix in medial environments.

3.1. Massive facies

The most proximal occurrence of the massive facies ignimbrite is 4 km from the vent although substantial (>10 m) thicknesses do not occur closer than 8 km. At the quebrada margins the ignimbrite forms erosional terraces up to 60 m high with gently dipping (3–5°) flat upper surfaces that lie between 5 and 20 m below the top of the plateau (Fig. 2, Loc A). Confinement of the flows by topography is clear.

The massive facies consists of poorly sorted pumice and lithic clasts in a matrix of poorly sorted white ash (Fig. 3a). White andesite to dacite (62–67 wt% SiO_2) pumices are the main juvenile components, but upper flow units contain abundant darker, more silica poor varieties, compositionally banded pumices and amphibole crystal rich pumices. Pumice densities are in the range 800–1400 $kg\,m^{-3}$ for crystal poor varieties and up to 2100 $kg\,m^{-3}$ for crystal rich types. Lithic content on an average comprises 59 wt% of the deposit (Fig. 4) with a range of 22–76 wt%. Grain size histograms and componentry analyses (Fig. 5a and b) show common bimodality (coarse modes at $-3\,\phi$ and fine modes at 2ϕ) and coarse tail grading. Md ϕ for massive facies commonly varies between 0.4 and 2.3 and $\sigma\,\phi$ values range between 2.1 and 4.6 (Fig. 5d and e), which are characteristic values for poorly sorted pyroclastic flow deposits (Walker, 1983).

Although the massive facies is typically structureless and ungraded there are some local variations and internal structures (Figs. 6 and 7). Coarse tail normal grading of lithics occurs, but more commonly lithics are found in concentration horizons at various levels throughout the deposits (Loc 96). Standard ignimbrite features of reversely graded basal layers and reversely graded pumice rich layers (Sparks et al., 1973) are common (Loc 43; Loc 522). Variations in the grading of pumice and lithic clasts and in particular reversely graded pumice layers are interpreted to represent upper boundaries of flow units. Undulating flow unit boundaries however, can often be traced horizontally into massive deposits with no detectable boundaries. In several localities, in both the Chaile and Soncor quebrada, a subtle layering or stratification of the deposit can be detected due to variations in the size and abundance of lithics and pumice clasts. The 50 m section of ponded deposits (Fig. 7) is interpreted as a succession of flow units 0.5–12 m thick, each distinguished by pumice rich tops. On the Tertiary plateau between the quebradas is an extensive drape of Soncor massive facies ranging from 2 to 6 m thick. This covers the entire western fan and accounts for around 2.3 km^3 of deposit. These deposits are neither continuous nor uniform over the whole area and are usually separated from the thickly accumulated deposits by the steep quebrada walls. Constituents are similar to the ponded deposits although they contain less large pumice and lithic clasts.

The lithic assemblage is heterogeneous. The vent-derived lithic suite was first ascertained by studying the lithic clasts in the Soncor fallout deposit (Fig. 2, Loc B; fig. 11 in Gardeweg et al., 1998). The fallout

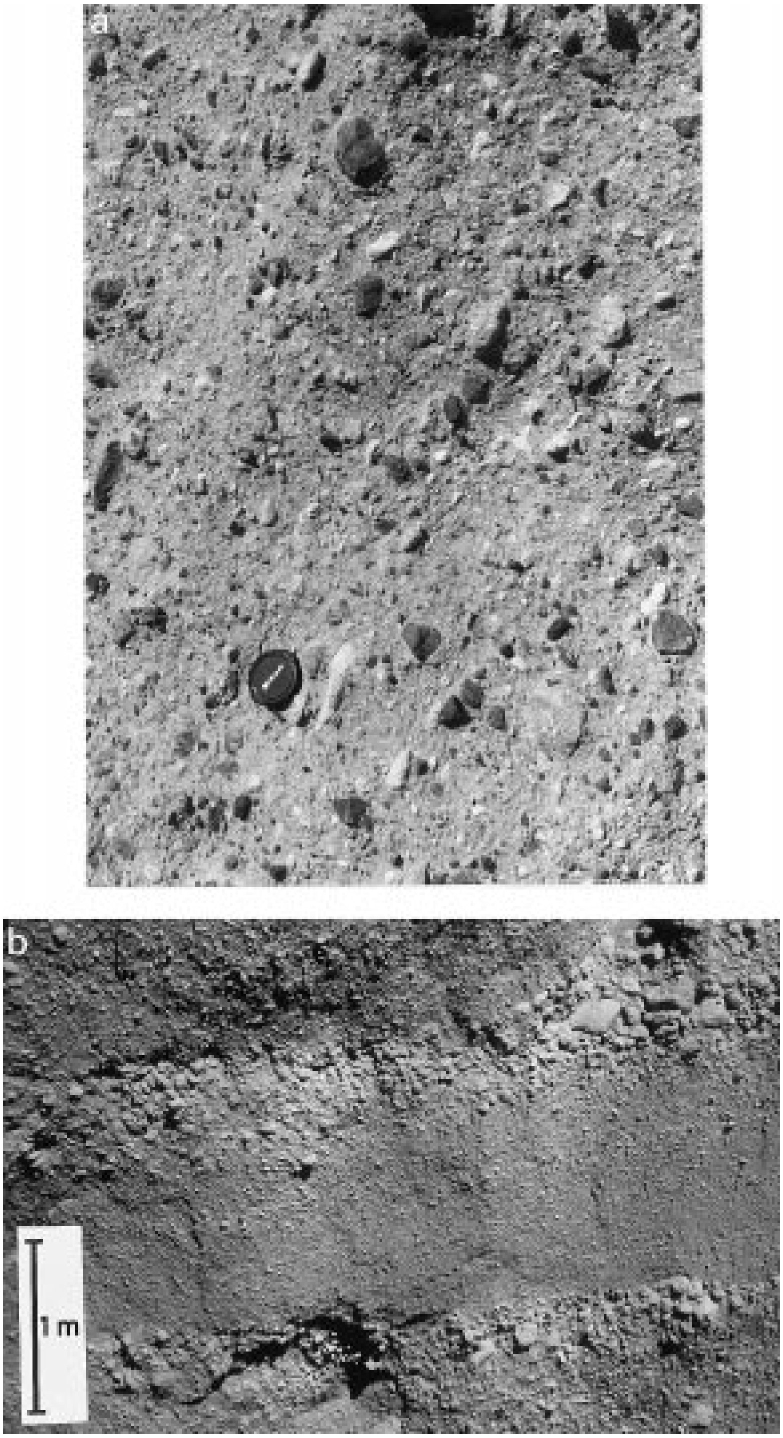


Fig. 3. Facies variations in the Soncor ignimbrite: (a) massive facies rich in lithic clasts which comprise the bulk of the Soncor ignimbrite (camera lens cover 5 cm); (b) multiple reversely graded flow units at Loc. 43 with upper pumice facies; (c) close up of a fine horizon of fine ash poor stratified lithic breccia; (d) interstratified lithic breccia found as a lens within the massive facies deposit at Loc C, note presence of fine ash matrix.

Fig. 3. (*continued*)

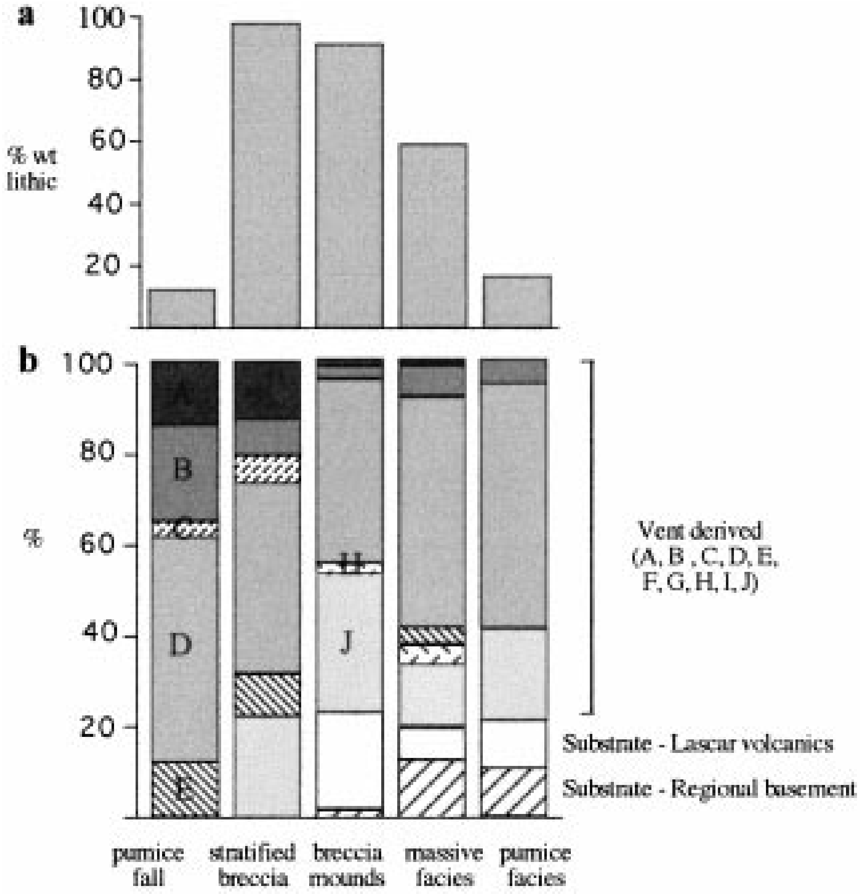


Fig. 4. Average wt% lithic components (a) and lithic assemblages (b) for each of the Soncor ignimbrite lithofacies compared to that of the plinian pumice fall deposit. Lithic types have been categorised (Table 2) into those derived from the vent (A–J), and those that are substrate-derived.

section comprises a basal, matrix-poor gravel layer (~1 m) of probable vulcanian origin, rich in fragments of microporphyritic white dacite overlain by 18 m of well-sorted, white dacite pumice (Fig. 8). This is capped by a 4 m thick mixed zone of dacite pumice (62 wt% SiO_2), grey andesitic pumice (59–61 wt% SiO_2) and compositionally banded pumice. The deposit is lithic poor (<5 vol%), with maximum size and abundance of lithics clasts decreasing with height through the section. Lithic populations from the >8 mm sieve fractions from seven horizons through the section were categorised in the field into groups (Table 2). The plinian lithic assemblage consists largely of dacitic rocks, interpreted as a pre-existing dome complex, a heterogeneous assemblage of altered volcanic rocks, Stage I andesite lava clasts and hypabyssal intrusive rocks.

For the main ignimbrite the average lithic assemblage content (>8 mm) for 27 sites (Fig. 4) is 58 wt% with ~21% of these clasts having been incorporated from the substrate. Maximum sizes of pumices (MP), vent-derived lithics (ML^V) and substrate-derived lithics (ML^S) were collected by averaging the dimensions of the three axes of the five largest clasts (for 40 localities). Substrate-derived lithics are found throughout the lower 30 m of the section shown in Fig. 7 and are conspicuously large (4–24 cm) in comparison to those derived from the vent which show only minor variation (1–4 cm) with height.

MP varies from 2 to 23 cm, increasing in pumice concentration zones.

Thermal remnant magnetisation studies to establish paleofield directions and intensities and emplacement temperatures were carried out on Soncor ignimbrite within the Quebrada de Talabre (Thomas, 1993). Groups of ten lithic samples ranging in size from 5 to 50 cm were taken from three localities within the massive facies in the zone 4–8 km from the vent. Emplacement temperatures were found to be consistent 580–600°C for all three sites, implying firstly that temperatures did not vary over a 4 km distance and secondly that substantial cooling occurred between eruption and proximal (<4 km) flow emplacement (estimated temperatures for this dacite magma are 800–900°C (Matthews et al., 1999)). Entrainment of air and degassing of juvenile clasts during fountain collapse (Druitt et al., 2001) and the incorporation of abundant cold lithics (e.g. Marti et al., 1991) contributed to cooling.

