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El Chichón volcano, April 4, 1982: volcanic cloud history and fine ash fallout

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Abstract This retrospective study focuses on the fine silicate particles (<62 μm in diameter) produced in a large eruption that was otherwise well studied. Fine particles represent a potential hazard to aircraft, because as simple particles they have very low terminal velocities and could potentially stay aloft for weeks. New data were collected to describe the fine particle size distributions of distal fallout samples collected soon after eruption. Although, about half of the mass of silicate particles produced in this eruption of $\sim$1 km^3 dense rock equivalent magma were finer than 62 μm in diameter, and although these particles were in a stratospheric cloud after eruption, almost all of these fine particles fell to the ground near (<300 km) the volcano in a day or two. Particles falling out from 70 to 300 km from the volcano are mostly <62 μm in diameter. The most plausible explanation for rapid fallout is that the fine ash nucleates ice in the convective cloud and initiates a process of meteorological precipitation that efficiently removes fine silicates. These observations are similar to other eruptions and we conclude that ice formation in convective volcanic clouds is part of an effective fine ash removal process that affects all or most volcanic clouds. The existence of pyroclastic flows and surges in the El Chichón eruption increased the overall proportion of fine silicates, probably by milling larger glassy pyroclasts.

Keywords El Chichón · Volcanic cloud · Volcanic ash · Fallout · Aircraft hazards

1 Introduction

This article aims to consider the fate and transport of fine (<50 μm in diameter) ash in the volcanic clouds of El Chichón's April 4, 1982 eruption. This eruption is one of the

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two most significant eruptive events of the satellite remote sensing era, based on atmospheric effects (Bluth et al. 1992, 1997). The eruption has been well studied from ground-based field methods (Sigurdsson and Carey 1984; Varekamp et al. 1984; Carey and Sigurdsson 1986; Gutiérrez-Coutiño et al. 1983), from satellite data (Matson 1984; Robock and Matson 1983; Schneider et al. 1999) and from aircraft atmospheric sampling (Mackinnon et al. 1984; Chuan and Woods 1984; Woods et al. 1985). This article summarizes the previous work with respect to fine ash, and presents and analyzes new data describing the size distribution of ash fallout. The fate of this fine ash from explosive eruptions is important to public health (Horwell and Baxter 2006) and to aircraft hazards (Rose 1986). It is also significant to global atmospheric effects, mainly, because ash is removed so quickly from most eruption clouds that its long lasting effects are small.

2 Background

The 1982 events at El Chichón (17.33° N; 93.20° W) represented a sudden revival of an almost unknown and little-studied volcano. There were three main explosive events of the eruption (A1 beginning 0532 UT on March 29; B at 0135 UT on April 4; and C at 1122 UT on April 4). Deposits of erupted materials were described and sampled by volcanologists (Sigurdsson and Carey 1984; Varekamp et al. 1984) who found that pyroclastic flows and surges were prominent features of the eruption, and that fallout of ash occurred especially to the east and NE of the volcano. In proximal locations, the fall deposits could be separated into distinct units associated with the three explosive events, but in more distal locations, where fine ash dominated, it was not easy to distinguish the individual fall units for the three closely spaced events. The A1 eruption caused mainly a phreatoplinian fall deposit, while the B and C events were associated with pyroclastic surges and pyroclastic flows (Gutiérrez-Coutiño et al. 1983; Sigurdsson and Carey 1984; Carey and Sigurdsson 1986). Overall, the erupted volume of material from all the three events was estimated at $\sim$5 km^3 dense rock equivalent (DRE) volume, with about 45 km^3 being found as ashfall and the remaining (12% according to Sigurdsson et al. 1987) as surge and pyroclastic flows. Most of this proximal fall volume (0.35 km^3) came from the two April 4 events (B and C). A later study (Carey and Sigurdsson 1986) suggested that based on the estimates of the sustained column heights of the eruptions, an additional 0.5–0.6 km^3 of distal ash (leading to a total volume estimate of 1.09 km^3 DRE) may have been associated with the eruption and was widely dispersed. Isopach maps of the fall deposits are available from three different sources. Work by Gutierrez-Coutiño et al. (1983), Sigurdsson and Carey (1984), and Carey and Sigurdsson (1986) emphasized proximal falls, while Varekamp et al. (1984) studied more distal fall. In proximal sections, the investigators were able to differentiate the B and C events, but this was difficult to do in the distal exposures (Fig. 1). In this article, we are interested in the distal materials, in particular, so we consider the two April 4 events together. The B and C events were subequal in volume and intensity. Figure 2 shows graphical portrayals of fallout volume. Another important feature of the 1982 El Chichón eruptions was the sulfur release to the stratosphere (Luhr et al. 1984; Krueger et al. 2007), which was 7.5 Tg, notably large with respect to the magma volume. More than three-fourth of this sulfur release (5.6 Tg) came in the B and C events on April 4 (Krueger et al. 2007).