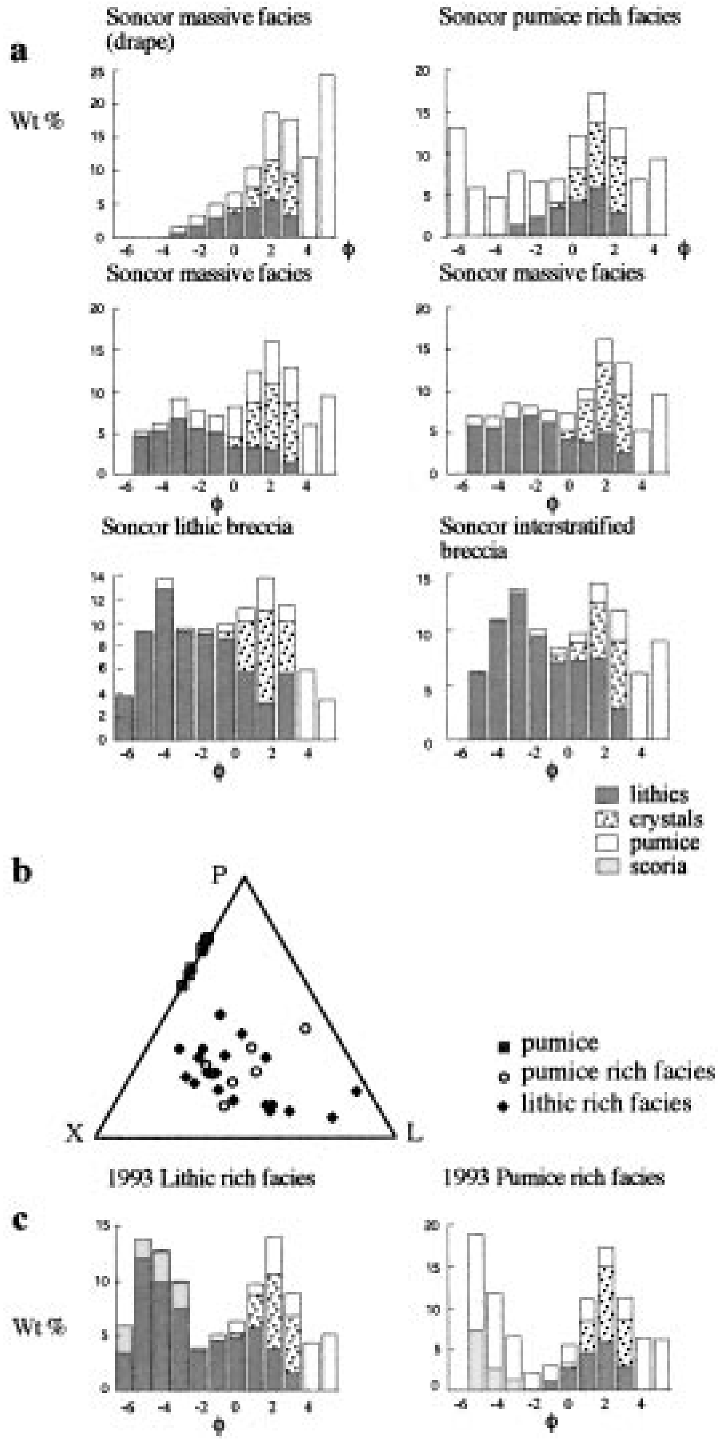
3.2. Pumice facies

Pumice rich facies constitute typically coarse, clast supported, well-rounded pumices with interstitial fine ash and rare small (<1 cm) lithics. Pumice facies have been recognised in three different situations within the Soncor ignimbrite (Fig. 2). First, pumice rich levees are abundant in the Quebradas de Tumbres and Chaile. They occur against the quebrada walls in high stratigraphic positions occasionally over spilling onto the interfluves. In Fig. 6, Loc 43, two flow units of pumice levees can be discerned, the upper coarse and predominantly of mixed or mafic pumice and the lower predominantly a white pumice unit. The compositional zonation of the two flow units is abrupt and coincides directly with the flow unit boundary as marked by a grain size break at the top of the reversely graded unit. Second, pumice rich layers and lenses are common in the interior of the massive facies ignimbrite (Fig. 7). The lenses are ~50 cm thick and 2–3 m in width with a convex upper surface and steep sided contacts. These lenses are commonly discontinuous over distances of 10s of metres and the nature of their steep terminations are reminiscent of constructional features of small lobe flow terminations indicating that they correspond to individual flows. The layers are 20–70 cm thick and include pumice rich tops of reversely graded units (Fig. 3b). The third situation for pumice facies are the flow fronts (strictly 'deposit' fronts) which are most conspicuous in distal areas. In the western fan, pumice rich deposit fronts occur >23 km down slope from the vent. They outcrop in a series of small channels and ridges formed by erosion of the originally lobate deposit termini (Fig. 2). The deposit fronts are 1–1.5 m high with steep sides and are composed predominantly of crystal rich dense pumices. Pumice lenses within the massive facies in the zone 15–25 km from the vent are thought to represent buried deposit fronts of earlier, less energetic flows. Small-scale topographical features such as boulders and small gullies also acted as traps for pumice deposition. These basal lenses lack the more mafic, later-stage pumices. Extensive beds of pumice rich facies also occur over large areas adjacent to the quebradas on top of the Tertiary ignimbrite plateau. These comprise drapes of matrix-rich pumice facies, but also include scattered large pumices (up to 35 cm) thought to represent stranded deposit tops and levees with the fines winnowed away.

Grain size distributions of the pumice facies are strongly bimodal with coarse modes at $> -6\phi$ and fine tail modes $\sim 3\phi$ and exhibit coarse tail grading (Figs. 5 and 6). Component analyses show the $<0\phi$ matrix is similar to that of the massive facies. Md ranges from -3.4 to 1.4ϕ and σ ranges $2.8–4.5\phi$. Pumice densities are typically in the range 500–1200 kg m^{-3} with crystal rich pumices having densities of up to 1900 kg m^{-3}. Pumice in this facies is therefore slightly less dense than those from the massive facies. Lithic clasts account for 5–22 wt% (with average of 18 wt%) of the samples with ~22% of the clast number having been derived from the substrate (Fig. 4).

3.3. Lithic breccias

Lithic breccias predominantly occur proximally. They range from clast-supported and fines-poor subfacies (Fig. 5e) to those with a pumiceous ashy matrix, which are gradational into the massive ignimbrite facies (Fig. 5a). Three sub-lithofacies are usefully distinguished: stratified fines poor breccias, isolated hummocks of coarse breccia, and sheets and lenses of breccia interstratified with massive facies.


a
Soncor massive facies (drape)
Soncor pumice rich facies
Wt %
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Soncor massive facies
Soncor lithic breccia
Soncor interstratified breccia
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1993 Pumice rich facies
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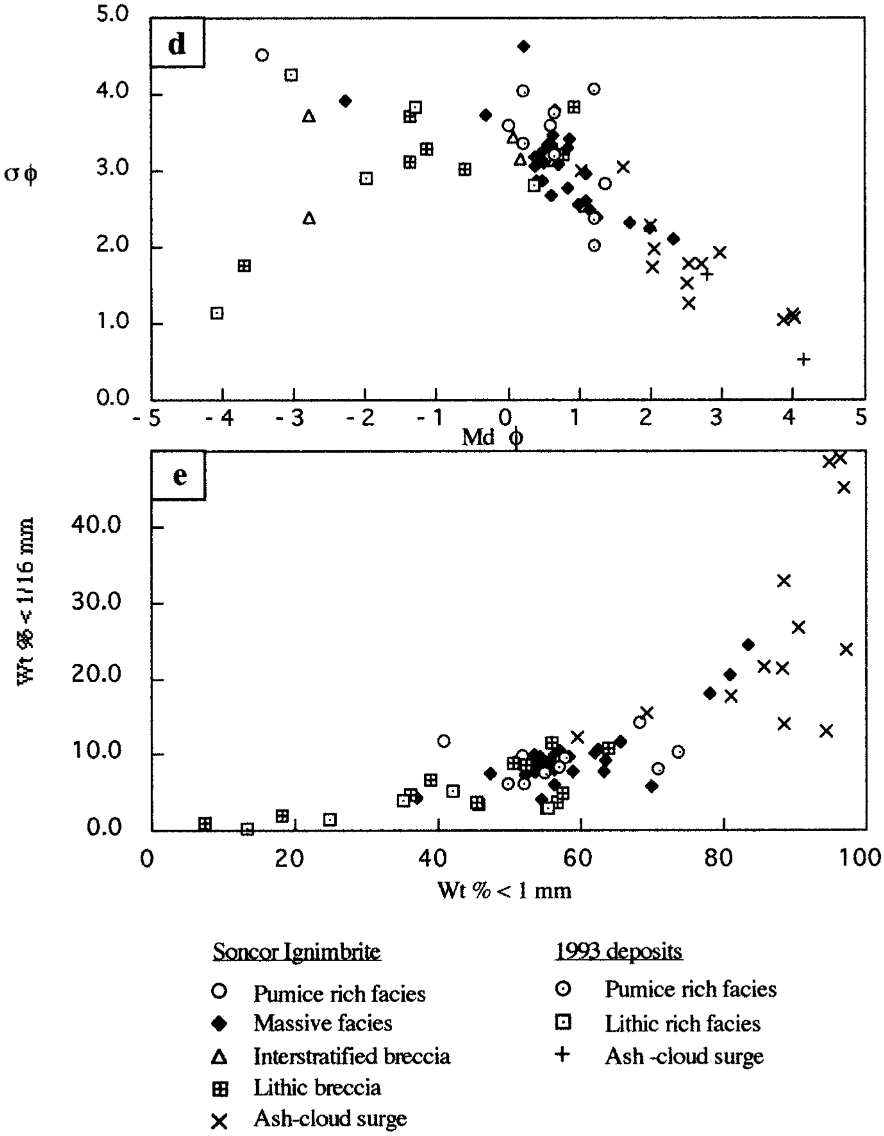


Fig. 5. (a) Representative grain size histograms and componentry analyses for six typical samples of the Soncor ignimbrite from each of the main lithofacies. (b) Ternary plot of componentry analyses for Soncor ignimbrite samples (lithic rich and pumice facies) compared to whole rock crystal content of juvenile pumice. (c) Representative grain size histograms and componentry analyses for typical samples of the lithic rich and pumice rich 1993 pyroclastic flow deposits. A distinction has been made between pumice (white) and scoria (pale grey) components in the >4 mm fraction. (d) Sorting (σ_ϕ) against median diameter (Md_ϕ) and (e) fines depletion diagram of Walker (1983), for both the Soncor ignimbrite and the 1993 pyroclastic flow deposits.

The stratified breccia sub-facies is best observed at Loc B (Fig. 2) where it reaches 7–8 m thick overlying the plinian pumice fall deposit on a slope of 13–15°. The clast supported lithic breccia is bedded on a decimetre to metre scale with bedding defined by variations in grain size with the coarsest beds containing blocks up to 75 cm and the finer gravel beds predominantly containing fragments <5 cm (Fig. 3c). Predominantly, grain sizes are blocks, lapilli and coarse sand, with little or no ash. Pumice is subordinate and occurs as small

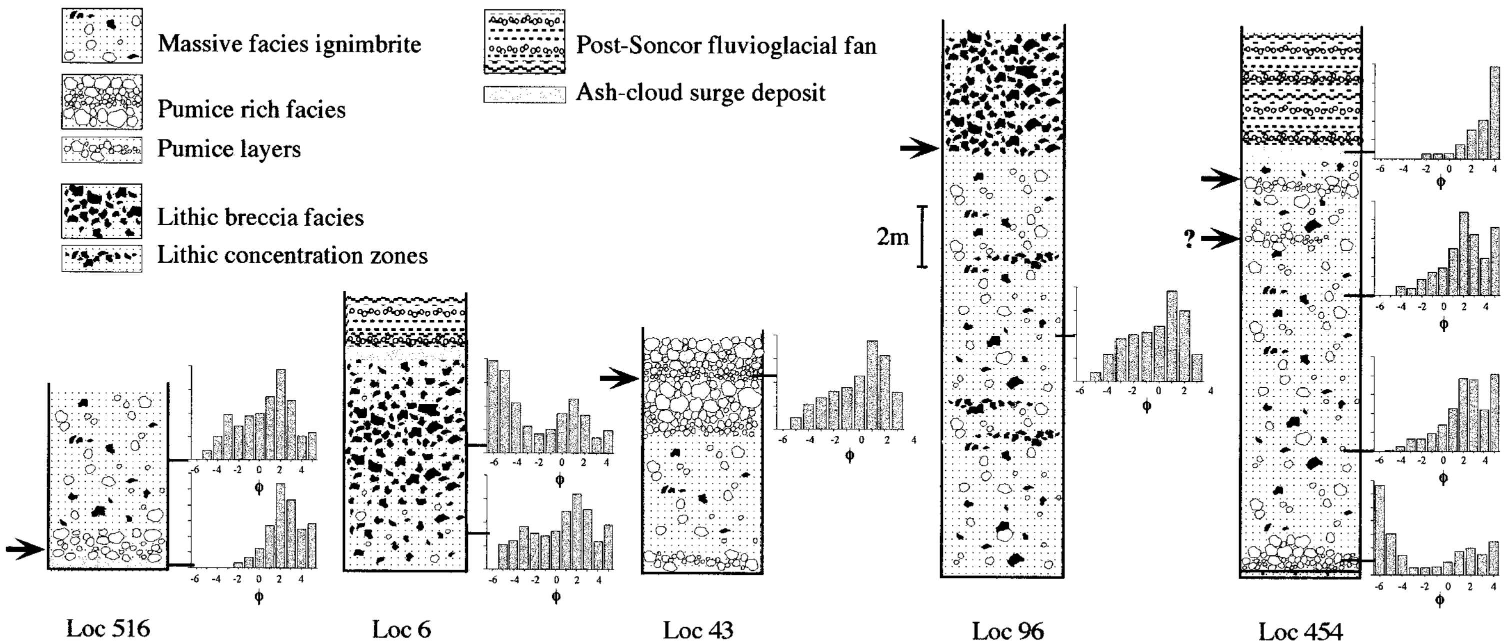


Fig. 6. Five representative stratigraphic sections through the Soncor ignimbrite are illustrated with grain size histograms for −6 to 5ϕ sieve fractions (on the vertical axis weight is illustrated in 5% intervals). The bulk of the ignimbrite comprises the massive facies with pumice occurring in rafts on the upper surface (Loc 43), in layers throughout the massive facies (Loc 454) and in basal lenses (Loc 516; Loc 43). Lithic breccias occur in concentration zones and non-continuous layers interdigitated with the massive facies ignimbrite (Loc 96) and also as discrete deposits in proximal environments (Loc 6). These pumice and lithic concentration zones and lenses are interpreted to define 'flow unit' boundaries i.e. they represent the upper and lower limits of the deposits that were emplaced by a single pyroclastic flow. Most of the sections of the Soncor ignimbrite are inferred to represent amalgamated deposits of several flow units. Examples of well-defined flow unit boundaries are illustrated by arrows but they are not always discernible and occasionally where they do occur they can be traced laterally into massive facies deposits with no obvious breaks.

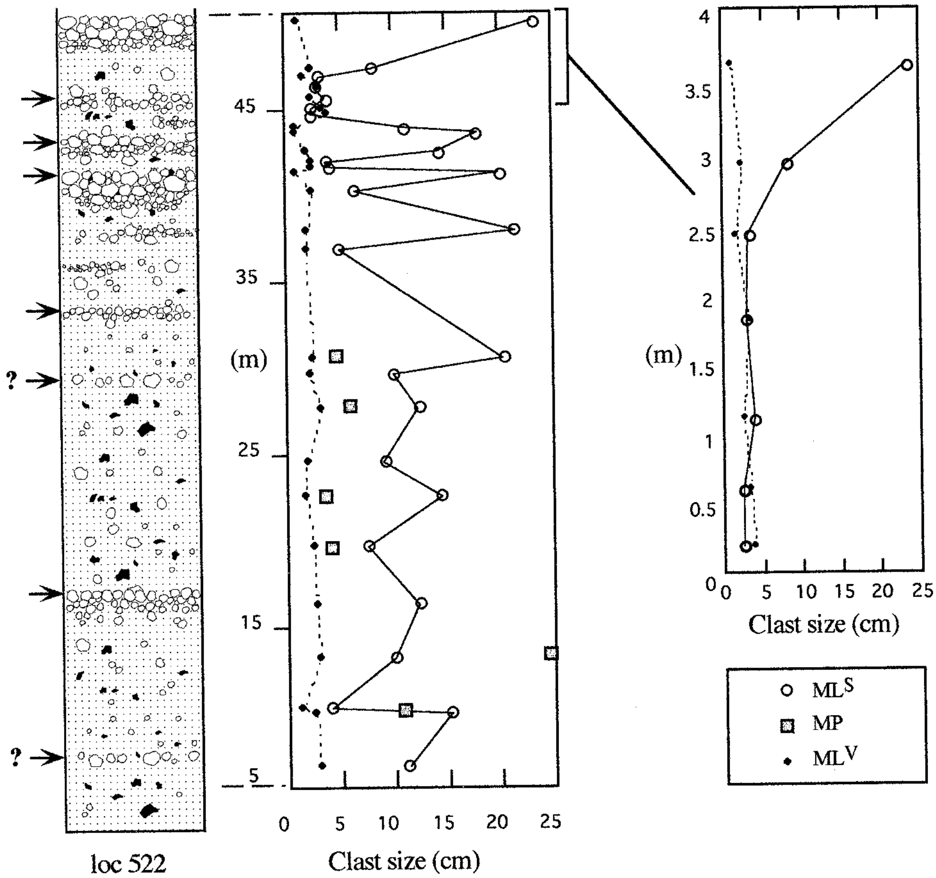


Fig. 7. Maximum vent-derived lithic, ML^V (small dot), maximum substrate-derived lithic, ML^S (large squares) and maximum pumice, MP (open circles), variations throughout a 50 m composite section of the Soncor ignimbrite, Loc 522 (Fig. 2). Arrows on left-hand side indicate locations of inferred flow unit boundaries. On the right-hand side, the inset shows a detailed profile of the upper flow unit with reverse grading of pumice clasts and subtle normal grading of lithic clasts. Large substrate-derived lithics were not found in this flow unit.

rounded clasts (<4 cm). Lithic assemblages are entirely composed of vent-derived lithics (Fig. 4), including >20% disaggregated prismatically jointed blocks (PJBs) which were not found in the underlying pumice fall layers (Table 2, Category J). PJBs comprise 2-pyroxene porphyritic andesite clasts, interpreted as remnants of the pre-Soncor eruption lava dome and grey/green basaltic andesites with hypabyssal textures (Matthews et al., 1999). Other clasts have been highly fractured, and disaggregate on contact, a texture which has previously been attributed to thermal effects (Druitt and Bacon, 1986).

Isolated hummocks of breccia occur between 1 and 6 km from the vent (Fig. 2). The hummocks are elongated parallel to the inferred flow direction and are 1–3 m high, 10–20 m wide and 20–80 m long and lie on slopes of 5–16°. Hummocky lithic breccias are massive, clast supported and largely composed of angular to sub-angular lithic blocks in an ashy matrix. With increasing distance from the vent the matrix commonly becomes richer in fine ash. Most lithic clasts are <1 m, but blocks as large as 4 m occur up to 5 km from the vent. Small, typically <2 cm white juvenile pumice lapilli are a ubiquitous but subordinate component. Some localities have larger (up to 10 cm) mafic pumice clasts that are characteristic of the late stage of the eruption. Lithics derived from the substrate are an average of 24 wt% (range 18–45%) although ~90% of these are Lascar volcanic lithologies derived from the edifice region (Fig. 4). Where flows passed over the

Table 2
Classification of vent-derived lithic clasts in the Soncor plinian deposit and ignimbrite

Plinian Deposit	
Category	Description of lithology
A	Pale grey/white microporphyritic or aphyric dacite with microphenocrysts of plagioclase, pyroxene
B	Pale grey/white coarse/porphyritc dacite with plagioclase, pyroxenes and amphiboles, also found as veins in (A), (Piedras Grandes dome complex)
C	Vent breccia, glassy andesite containing mixed clasts
D	Hydrothermally altered clasts Old weathered lithologies from edifice
E	Red/brown haematite coated andesites
F	Coarse grained/porphyritic granodiorite and intrusive rocks
G	Dark vesicular and non-vesicular glassy microporphyritic andesites with phenocrysts of plagioclase (Stage I lavas)
Additional types found in Co-ignimbrite Breccia	
H	Agglutinates, dense poorly vesicular crystal-rich glassy andesite containing anglular clasts of andesitc lavas and type (A) and(B) porphyritic rocks
I	Vitrophyres, pale cream poorly vesicular dacitic welded rocks consisting of glassy fiamme and unflattened to slightly flattened dacitc pumice
J	Prismatically jointed blocks (PJBs) Pale two-pyroxene porphyritic dacites (Soncor dome complex) Pale to dark green medium grained basaltic andesites porphyritic to holocrystalline with hypabyssal textures

Stage I andesite lavas, blocks up to 2 m diameter were transported several hundreds of metres downstream and deposited in breccia hummocks.

The third sub-facies are found as discontinuous sheets in proximal areas (Fig. 2) and intimately interstratified sheets and lenses within the massive facies. They are clast to matrix supported, and are transitional in character to the massive facies ignimbrite. They are poor in blocks >20 cm and have abundant fine, pumiceous matrix identical to that of the massive facies (Fig. 3d). Pumice clasts are well rounded, and up to 12 cm diameter. Lithics are clast to matrix supported and assemblages are diverse. This breccia sub-facies occur on slopes ($<6°$) at the foot of the edifice and within quebradas in the medial (7–20 km) areas. They occupy the zone between the maximum limits of the hummocky lag breccias and the onset of thickly ponded massive facies. In the Quebrada de Soncor (Fig. 2, Loc C), thickly ponded deposits of the massive facies contain five discernible lithic breccia layers, which are laterally discontinuous for distances of more than a few tens of metres.

3.4. Other facies

Ash-cloud surge deposits (Fisher, 1979) and co-ignimbrite ash fall deposits (Sparks and Walker, 1977) occur sporadically. These 3–4 cm thick crystal rich bedded and cross stratified ash layers have been preserved by burial below deposits from subsequent flows. At the sides of quebradas they have been preserved under subsequent pumice levee deposits, and fluvial deposits capping many sections have covered and preserved fine co-ignimbrite ash layers in at least two localities (Fig. 6, Loc 6 and 454).

4. The 1993 eruption

On the 18th April 1993, Lascar entered a new phase of explosive activity. The eruption commenced with

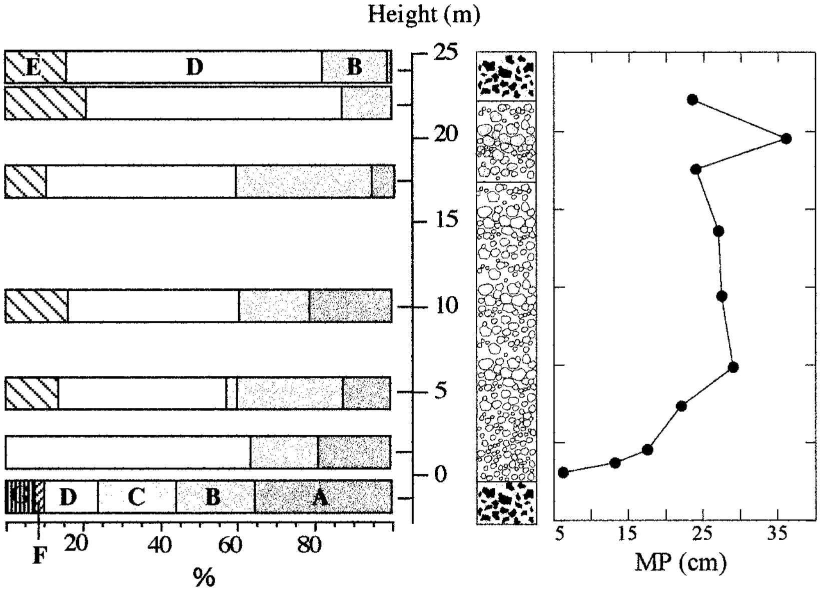


Fig. 8. Stratigraphic section through the Soncor plinian fall deposit at its thickest and most proximal locality, Loc B (Fig. 2) illustrating the reverse grading from maximum pumice size data. The zones of white dacitic pumice and darker andesitic and hybrid banded pumice (grey shading) have been distinguished. Lithic breccias occur at the base (vulcanian deposit) and capping the section. Lithic assemblages for seven horizons throughout the section have been analysed according to the categories A–J (Table 2). The stratified breccia sub-facies lies directly above this section.

two vulcanian explosions, disrupting the 1992 lava dome within the Stage IV crater, and developed over night into an eruption column between 5 and 23 km in height (Gardeweg and Medina, 1994). The eruption continued for 32 h, pulsating in intensity and dispersing coarse pumice fall deposits to the south-west. Instability and short-lived collapse of the column occurred on at least nine occasions producing pyroclastic flows which descended the north-western and southern flanks. Photographs taken on the 19th April (Fig. 9a) show pyroclastic flows descending the north-western flanks over the Tumbres–Talabre lava with reported average flow front velocities of ~55 ms^{-1} for a runout distance of 6 km.

4.1. Pyroclastic flow deposits

The deposits extend to the north-west for 9 km and to the south-east for 4 km and were mapped (Fig. 10) using aerial photographs of 26th April 1993. The fans consist of numerous overlapping lobate flow units with well-developed 0.2–1.2 m high pumice rich levees, channels and deposit front features. The accumulated deposits have a maximum thickness of 3–5 m and a volume of ~0.06 km^3 (in situ). The pyroclastic flows that formed the northern fan flowed into the upper reaches (4250 m) of the Quebrada de Talabre and continued westwards for a further 4.5 km. These flows moved over the Tumbres–Talabre lava flow (7.1 ka) eventually over spilling and travelling beyond the lava flow front (Fig. 9b). The smaller southern fan is limited to the immediate flanks of the volcano only spilling out onto the Pampa Lejia plain for a few hundred metres. On the upper flanks the flows were largely channelled through relatively narrow valleys spreading out into fans where the slope decreased to <12°.

Thin (typically <5 cm) ash-cloud surge and co-ignimbrite ash deposits were identified which could be traced a few hundred metres beyond the margins of the fan (Fig. 10). The distribution of this facies indicates clearly that thick and laterally extensive surge clouds occurred only on the upper flanks of the volcano. This is supported by photographic records (Fig. 3 in Guarinos and Guarinos, 1993). These

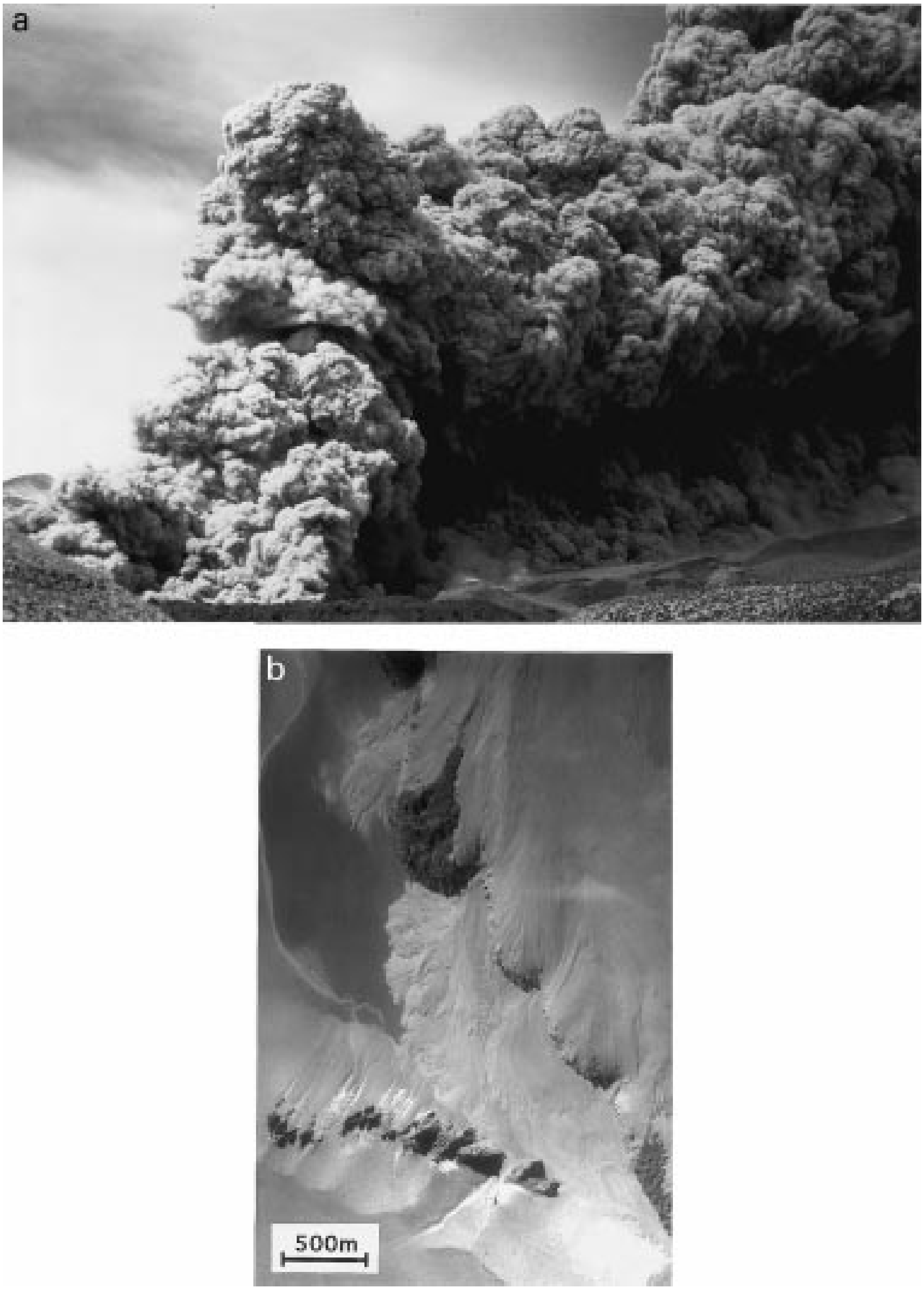


Fig. 9. (a) 1993 pyroclastic flows, photograph courtesy of J. Guarinos (Guarinos and Guarinos, 1994) showing advancing pyroclastic flow formed by the 13:15 explosion on 19 April 1993, taken 7.5 km from the crater at an altitude of 3900 m. (b) Pumice rich lobes of the 1993 pyroclastic flow deposits produced as the flows descended over the front of the Tumbres–Talabre andesite lava flow.