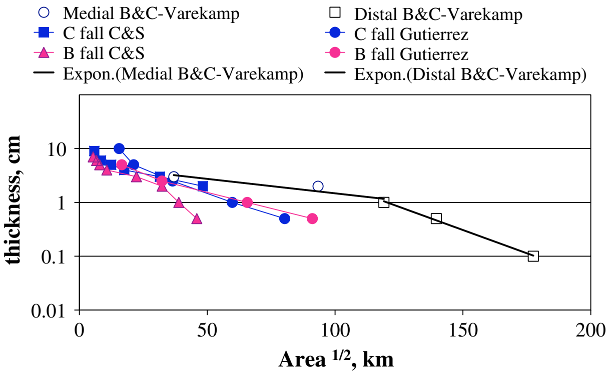


Fig. 1 Thickness/area plots for El Chichón B and C fall deposits, based on the data from isopach maps made by Gutiérrez-Coutiño et al. (1983), Carey and Sigurdsson (1986), and Varekamp et al. (1984). The maps of Gutiérrez-Coutiño et al. (1983) and Carey and Sigurdsson (1986) are based on the proximal field observations and consist of separate measurements for the B and C eruptions, while the data of Varekamp et al. (1984) help to constrain the medial and the distal areas and combine the B and C fall units

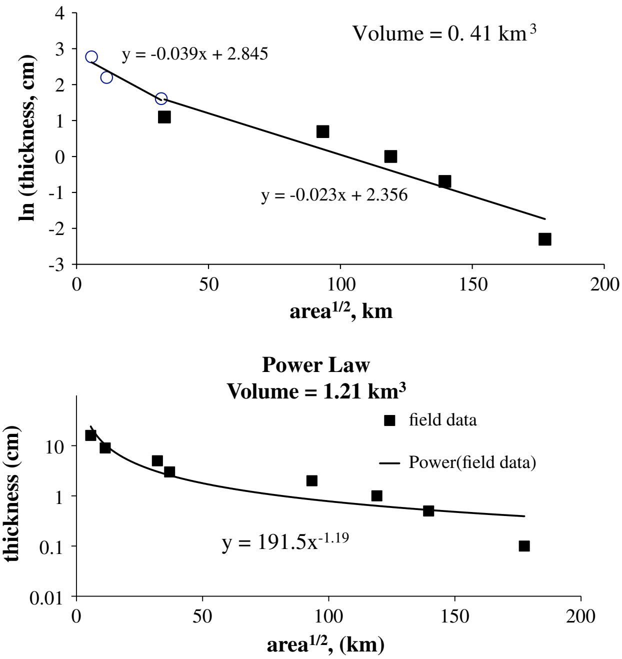


Fig. 2 Volume calculations for the B and C fall units of El Chichón. Plot above shows a construction to facilitate the application of the Pyle ashfall volume, while the plots below lead to power law and exponential volume estimates (Bonadonna and Houghton 2005). There is large uncertainty in the total volume of the B and C eruptions, probably because the distal data are too sparse. Volumes listed on these plots are bulk volumes, and are not corrected to dense rock equivalents (DRE). This correction would decrease the volume estimates by roughly 50%. See text for discussion