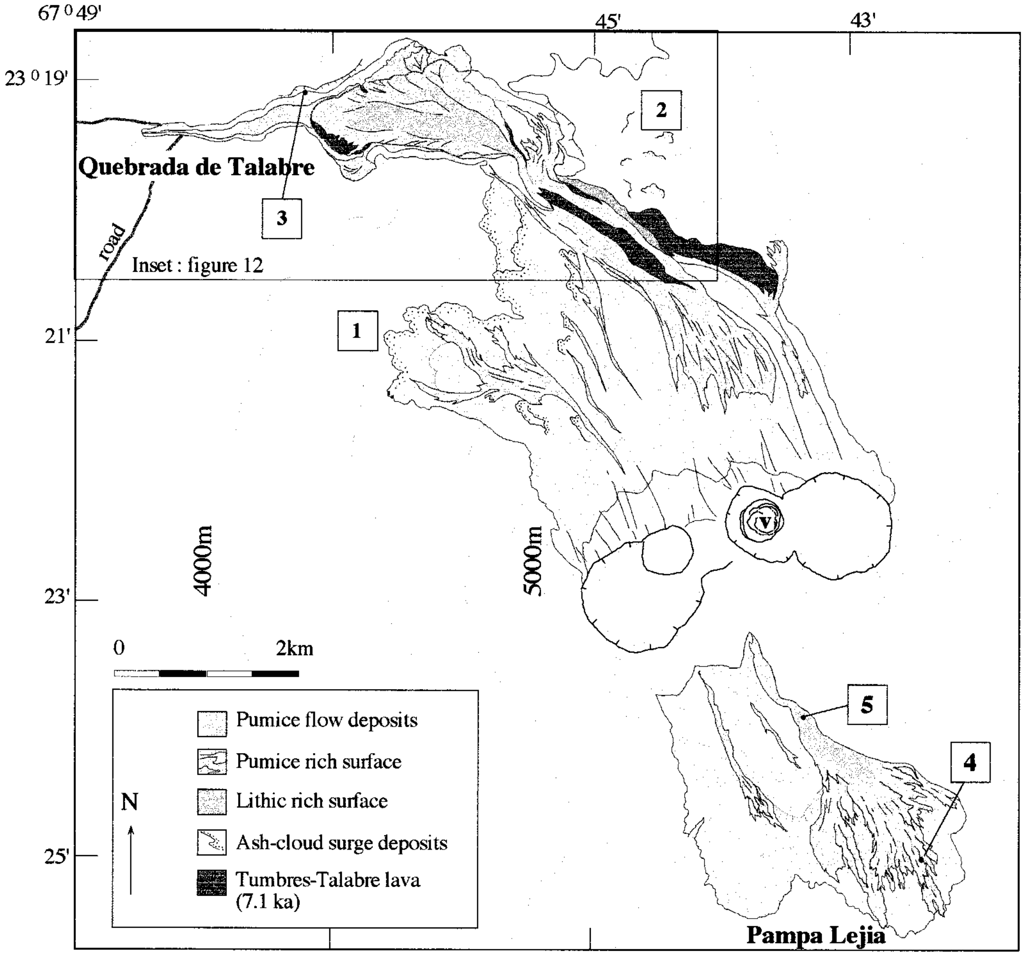


Fig. 10. Distribution of the deposits from the 18–20 April 1993 pyroclastic flows. The two main lithofacies, the lithic rich facies and the pumice rich facies are shown, along with the distribution of the ash-cloud surge deposits. The source vent is marked V and the Tumbres–Talabre andesite lava flow (7.1 ka) is illustrated in dark stipple. Locations of examples of: (1) ash-cloud surge deposits; (2) detached ash-cloud surge deposit; (3) limited surge deposit; (4) pumice-rich lobes and (5) narrow erosional gully are illustrated.

surge clouds had a significant component of lateral motion and similar surges in Montserrat are known to develop in the highest velocity phases of pumice flow emplacement (Druitt et al., 2001). The 1993 surges travelled up to 3 km from the vent before buoyant lofting occurred (Fig. 10, Loc 1). Loc 2 (Fig. 10) highlights a region where local surge detachment from the basal flow occurred at a bend in the flow path, depositing ash on a series of small ridges to the north of the main flow deposits. In the region 3–10 km from the vent, ash-cloud surge deposits and singe zones are limited to only a few metres marginal to the main coarse grained flow deposits (Fig. 10, Loc 3). It appears that the energetic laterally driven ash-cloud surges either run out of energy or transform by sedimentation into low energy fluidised flows. The ash-clouds generated by elutriation from the moving pyroclastic flows in the lower valley are thus distinct from the extensive laterally mobile surge clouds generated in proximal environments close to the region of collapsing fountain.

The deposits of the 1993 flows comprise pumice

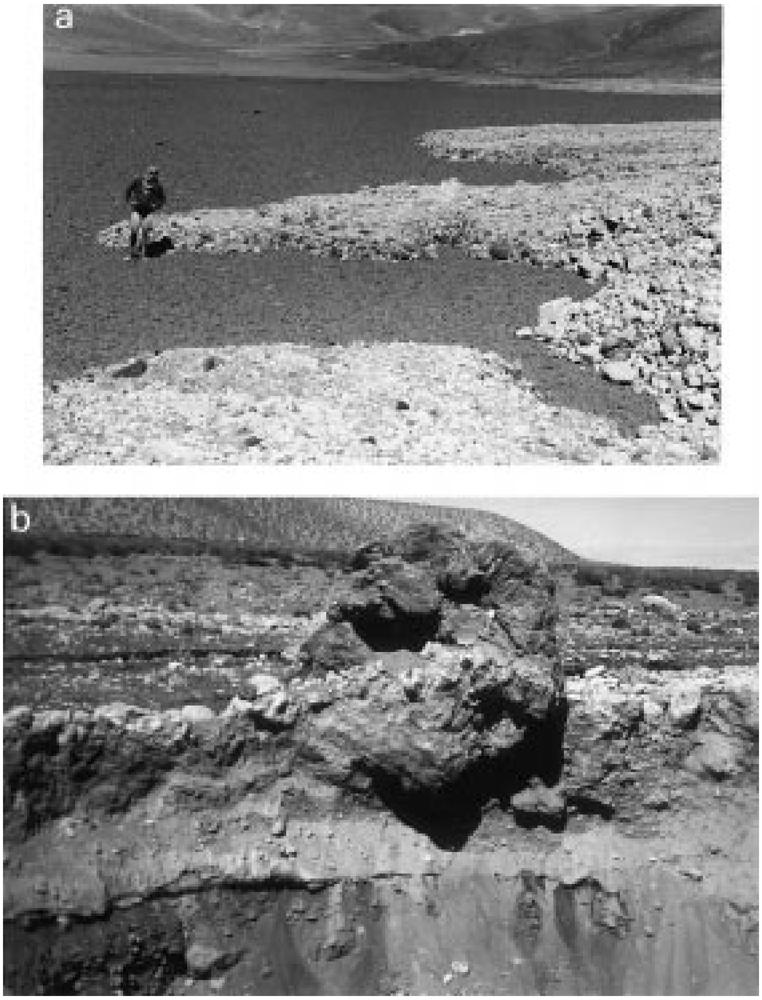


Fig. 11. Facies variations of the deposits of the 1993 pyroclastic flows. (a) Pumice rich deposit fronts of 0.3–1.5 m high with little/no interstitial matrix. (b) A section through a flow unit showing a thin layer of pumice on the surface and exposing a more lithic rich interior. Embedded in the flow unit (~60 cm thick) is an 80 cm block of vent breccia which has travelled 8 km from the vent. (c) Lithic breccia surface of the 1993 flow deposits 100 m downstream from the plunge pool at the front of the Tumbres–Talabre lava flow. Upstream from the block (~1 m), a mound of coarse lithic breccia has been trapped as the flow continued downstream (towards lower right) producing a crag and tail morphology.

rich and lithic rich lithofacies. Pumice rich areas are lighter in surface colour and possess more marked constructional features such as levees and lobate deposit fronts (Fig. 10, Loc 4). Lithic rich facies occupy the interiors of the deposits and are only exposed in limited fluvial cuttings or where eroded into by pyroclastic flows later in the eruption. Eroded areas identified from the aerial photographs, are generally darker and have a negative relief, corrugated surface texture.

4.2. Pumice rich facies

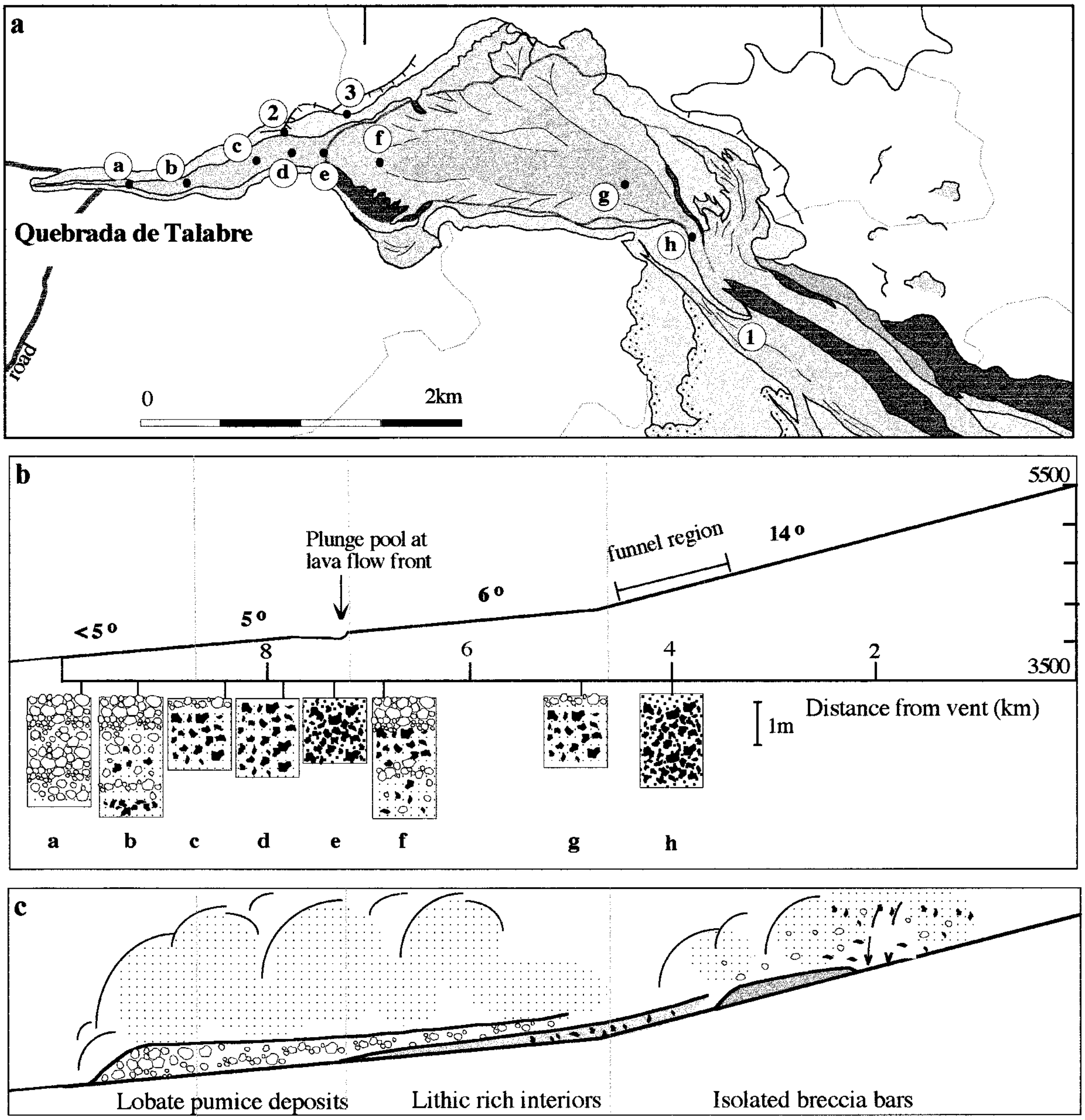
The surfaces of much of the fans are pumice rich. The pumice rich facies consists of abundant, well-rounded, decimetre sized pumice clasts set in a poorly sorted ash matrix. Samples display a strongly bimodal grain size distribution (Fig. 5c–e) with coarse modes at $>5\phi$ and fine tail modes at $\sim 2\phi$ although levee structures often appear matrix free. Juvenile clasts are dominantly pale grey or pink, silicic

Fig. 11. (*continued*)

andesite pumice (60.4–61.4 wt% SiO_2) with an average density of 900 kg m^{-3} and a range 500–1100 kg m^{-3}. These deposits contain minor amounts of dark grey juvenile mafic andesite scoria (57.6–58.7 wt% SiO_2) with average density of 1700 kg m^{-3} (range 1300–2000 kg m^{-3}). There are also compositionally banded clasts of white pumice and dark scoria. Dark pumice and mafic scoria are more abundant in the upper flow units. Lithic clast content is typically <15 wt% and maximum lithic size is usually <2 cm. Pumice rich facies typically occur at deposit fronts (Fig. 11a), fan margins and as thin veneers on the surface of lithic rich deposits (Fig. 11b). This facies dominates areas where the slope gradient is <5° and characteristically displays abundant constructional features and matrix free zones. In section the deposits show scattered gas escape pipes, coarse tail grading and fine grained basal layers (~2 cm), all typical characteristics of ignimbrites (Sparks et al., 1973). Deposit interiors are often lithic rich even though the upper surface is pumice rich (Fig. 11b). These pumice rich surface layers are commonly one clast thick and have a corrugated upper surface. The same flow unit can be traced downstream and to the margins into pumice rich zones (Fig. 12a and b).

4.3. Lithic rich facies

This facies consists of lithic breccias in which the pale grey pumice is often a minor component but dense scoria is a major component. Blocks up to 3 m include vent derived bread-crusted fragments (0.2–2 m) of the 1992 andesite lava dome, welded vent and dome breccias, PJBs and distinctive entrained substrate lithologies, including Tertiary ignimbrite, Quaternary Cerro de Saltar dacite and Lascar Stage I red Saltar scoria (Table 1). These breccias range from those with a poorly sorted matrix of fine ash to hummocky mounds of lithic blocks with no fine ash matrix. The latter deposits are interpreted as lag breccias. Lithic rich facies display variably bimodal grain size distribution with coarse modes $\geqslant -5\phi$ and fine tail, modes $\sim 2\phi$ (Fig. 5c–e). Lithic breccias and fines depleted lithic facies are found where the pyroclastic flows descended the steep front of the Tumbres–Talabre lava (Fig. 12a, Loc e, d). Here a plunge pool structure has been eroded by the flows at the base of the step. The base of the pool is filled with coarse matrix-poor lithic breccia, which grades downstream into fines-rich breccia and eventually into a thin pumice rich layer overlying a lithic rich base (Fig. 12a, Loc c). A similar relationship was found on the southern fan at Loc 5 (Fig. 10) where the flows descended a steep narrow gully and at the break in slope, subsequently spread out. A relationship between the minimum slope on which deposition occurred and the composition of the deposit has been reported (Sparks et al., 1997). Exposed lithic



rich deposits were only found deposited on slopes from 6–14° and their surfaces exhibit negative relief furrow and "Crag and tail" structures (Fig. 11c).

5. The distribution of substrate-derived lithic clasts

We have distinguished vent-derived and locally entrained lithics in the deposits of both the Soncor and the 1993 eruptions. ML^V may be considered to define transport capacity at a given distance, whereas, ML^S is typically larger (Fig. 7). A distribution map of the two main groups of substrate-derived lithics in the Soncor ignimbrite has been compiled (Fig. 13a). The lithics comprise Lascar volcanic rocks (Stage I lavas, Saltar and Chaile scoria and Piedras Grandes andesite) and regional basement rocks (Tertiary ignimbrites, Tumisa, Cerro Corona, and Cerro de Saltar dacite). Locally, entrained lithics account for up to 65% of the lithic population. Lithic assemblages of medial localities are dominated by Lascar lithologies while more distally, where the flows have travelled over the pre-Lascar basement, assemblages are dominated by the regional basement lithologies (Fig. 13a).

Lithic assemblages in sequential localities in traverses down the Tumbres, Soncor and Chaile quebradas (Fig. 13b) are strongly dependant on the underlying geology and the specific flow path. A Permo-Triassic granite hill (Cerro Opla), 20 km downstream from the vent, rises ~250 m above the upper surface of the ignimbrite. At the foot of the hill, on the stoss side, piles of breccia have been deposited as the flow was diverted around the hill. A well-defined (1 m wide) swash-up mark ranges from 15 to 20 m above the deposits. Downstream the ignimbrite becomes enriched in granite lithics (Fig. 13b). Systematic measurements of these entrained clasts and the corresponding vent-derived clasts were made along a 6 km traverse downstream (Fig. 14a). The region downstream of Cerro Opla is characterised by complex facies variations, lithic breccias and pumice lenses are found interstratified with the massive facies. Substrate-derived lithics are consistently larger, but ML^S and ML^V are primarily a function of the host facies and do not simply reflect distance from source. Lithics may also have been entrained from downslope granite talus and thus grain size might also partially reflect talus distribution. At the head of the Quebrada de Soncor, 50% of the lithics in the ignimbrite are andesitic Piedras Grandes clasts reflecting the path of the flow over the older unconsolidated block-and-ash flow deposits (Fig. 13a and b). Downstream, the deposits contain clasts of Permian lavas that comprise 18–43% of the lithic content, reflecting the passage of the flow through a narrow gully cut through Cas formation Permian lavas (Fig. 2, Loc A). In the Quebrada de Tumbres pumice rich facies contain fewer entrained lithics than the adjacent massive facies ignimbrite (Figs. 7 and 13b).

Substantial variations in the proportions of vent-derived lithics were also observed (Fig. 13b) which partially arise from the spatial distribution of different flow units. The Quebrada de Talabre traverse was rich (up to 40%) in glassy andesite vent breccia (Table 2, Category C), which is relatively rare elsewhere. PJBs (Category J) are abundant in units associated with a higher proportion of mixed pumices and mafic andesite scoria. Glassy vent breccia was only discharged from the vent at the onset of the eruption (Fig. 8), while PJBs were only found in the stratified lithic breccias capping the plinian deposit (Fig. 4), indicating late stage generation.

The small 1993 flows were locally highly erosive even in distal localities. Where they spilled over the front of the Tumbres–Talabre lava flow (Fig. 9b) large andesite blocks (1.6 m) were carried several hundred metres downstream. Lithic clast sizes for three lithologies were measured along a 1.2 km traverse downstream from the lava flow front (Fig. 14b). ML^V ranged between 15 and 65 cm, the largest blocks consistently being glassy vent breccia and bread crusted dacitic bombs. As well as the andesite lava lithics, the deposits also contained conspicuous

Fig. 12. (a) Inset of 1993 deposit map (Fig. 10) showing sequential localities (a–h) in a traverse down the north-western fan of the 1993 flow deposits. Localities shown are: (1) head of funnel region with Tumbres–Talabre andesite directly to the north; (2) scoured basal cliff locality; (3) locality of furrows and striated colluvium blocks. (b) Sections from the traverse of the 1993 flow deposits showing lateral facies distribution and average slope changes. Distance from the vent is shown in km. Sections a, b and f each comprise two well-defined flow units. In sections b and f these are defined by upper pumice rich layers and in section a, the flow units boundary is defined by the grain size break between the reversely graded pumice units. (c) Conceptual model for the derivation of the pumice rich and lithic rich facies variation in the 1993 pyroclastic flows. Proximal regions on the upper flanks of the volcano are characterised by relatively little deposition. Deposits, where present, are coarse fines-poor lithic breccias. The equivalent deposits of the Soncor eruption are the stratified breccias directly overlying the plinian pumice deposits which are considered to be progressively aggraded. Coarse clasts are then rapidly sediment from the inflated current to produce a concentrated granular underflow. Segregation of pumice and lithic clasts occurs progressively within the flow as it travels downslope. Lithic rich portions of the flow have a higher internal coefficient of friction and are therefore deposited on relatively steep slopes (14–6°). Pumice rich portions of the flow are mobile in comparison, and are not deposited until the flow reaches slopes of <5°. A thin pumice rich lag layer representing the detachment horizon is commonly preserved on the surface of the lithic rich deposits.

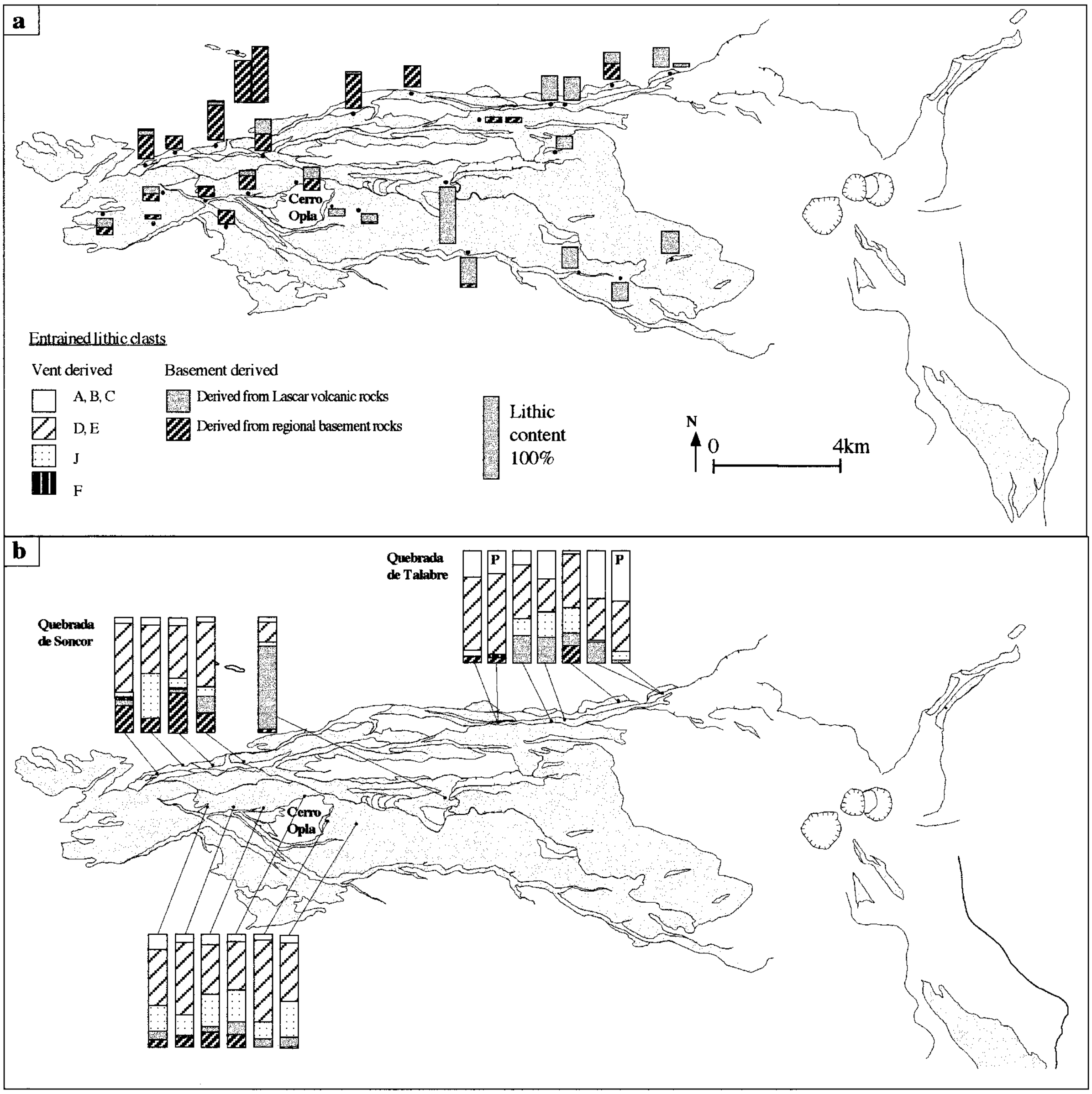


Fig. 13. (a) Entrained lithic population maps for the two main groups of substrate-derived lithics in the Soncor ignimbrite; Lascar volcanics and regional basement lithic fragments. Proportions are represented by height of the bar where total lithic content (100%) is given by the bar (14 mm) at the foot of the map. (b) Map of sequential lithic populations for three quebradas that contain inliers of distinctive basement lithologies. This illustrates variations of both substrate-derived and vent-derived lithics.

red clasts of the Stage I Saltar scoria flow deposits. ML^S (Saltar scoria) remained consistently <25 cm along the traverse, reflecting either their incorporation in the flow at distances of >3 km upstream, their relatively low density and friable nature or their original size distribution. ML^S (Tumbres–Talabre andesite) sizes are seen to range between 45 and 275 cm. Up to 800 m from the lava flow front the 1993 flows were able to transport dense andesite blocks of 160 cm in diameter while 80 cm vent-derived

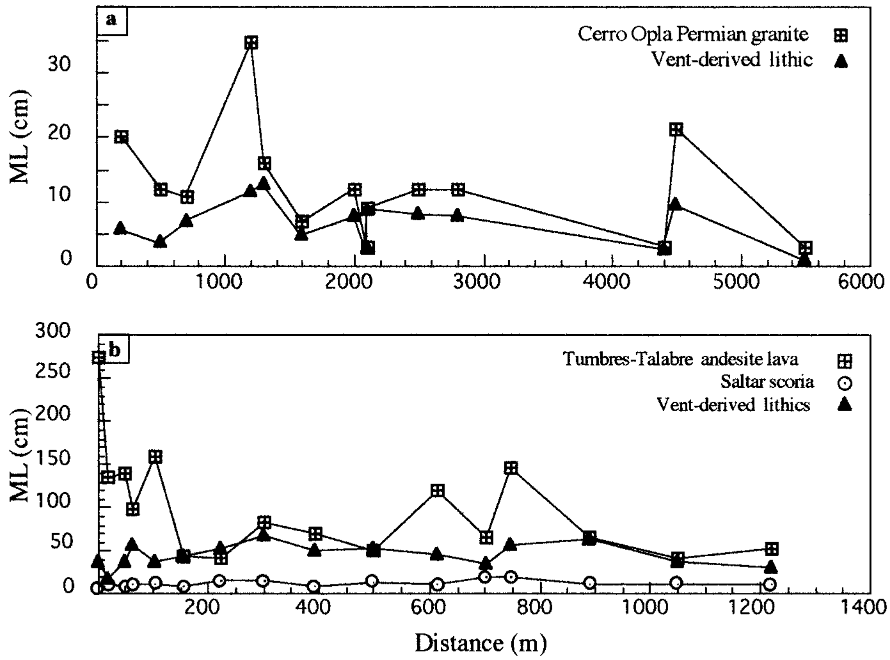


Fig. 14. Maximum vent-derived lithics (ML^V) and maximum substrate-derived lithics (ML^S) data from: (a) the Soncor deposits in a traverse down the Quebrada de Chaile downstream of Cerro Opla granite inlier; and (b) the 1993 flow deposits following a traverse downstream from the Tumbres–Talabre lava flow front. In (b) two substrate derived lithologies have been considered, Tumbres–Talabre andesite lava and Saltar scoria, the source of which is 3 km upstream. The co-variation of ML^V and ML^S seen in (a) is a function of diverse host facies variation.

blocks had travelled ~8 km (Fig. 11b). The convincing co-variation of ML^S (Tumbres–Talabre andesite), ML^S (Saltar scoria) and ML^V, in all but the first 100 m of the traverse, reflects lithic content of host facies which varied from coarse breccias to pumice rich facies.

6. Segregation of lithic clasts during transport

Maximum size data for lithics in 40 localities in the Soncor ignimbrite (Fig. 15a) show that at any distance ML values are variable, but that maximum ML decreases away from the vent in both vent derived and substrate derived lithics. The decrease in ML^S implies a general decrease in flow competence and transport capacity with distance. These data do not show the marked break in slopes which have been attributed to the transition between region of column collapse and that of lateral flow (Walker, 1985). Maximum pumice size (MP) with distance (Fig. 15b) shows the lack of a systematic relationship although the data reflect the occurrence of pumice rich deposit fronts at distal localities. An important concept is that of aerodynamic equivalence. A negative correlation is obtained when ML^V is plotted against MP for each facies (Fig. 16a). Pumice clasts in the breccia facies are commonly an order of magnitude smaller than the lithic blocks and vice versa for small lithic clasts in the pumice facies. The data support the view that there is a continuum between the three facies.

Substrate-derived lithics are distributed throughout the thickness of the deposits (Fig. 7). Ratios for ML^S:ML^V (Fig. 16b) within the pumice facies are slightly greater than 1, implying the erosive capability upstream of those parts of the flow, or at least the ability to retain entrained lithics is weak. Lag breccias, on the other hand, contain local lithics up to an order of magnitude larger than those transported from the vent and furthermore these have been carried for appreciable distances (up to 5 km). The same relationship normalised to MP (Fig. 16c) illustrates that as the facies gets richer in lithics, the trend deviates from the unity line reflecting increased upsteam

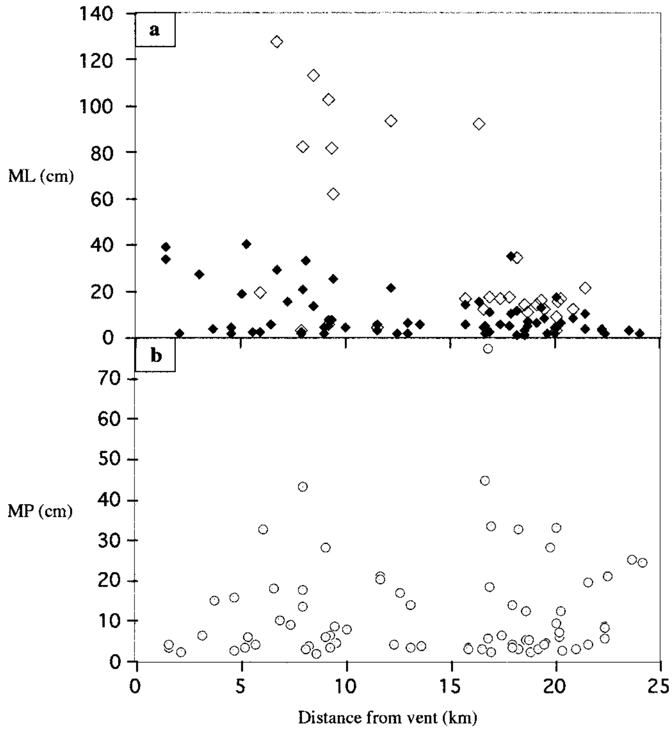


Fig. 15. (a) Maximum vent-derived lithics, ML^V (filled diamonds) and maximum substrate-derived lithics, ML^S (open diamonds) with distance from the vent in Soncor ignimbrite. (b) Maximum pumice (MP) with distance from the vent in the Soncor ignimbrite.

erosive ability and transport capacity to location of deposition.

7. Concepts for the transport and emplacement of pyroclastic flows

There are alternative concepts concerning transport and emplacement mechanisms of pyroclastic flows. Some models treat pyroclastic flows as dilute turbulent suspension currents (Dade and Huppert, 1996; Bursik and Woods, 1996). Other models consider pyroclastic flows as avalanche-like granular flows with high particle concentration, analogous to debris flows and rock avalanches (Sparks, 1976; Calder et al., 1999). Variants of models involving high particle concentration granular flows emphasise non-Newtonian rheology (Wilson and Walker, 1982), fluidisation effects (Sparks, 1976; Wilson, 1980, 1984) and hindered settling (Druitt, 1995). A conceptual model of pyroclastic flows has recently been promoted in which progressive aggradation occurs from a suspension in which a depositional boundary layer separates a static deposit from the flow (Branney and Kokelaar, 1992; Bryan et al., 1998). Vertical variations in deposit composition, such as pumice and lithic horizons, are interpreted in terms of fluctuations in the velocity and composition of the overlying current. In Branney and Kokelaar (1992, 1997) and Bryan et al. (1998), the lower part of the flow has a high concentration, so that the flow is stratified in terms of particle concentration. Both aggradation and granular flow models envisage within-flow segregation processes to produce vertical and lateral facies variations. Aggradation models however, contrast with models that envisage that pyroclastic flows spread out in a fluid-like manner with shear concentrated at the base with the flow rapidly coming to rest when it runs out of energy. Discussions of these alternative models have tended to become polarised, apparently based on the assumption that the different concepts are incompatible.

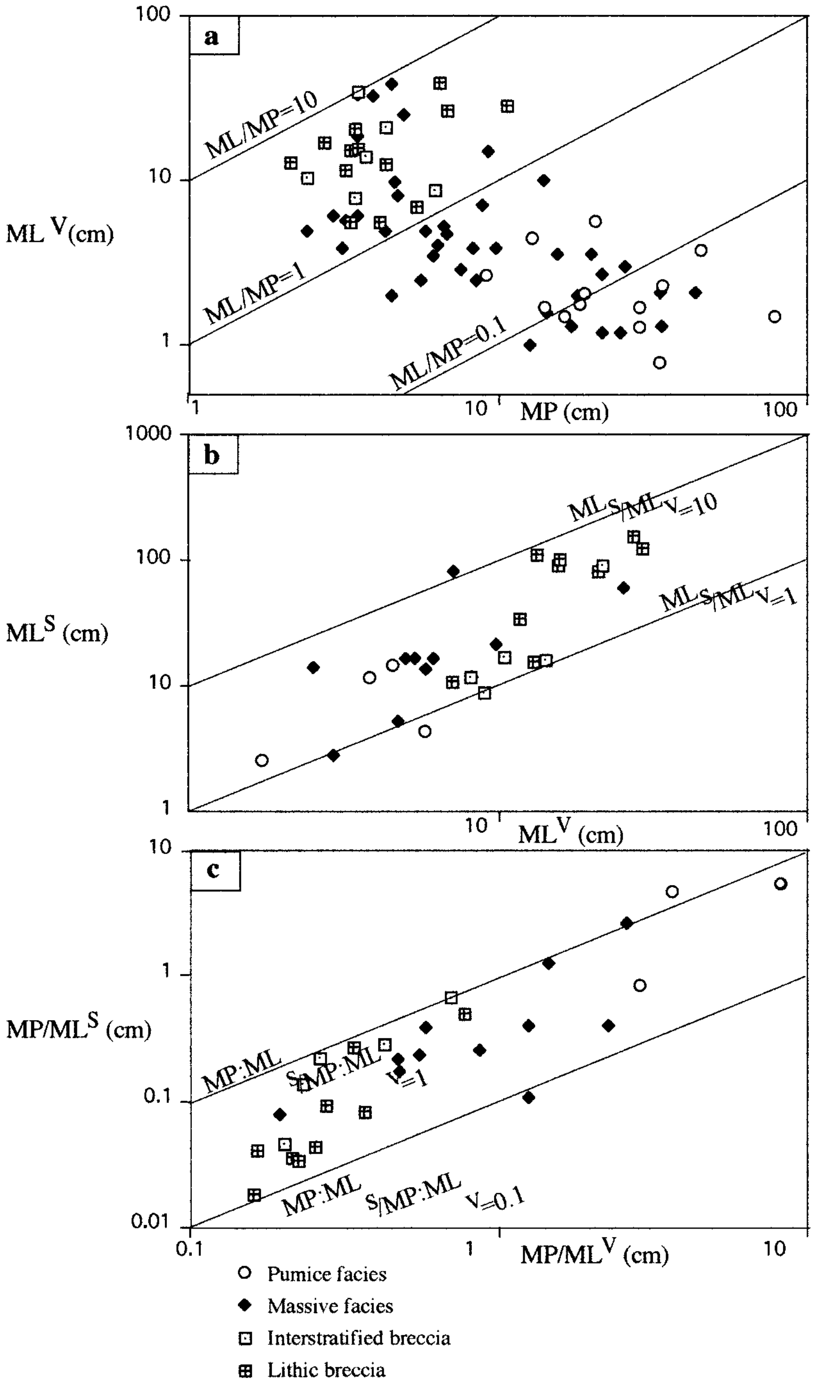


Fig. 16. Maximum size relations of pumice and lithic clasts for the main lithofacies within the Soncor ignimbrite. (a) ML^V against MP, illustrating the lack of aerodynamic equivalence between pumice and lithic clasts. Ratio lines highlight the size differences between pumice and lithic clasts within each facies. (b) ML^S against ML^V showing the size differences between lithic types. (c) The ratio $MP:ML^S$ against $MP:ML^V$, illustrates the above relationship normalised to MP and shows how as the facies becomes more pumice rich, the difference in lithic sizes is reduced.

Small volume, end-member flows, such as those formed from fountain collapse during vulcanian explosions and dome collapse events are short-lived, occur in discrete pulses and comprise relatively dense material. Numerous observations (Nairn and Self, 1978; Hoblitt 1986; Yamamoto et al., 1993; Boudon et al., 1993; Cole et al., 1998; Druitt et al., 2001) describe separate mobile systems in which a granular underflow or dense basal avalanche occurs beneath an overriding turbulent ash cloud. There are few direct observations however, of large and medium volume pyroclastic flow events. These comprise mainly ash and low-density pumice and the time scale over which emplacement occurs is poorly constrained. It is the extent to which these flows develop density stratification or dense underflows and how their deposits relate to flow dynamics which remains contentious. The Soncor ignimbrite ($10\ km^3$) and the deposits from the 1993 pyroclastic flows ($0.06\ km^3$) sit in the small to medium volume range, but both were produced during Plinian eruptions which (in the case of the 1993 eruption) continued for periods of tens of hours. During the 1993 eruption, pyroclastic flows were observed to have been generated in a number of discrete pulses associated with discrete periods of fountain collapse (Guarinos and Guarinos, 1993; Gardeweg and Medina, 1994).

8. Interpretation of Lascar pyroclastic flow deposits

8.1. Expanded vs concentrated flow

The Lascar deposits display valley confined characteristics, where the deposit thickness is largely governed by topography. The deposits are coarse-grained and have high lithic contents. We interpret their characteristics as indicating that transport was predominantly in a highly concentrated granular flow. The anti-correlation of MP and ML sizes (Fig. 16a) is quite different to the relationship expected in dilute turbulent suspensions where pumice and lithic sizes should be positively correlated (Dade and Huppert, 1996). This relationship indicates a lack of aerodynamic equivalence, a condition anticipated in deposits of high concentration flows (Sparks, 1976). Deposit distributions also show that the Lascar flows were strongly channelled by topography, were diverted by topographic highs (>15–20 m for Soncor flows at 15 km from source) and the deposits have abrupt lobate terminations. These features imply, that for most of their transport, the flows were avalanche-like in character and not highly expanded. A more expanded character to the Soncor flows is, however, indicated in proximal areas by the stratiform lithic breccias sub-facies deposited above the plinian section. These are interpreted as lag breccias deposited from an expanded, turbulent suspension current. The deposits are highly fines depleted and clearly bedded and can be reasonably attributed to progressive aggradation under the influence of the collapsing fountain (Branney and Kokelaar, 1997). Stratification may record variations in velocity or discharge in a continuous or pulsating eruption column collapse. This is supported by the inclusion of late stage andesite scoria and PJBs in the ignimbrite, suggesting syn-postgeneric formation with the plinian fall deposits (Fierstein and Hildreth, 1992).

These observations suggest that flow transformations occurred from proximal highly expanded flows that deposited by progressive aggradation to those that were emplaced as granular flows. The debate, therefore, moves onto the issue of where and how the transformation takes place. For the 1993 flows, the granular flow character was certainly established close to the source for the following reasons. The ash-cloud surge component only extends 3–4 km from source; thereafter the ash deposits at the flow margin are extremely limited. Secondly, the constructional, lobate, deposit morphology can be observed throughout the fan even in areas as close to the vent as 2 km (Fig. 10). For the Soncor ignimbrite we interpret the transformation to have occurred where the massive valley-ponded facies becomes dominant and the lithic breccias thin out at 5–8 km distance.

8.2. Single vs multiple flow

The Lascar pyroclastic flow deposits represent the amalgamation of large numbers of individual flows. In the case of the 1993 eruption at least nine separate episodes of fountain collapse were observed (Gardeweg and Medina, 1994) and the fans show numerous individual overlapping deposit lobes with characteristic channel and levee morphology. Overlapping deposit lobes (as seen from surface morphology) can be directly correlated with multiple reversely graded pumice layers (seen in cross-section), interpreted to be flow units (Fig. 12, Loc a). Similar, although somewhat degraded surface morphology is preserved distally in the Soncor ignimbrite. Flow unit boundaries are also detected by features such as layer 2a basal layers and pumice concentration zones (Fig. 7). We have traced such boundaries laterally into massive deposits where flow unit boundaries are not detectable. Thus, massive facies with no detectable breaks can still represent amalgamations of many emplaced units. Some pumice concentration zones end abruptly when traced laterally and represent buried deposit terminations. These pumice lenses display sharp, steep angled contacts, features not consistent with a mechanism of formation by gradual build up from base by a depletive suspension current which might be expected to thin gradually. Lithic assemblages co-vary through a vertical section but evolve in composition with distance from the vent, providing strong evidence that lateral zonation of lithologies is not due to a changing supply. Lithic distributions in the fans cannot therefore be interpreted simply as the result of a single fluctuating steady current (Bryan et al., 1998). Thus, at least some vertical variations are the consequence of amalgamation of discrete emplacement units. Vertical variations due to fluctuations within individual units are certainly possible if progressive aggradation occurs. The concept of progressive aggradation from a sustained current however, is not viable in areas close to the abrupt flow terminations and margins.

8.3. Development of pumice and lithic rich facies

The lithic rich breccias represent the heaviest constituents of the flows, segregating out early to form proximal deposits. In the Soncor ignimbrite, the various types of breccias can be conceived to form a gradational sequence with proximal stratified fines-depleted facies (progressively aggraded) grading laterally into breccias deposited from the base of the flows and then into breccia lenses deposited within the massive ignimbrite facies.

Isolated elongate lithic breccia hummocks deposited at the foot of the edifice vary between fines depleted and fines rich types. We suggest a close analogy with isolated gravel bars created by catastrophic floods and the whaleback bars of Scott (1988) formed in medial lahar deposits of 18 May eruption of Mount St. Helens. Scott (1988) observed abraded basement directly upstream reflecting the grinding to a stop of the basal flow of coarse clasts. Identical elongate hummocks and localised breccia sheets were formed in the proximal areas of energetic pyroclastic flows at the Soufriere Hills Volcano, Montserrat in an area of prominent erosion (Sparks et al., 2001). These observations and analogies indicate that this lithic breccia facies is formed in proximal environments, where the breccia bedforms and facies are deposited from high-energy pyroclastic flows. Lag breccias with a hummocky morphology have been observed at Lenegai (Leat, 1985) and at Crater Lake (Druitt and Bacon, 1986). The latter postulated that fines depleted breccias were produced within the deflation zone of the collapsing column and that fines enriched breccias were lag flows in the medial distances. The Lascar hummock breccias are interpreted to have been deposited by partial or entire frictional freezing of the traction layer.

Further from the source, Soncor ignimbrite breccias are typically matrix-rich and interstratified with massive facies, with which they are intergradational. They occur as sheets, in at least one location, at a valley confluence where flows amalgamated, and as accumulations downstream of obstacles, breaks-in-slope and constrictions. Druitt and Bacon (1986) observed the lateral transition of similar lithic breccia drape into valley filling medial facies of the Mazama ignimbrite 7–10 km from the vent and interpreted this as lithic rich flow material. Breccia layers are also interpreted as representing deposits of discrete lithic rich flows (Walker, 1985) or to result as a consequence of segregation processes creating lithic rich basal portions to flows which become decoupled from the pumice rich parts due to contrasted flow properties (Buesch, 1992).

Within the pumice facies deposits, constructional features, such as steep sided levees, channels and deposit termini (as observed in the 1993 deposits), are classical features of pumiceous pyroclastic flow deposits (Wilson and Head, 1981; Rowley et al., 1981). Levees are formed by upper pumice rich portions of the flow that have been swept to the side and stranded as the flow moves forwards. Pumice rich facies occur on the upper surface on slopes <4° in the 1993 deposits and are laterally contiguous with the lithic rich facies. Lithic rich interiors can be traced into pumice rich margins. Large pumice clasts are concentrated at deposit margins, deposit fronts and in concentration zones by flotation due to buoyancy (Sparks, 1976). Pumice densities indicate that flow densities could not have been much less than the final deposit densities.

Distribution of pumice and lithic rich facies is not simply a matter of distance. Pumice facies in proximal to medial areas can record flows that were of lower velocity, margins of flows that have spilled out of deep valleys and remnants of pumice rich deposit tops that have banked up against topographic obstacles. Lithic breccias can also form in distal areas where local topographic conditions, such as constrictions, obstacles and sudden changes in slope, cause flow acceleration and erosion with entrainment of local lithics and formation of downstream breccia facies. A variety of processes are thought to have contributed to the development of pumice and lithic rich facies. Fluctuations in lithic content of successive flow pulses from the vent, variation in the flow paths and availability of loose material for entrainment will contribute to compositional variations in both time and space. We suggest however, that intra-flow segregation is the dominant factor in generating vertical and lateral facies variations.

The relationship between pumice rich and lithic rich facies can be explained by the following model (Fig. 12c). We envisage a flow mechanism whereby decoupling of components within the high concentration basal avalanche of the pyroclastic flows works at two levels. During transport the flow is segregated into lithic rich and pumice rich regions. Buoyant components are organised towards the top of the flow by particle interactions, dispersive forces and kinetic sieving effects. Dense components, controlled by gravitational forces, migrate towards the base of the flow where concentration and bulk density may be further enhanced by entrainment of clasts. This self-organisation behaviour has been reproduced experimentally in granular flows by Vallance (1993) and computationally simulated by Straub (1996) and Straub and Valentine (1998). Recent developments suggest that emplacement of these flows as non-shearing plug flows is an over-simplification (Palladino and Valentine, 1995). In granular flows, particle interactions create random internal movements and vertical momentum transfer and indeed particle interactions are critical to the segregation of components of different density. Such flows can have internal velocity gradients and shear throughout the flow (Palladino and Valentine, 1995; Hughs and Druitt, 1998; Straub and Valentine, 1998), so that true plug behaviour as in a bingham fluid is unlikely.

Pumice and lithic rich portions of the flows will have substantially different properties such as bulk density, momentum and friction coefficient so that the interface between them becomes the zone of greatest shear. We postulated in Sparks et al. (1997) that the friction resistance of the lithic rich basal part is greater so that deposition occurs on higher angle slopes and generally closer to the source. The lower density and more mobile pumice rich top continues to flow and detaches from the rapidly decelerating or stationary lithic rich base at the interface. The thin pumice corrugated layer on the surface of the lithic rich facies of the 1993 deposits represents this detachment horizon. The remaining pumice rich material moves to the flow margins and the more distal regions only coming to rest on slopes <4°. The lateral facies variations are thus produced by shearing and progressive decoupling of the upper (pumice rich) and lower (lithic rich) portions of a flow. Facies variations lie in clusters along the broad trend (Fig. 16a), supporting sequential derivation by the segregation processes as the flows proceed.

Decoupling may be accentuated by a number of processes. Palladino and Valentine (1995) attributed reverse lateral grading of pumice clasts to vertical velocity gradients in ignimbrites at Latera volcanic complex. Buesch (1992) suggested decoupling may occur when momentum of the overriding pumice is not effectively transferred to the dense flow base. Incorporation of substrate lithics into flow bases will also enhance rheological and density contrasts between lithic and pumice rich parts of the same flow. Calder et al. (1999) illustrate pumice rich pyroclastic flows from Montserrat are more mobile, spreading over a greater distance, than block-and-ash flows of the same volume. This indicates an inherently high mobility of pumiceous granular material. Topographic parameters control the velocity and shearing of the two units as illustrated by the relationship between slope gradient and facies observed in the 1993 deposits (Fig. 12a,b). Lithic rich components can also become decoupled by falling away from the base of the flow after cresting a topographical high.

Lithic assemblages are instructive in terms of when segregation occurred in the flows. An average ~20% substrate lithics occurs in the lithic fraction of the pumice facies, the massive facies and the breccia mounds (Fig. 4). Furthermore, the proportions of Lascar volcanic lithics and regional basement lithics are similar in the pumice and massive facies. However, lithics in the pumice facies are much smaller. These observations either mean incorporation and thorough mixing of the basement lithics occurred before segregation of the pumice rich facies, which then must have occurred distally, or the pumice rich flow phase did in fact entrain small substrate lithics once it spread beyond the limits of the underlying lithic rich facies. Based on observations at Lascar and Montserrat (Druitt et al., 2001; Cole et al., 2001) we favour the former explanation. The emplacement of lobate pumice rich deposits appears to occur with minimal disturbance to underlying material, and for both the Soncor and 1993 pyroclastic flows, zones of segregated pumices occupy a volumetrically small portion at the flow deposit margins.

8.4. Erosion and flow bulking

Exposed scoured surfaces of substrate geology, and incorporated substrate-derived clasts are ubiquitous features of both deposits. The erosion features produced by the 1993 pyroclastic flows are described in Sparks et al. (1997). Abraded bedrock surfaces were corrugated into furrows, striated parallel to flow direction and displayed numerous oblique percussion marks. Similar features have also been identified at the base of the Soncor ignimbrite in the Quebrada de Chaile.

The process of flows incorporating substrate material or 'bulking' is well known in the turbidite, lahar and debris flow literature (Scott, 1988). As flows gather clasts the bulk density, energy and volume of the flow increases and their erosive capability increases further. Coarse clasts are concentrated in basal carpets, which in turn, increase the basal scouring capacity of the flows. In the Lascar pyroclastic flows this is further enhanced by the density contrast between pumice and lithic components. The original lithic content in the flow and the erosive susceptibility of substrate lithologies are important factors. In the Soncor eruption, deep explosive cratering into the interior of the volcano is inferred to have occurred by the high percentage of vent-derived hypabyssal and intrusive clasts and this imparted to the flow its scouring potential. Parts of the flow rich in these lithics were more erosive as shown by the content of entrained material and larger clast sizes. Clasts toughness and the ability to sustain angularity in order to be an efficient erosional tool may thus be an important characteristic. In contrast, pumice rich parts of flows have relatively weak capability to abrade and entrain local lithics; those that are entrained are a minor component of the flow and are small. This may be due to a combination of limited eroding capabilities and insufficient competency within the more loosely packed lower density portion of the flow so that efficient kinetic sieving and gravitational effects occur. Therefore, as the flows proceed, in medial to distal runout, when coarse dense clasts have been deposited, the rheological characteristics of the flows evolve becoming less able to abrade substrate and entrain material.

The degree to which fragments are entrained is also determined by the susceptibility of the substrate to erosion and/or the availability of loose detritus. Manifestations of the erosion on different substrate lithologies are determined by toughness of the rock type. The Tumbres–Talabre andesite lava, for example is incorporated as clasts or boulders but striated surfaces have not been observed. Conversely the Tertiary ignimbrite is commonly striated, but large incorporated clasts are less common than one might expect, indicating that the soft rock was gradually abraded down.

The systematic decrease in ML^V with distance is consistent with segregation of larger lithics towards the base of the flows with the upper parts of the flows ultimately spreading further than the basal parts. Mobile, pumice rich parts of the flows are less able to carry large substrate derived lithic clasts. Substrate-derived lithics are systematically larger than those that have travelled from the vent but ML^S also decreases with distance from source reflecting decreasing energy and carrying capacity of the flows. Over short distances, ML^S decreased from the excess to the equilibrium value given by ML^V which may indicate that it is not ML^V but ML^S that defines the flow's transport capacity. ML^V could be smaller than the allowable limit because larger lithics were lost during weaker flow more proximally. The residence time of oversized entrained lithics in the flow is hard to ascertain unless the source and flow velocity is known. In 3–5 km traverses in the Soncor deposit (Fig. 13b; Fig. 14a) entrained lithologies (those with excess ML sizes) are seen to appear and disappear in succession as lithic assemblages return to equilibrium size. The compositions of substrate-derived lithics vary with distance from the vent with pre-Lascar basement becoming important downstream. These observations suggest that the entrained outsized lithic clasts are typically transported distances of a few hundred metres to a few kilometres.

Interplay between erosion and deposition in sediment gravity currents is a topical issue. Evidence from the Lascar deposits suggests this is highly sensitive to local slope gradient. Erosional features are concentrated on the steep upper flanks where the flow had maximum kinetic energy. Where topography shallows, the predominantly erosional regime is superseded by deposition and thicker accumulations of deposit occur due to the depletive capacity (Kneller and Branney, 1995). The flows however, can rapidly revert to being strongly erosional in distal localities due to local topographic effects and slope changes as illustrated by lithic entrainment and plunge-pool features. Erosion is enhanced where the flows travel in confined environments where increased contact with the side walls and flow thickening may improve plucking power. Observations of erosion by the Montserrat 1996–1997 pyroclastic flows (Cole et al., 1998) illustrate that this process is rapid, flow activity lasting minutes to hours eroded tens of metres of substrate rock, drastically modifying the local topography.

8.5. Outsized lithic clasts

Outsized lithics can be retained by the flow for appreciable distances even although sedimentation might be expected to be rapid as their sizes are out of equilibrium with the vent-derived lithics in the flow. Over distances of 5 km with flow velocities in the range 15–50 m s^{-1}, this corresponds to outsized clast transport duration times of between 1.6 and 5.6 min. The ability to retain outsized clasts for time scales needed to travel distances of a few hundred metres to kilometres implies they are held in a densely packed suspension.

Transport of these oversized lithics and their emplacement 'floating' in the massive facies deposit is a contentious issue. Concepts introduced in Branney and Kokelaar (1992) and later developed in Kneller and Branney (1995) and Kokelaar and Branney (1996) involve the transport of these clasts saltating and rolling in a concentrated depositional boundary layer. Likewise, Bryan et al. (1998) considered that large lithics in Quaternary ignimbrites on Tenerife, travelled in a tractional regime at the base of the current and were deposited on aggraded deposit surfaces and supported by the yield strength of the underlying deposits. Conversely, in granular flow models, the process of mixing clasts within the flow interiors is considered akin to 'random granular diffusion' modelled by Straub and Valentine (1998) using discrete particle simulations in the rapid granular flow regime.

Our data show that the Lascar pyroclastic flows were able to entrain lithics an order of magnitude larger than those already in the flow. These lithics (up to 1.3 m) travelled for distances of up to 6 km from the location of entrainment over rough terrain. This is considered consistent with a tractional transport mechanism at the base of a current but only in the late stage as the flows run out of energy and deposit. Fig. 11b shows a ~80 cm lithic block embedded within a flow unit only 60 cm thick. Blocks such as these were carried by, or entrained within, the deposits in which they are embedded, indicating that for the most part transport is as a concentrated flow.

9. Concluding remarks

The Lascar flows are considered to have been high concentration granular flows which were derived by a process of rapid sedimentation from more dilute energetic flows close to the volcano. This is consistent with the model of Druitt (1998) where development of widespread dense underflows in ignimbrite forming eruptions is seen as depending on the rate of proximal suspension-load fallout. These dense underflows outrun the parent suspension current and form the dominant portion of the deposit. The observations at Lascar give clues as to the nature of such flows. There were stages clearly in their emplacement where they were either erosive or were sliding across the terrain to produce striated, furrowed and abraded surfaces. Outsize lithic clasts were mixed into the flow interiors. By this process some flows developed strong density stratification. These features can be envisaged in terms of flows where particle interactions are dominant.

We suggest that analogies with simple fluid flow systems such as Newtonian laminar flow or turbulent suspension currents (Dade and Huppert, 1996; Bursik and Woods, 1996) can be misleading as such concepts neglect the importance of particle interactions. For example, granular flows can be organised yet display internal mixing due to particle interactions. Granular flows can also be expected to mimic non-Newtonian fluids in the sense that the response of granular materials to shear is highly non-linear. Granular flows exhibit fluid-like properties and we suggest that these flows spread over most of the area that they inundate before coming to a fairly abrupt halt. Whether the flows ultimately cease motion because they freeze or by rapid upward aggradation remains an open question. Features, such as elongate hummocky lag breccia bars, imbrication and crude stratification in lag breccias, are however, consistent with progressive aggradation and tractional effects as the lithic rich parts of the flows decelerate and deposit.

A variety of effects and processes are thought to have contributed to the development of pumice and lithic rich facies. Fluctuations in the lithic content of successive flow pulses from the vent, variation in the flow paths and availability of loose material for entrainment will contribute to compositional variations with time. Observations of the 1993 flows in particular show that lithic rich flows deposit on steeper slopes than pumice rich flows which are generally more mobile and only begin deposition on gentle slopes ($<4°$). As slope decreases away from source lateral separation of pumice and lithic rich deposits is a natural consequence. Observations on the 1993 deposits also indicate that segregation can take place during flow with pumice rich upper parts of the flow detaching from lithic rich lower parts. Incorporation of lithics into flow bases will enhance rheological and density contrasts between lithic and pumice rich parts. Characteristics of erosion features indicate that the rheology of these dense underflows may change significantly as dense lithic components are sedimented out and the flows become progressively more dominated by pumice.

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References

Boudon, G., Camus, G., Gouraud, A., Lajoie, J., 1993. The nuée-ardente deposits of Merapi volcano, Central Java, Indonesia: stratigraphy, textual characteristics and transport mechanisms. Bull. Volcanol. 55, 327–342.

Branney, M.J., Kokelaar, P., 1992. A reappraisal of ignimbrite emplacement: progressive aggradation and changes from particulate to non-particulate flow during emplacement of high-grade ignimbrite. Bull. Volcanol. 54, 504–520.

Branney, M.J., Kokelaar, P., 1997. Giant bed from a sustained catastrophic density current flowing over topography: Acatlan ignimbrite, Mexico. Geology 25, 115–118.

Bryan, S.E., Cas, R.A.F., Marti, J., 1998. Lithic breccias in intermediate volume phonolitic ignimbrites, Tenerife (Canary Islands): constraints on pyroclastic flow depositional processes. J. Volcanol. Geotherm. Res. 81, 269–296.

Buesch, D.C., 1992. Incorporation and redistribution of locally derived lithic fragments within a pyroclastic flow. Geol. Soc. Am. Bull. 104, 1193–1207.

Bursik, M.I., Woods, A.W., 1996. The dynamics and thermodynamics of large ash flows. Bull. Volcanol. 58, 175–193.

Calder, E.S., Cole, P.D., Dade, W.B., Druitt, T.H., Hoblitt, R.P., Huppert, H.E., Richie, L., Sparks, R.S.J., Young, S.R., 1999. Mobility of pyroclastic flows and surges at the Soufriere Hills Volcano, Montserrat. Geophys. Res. Lett. 26, 537–540.

Cole, P.D., Calder, E.S., Druitt, T.H., Hoblitt, R., Robertson, R., Sparks, R.S.J., Young, S.R., 1998. Pyroclastic flows generated by gravitational instability of the 1996–97 lava dome of Soufriere Hills volcano, Montserrat. Geophys. Res. Lett. 25, 3425–3428.

Cole, P.D., Calder, E.S., Sparks, R.S.J., Clarke, A.B., Druitt, T.H., Young, S.R., Herd, R.A., Harford, C.L., Norton, G.E., Robertson, R. 2001. Pyroclastic flow deposits formed during 1996–99 at Soufriere Hills volcano, Montserrat. Submitted to the Special Publication of the Geological Society of London: The 1995–1999 eruptions of the Soufriere Hills Volcano, Montserrat, Antilles.

Dade, B., Huppert, H.E., 1996. Emplacement of the Taupo ignimbrite by a dilute turbulent flow. Nature 381, 510–512.

Druitt, T.H., 1995. Settling behaviour of concentrated dispersions and some volcanological applications. J. Volcanol. Geotherm. Res. 65, 25–39.

Druitt, T.H., 1998. Pyroclastic Density Currents. In: Gilbert, J.S., Sparks, R.S.J. (Eds.), The Physics of Explosive Volcanic Eruptions. Geol. Soc. London Spec. Publ., pp. 145–182.

Druitt, T.H., Bacon, C.R., 1986. Lithic breccia and ignimbrite erupted during the collapse of Crater Lake Caldera, Oregon. J. Volcanol. Geotherm. Res. 29 (1–4), 1–32.

Druitt, T.H., Young, S., Baptie, B., Calder, E.S., Clarke, A., Cole, P.D., Formenti, Y., Harford, C., Herd, R.H., Luckett, R., Ryan, G., Sparks, R.S.J., Voight, B. 2001. Periodic vulcanian explosions and fountain collapse at the Soufriere Hills Volcano, Montserrat, 1997. Submitted to the Special Publication of the Geological Society of London: The 1995–1999 eruptions of the Soufriere Hills Volcano, Montserrat, Antilles.

Fierstein, J., Hildreth, W., 1992. The Plinian eruptions of at Novarupta, Katmai-National Park, Alaska. Bull. Volcanol. 54, 646–684.

Fisher, R.V., 1977. Erosion by volcanic base-surge density currents: U-shaped channels. Geol. Soc. Am. Bull. 88, 1287–1297.

Fisher, R.V., 1979. Models for pyroclastic surges and pyroclastic flows. J. Volcanol. Geotherm. Res. 6, 305–318.

Gardeweg, M.C. 1991. The geology, petrology and geochemistry of the Tumisa volcanic complex, North Chile. PhD thesis, Kingston Polytechnic, London.

Gardeweg, M.C., Medina, E., 1994. La erupcione subpliniana del 19–20 de Abril de del volcan Lascar, N de Chile. Actas 7 Congreso Geologico Chileno 1, 299–304.

Gardeweg, M.C., Ramirez, C.P., 1987. La Pacana Caldera and the Atana ignimbrite — a major ash-flow and resurgent caldera in the Andes of Northern Chile. Bull. Volcanol. 49, 547–566.

Gardeweg, M.C., Sparks, R.S.J., Matthews, S.J., 1998. Evolution of Lascar Volcano, Northern Chile. J. Geol. Soc. 155, 89–104.

Guarinos, J., Guarinos, A., 1993. Contribution a l'etude de l'eruption du Volcan Lascar (Chili) d'avril 1993. Archs. Sci. Geneve 46, 303–319.

Hildreth, W., Mahood, G.A., 1986. Ring-fracture eruption of the Bishop Tuff. Geol. Soc. Am. Bull. 97, 396–403.

Hoblitt, R.P. 1986. Observations of the eruptions of July 22 and August 7 at Mount St. Helens, Washington. U.S. Geol. Surv. Prof. Pap.

Hughs, S.R., Druitt, T.H., 1998. Particle fabric in a small, type-2 ignimbrite flow unit (Laacher See, Germany) and implications for emplacement dynamics. Bull. Volcanol. 60, 125–136.

Kieffer, S.W., Sturtevant, B., 1988. Erosional furrows formed during the lateral blast at Mount St. Helens, May 18, 1980. J. Geophys. Res. 93, 14 793–14 816.

Kneller, B.C., Branney, M.J., 1995. Sustained high density turbidity currents and the deposition of thick massive sands. Sedimentology 42, 607–616.

Kokelaar, P., Branney, M.J., 1996. On pyroclastic flow emplacement — Comment. J. Geophys. Res. 101, 5653–5655.

Marti, J., Diez-Gil, J.L., Ortiz, R., 1991. Conduction model for the thermal influence of lithic clasts in mixtures of hot gases and ejecta. J. Geophys. Res. 96, 21 879–21 885.

Matthews, S., Gardeweg, M.C., Sparks, R.S.J., 1997. The 1984 to 1996 cyclic activity of Lascar Volcano, northern Chile; cycles of dome growth, dome subsidence, degassing and explosive eruptions. Bull. Volcanol. 59, 72–82.

Matthews, S., Sparks, R.S.J., Gardeweg, M.C., 1999. The Piedras Grandes — Soncor event, Lascar Volcano, Chile; evolution of a zoned magma chamber in the Central Andean upper crust. J. Petrol. 40, 1891–1919.

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

Palladino, D.M., Valentine, G.A., 1995. Coarse-tail vertical and lateral grading in pyroclastic flow deposits of the Latera Volcanic Complex (Vulsini, central Italy): origin and implications for flow dynamics. J. Volcanol. Geotherm. Res. 69, 343–364.

Rowley, P.D., Kuntz, M.A., MacLeod, N.S. 1981. Pyroclastic flow deposits. In: Lipman, P.W., Mullinewaux, D.R. (Eds.), The 1980 Erutions of Mount St. Helens, Washington. U.S. Geological Survey Professional Paper 1250, pp. 489–512.

Scott, K.M. 1988. Origins, behaviour and sedimentology of lahars and the lahar-runout flows in the Toutle–Cowlitz river system, U.S. Geol. Surv. Prof. Pap. 1447-A, pp. 6–40.

Sparks, R.S.J., 1976. Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. Sedimentology 23, 147–188.

Sparks, R.S.J., Walker, G.P.L., 1977. The significance of vitric-enriched air-fall ashes associated with crystal-enriched ignimbrites. J. Volcanol. Geotherm. Res. 2, 329–341.

Sparks, R.S.J., Self, S., Walker, G.P.L., 1973. The products of ignimbrite eruptions. Geology 1, 115–118.

Sparks, R.S.J., Gardeweg, M.C., Calder, E.S., Matthews, S.J., 1997. Erosion by pyroclastic flows on Lascar volcano, Chile. Bull. Volcanol. 58, 557–565.

Sparks, R.S.J., Barclay, J., Calder, E.S., Herd, R.H., Luckett, R., Norton, G.E., Pollard, L., Robertson, R.E.A., Ritchie, L., Voight, B., Young, S.R., Woods, A.W. 2001. Generation of a debris avalanche and violent pyroclastic density current: the Boxing Day eruption of 26 December 1997 at the Soufriere Hills Volcano, Montserrat. Submitted to the Special Publication of the Geological Society of London: The 1995—1999 eruptions of the Soufriere Hills Volcano, Montserrat, Antilles.

Straub, S., 1996. Self-organization in the rapid flow of granular material: evidence for a major flow mechanism. Geol. Rundsch. 85, 85–91.

Straub, S., Valentine, G. 1998. 3-D modelling of rapid granular flows and its application to high-concentration pyroclastic flows. Conference abstract, Sediment Transport and Deposition by particulate gravity currents, Leeds University, 7–9 September.

Suzuki-Kamata, K., 1988. The ground layer of Ata pyroclastic flow deposit, southwestern Japan — evidence for the capture of lithic fragments. Bull. Volcanol. 50, 119–129.

Thomas, R.M.E. 1993. Determination of the emplacement temperature of pyroclastic deposits by theoretical and paleomagnetic methods. PhD thesis, University of Bristol.

Vallance, J.W. 1993. Particle sorting and the origin of graded bedding in debris flows and pyroclastic flows. Conference abstract, IAVCEI General assembly, Canberra, p. 116.

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

Walker, G.P.L., 1985. Origin of coarse lithic breccias near ignimbrite source vents. J. Volcanol. Geotherm. Res. 25, 157–171.

Wilson, C.J.N., 1980. The role of fluidisation in the emplacement of pyroclastic flows: an experimental approach. J. Volcanol. Geotherm. Res. 8, 231–249.

Wilson, C.J.N., 1984. The role of fluidisation in the emplacement of pyroclastic flows 2: experimental results and their interpretation. J. Volcanol. Geotherm. Res. 20, 55–84.

Wilson, C.J.N., 1985. The Taupo eruption, New Zealand. II. The Taupo Ignimbrite. Philos. Trans. R. Soc. London Series A 314, 581–592.

Wilson, L., Head, J.W. 1981. Morphology and rheology of pyroclastic flows and their deposits, and guidlines for future observations. In: Lipman, P.W., Mullineaux, D.R. (Eds.), The 1980 Eruptions of Mount St. Helens, Washington. U.S. Geol. Surv. Prof. Pap. 1250, 489–512.

Wilson, C.J.N., Walker, G.P.L., 1982. Ignimbrite depositional facies: the anatomy of a pyroclastic flow. J. Geol. Soc. London 139, 581–592.

Yamamoto, T., Takarada, S., Suto, S., 1993. Pyroclastic flows from the eruption of Unzen volcano, Japan. Bull. Volcanol. 55, 166–175.