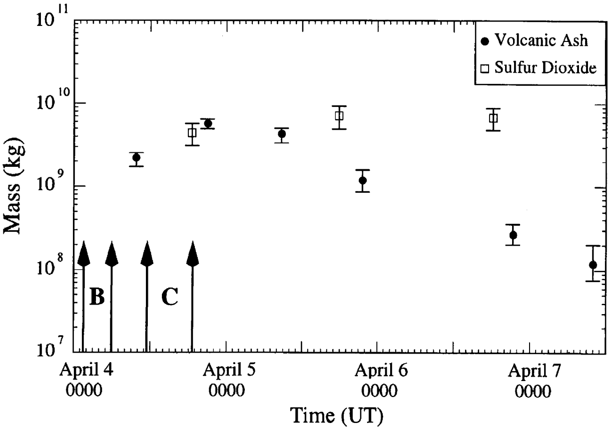


Fig. 3 Mass retrievals of AVHRR (volcanic ash) and TOMS (SO_2) instruments for the El Chichón volcanic clouds after eruptions B and C (Schneider et al. 1999). Note that ash declines, while SO_2 remains high during several days after eruption

3 Satellite observations of volcanic ash and SO_2 in the B and C eruptions

A careful and thorough study of TOMS and AVHRR satellite-based remote sensing for the B and C eruptions of El Chichón was done by Schneider et al. (1999). Results showed: (1) A vertical separation of the dispersing volcanic cloud occurred with the SO_2 cloud being at 22–26 km height asl and dispersing toward the west, while the ash was mainly seen at 19–21 km height and it moved eastward and then toward the south. (2) Elongation of the volcanic cloud in visible and thermal infrared bands of NOAA-6 (Robock and Matson 1983) in TOMS aerosol index (Krueger et al. 2007) and in AVHRR split window (Schneider et al. 1999) all show that ash in the volcanic cloud was essentially entirely in the east traveling portion. The fine ash mass retrievals of the volcanic cloud from AVHRR, using the method of Wen and Rose (1994), show that the ash mass decreased by at least an order of magnitude in 2 days (Fig. 3), as it moved over the Mexican states of Tabasco, Campeche, and Chiapas and Guatemala. The earliest AVHRR maps of the B and C volcanic cloud (Fig. 4) depict discontinuous volcanic ash clouds with gaps or holes, which is consistent with the presence of ice along with ash in the cloud. Ice is an ephemeral but important constituent of volcanic clouds (Rose et al. 1995, 2004, 2007), particularly in the first day after stratospheric emplacement, and in tropical latitudes where water vapor is abundant in warm tropical tropospheric air that gets entrained into eruption plumes. Ice was very important in the fallout of Pinatubo's 1991 ash (Guo et al. 2004a, b), which was also largely removed from the atmosphere in 2 days.

Fig. 4 Three false color displays of AVHRR data of the El Chichón B and C eruptions collected at 2100 UT on April 4, 1982 (Schneider et al. 1999). (**a**) Brightness temperatures (BT) from 10 μm thermal IR (Band 4 of AVHRR) with colors ranging from violet (50°C) to red (−80°C). Image shows a cold and dense cloud extending NE of El Chichón. (**b**) Brightness temperature difference (BTD) image (Split window) of 11 μm IR BT (Band 4) minus 10 μm IR BT (Band 4). Colors shown are Black (BTD > −0.5) and from violet (BTD = −0.5) to Red (BTD = −8.3). This image shows where fine (diameter < 25 μm) volcanic ash is being detected by AVHRR. Note that this cloud's position is quite different from (**a**), showing that much of the high cloud in A is not showing detectable ash (negative BTD). (**c**) Retrieval image showing the burden of ash retrieved from the volcanic cloud where negative BTD was found (**b**). Violet shows low burdens and red indicates 65,000 kg/km^2. Here, note that high burdens are found along the eastern edge of the cloud and is cut off where the dense high cloud is found in (**a**). We interpret this as a cloud transition area, where ice is dominant over ash. Thus the eastern portion of the high cloud outlined in (**a**) contains both ash and ice, but still gives a positive BTD that is not included in the cloud outline of (**b**) ▶

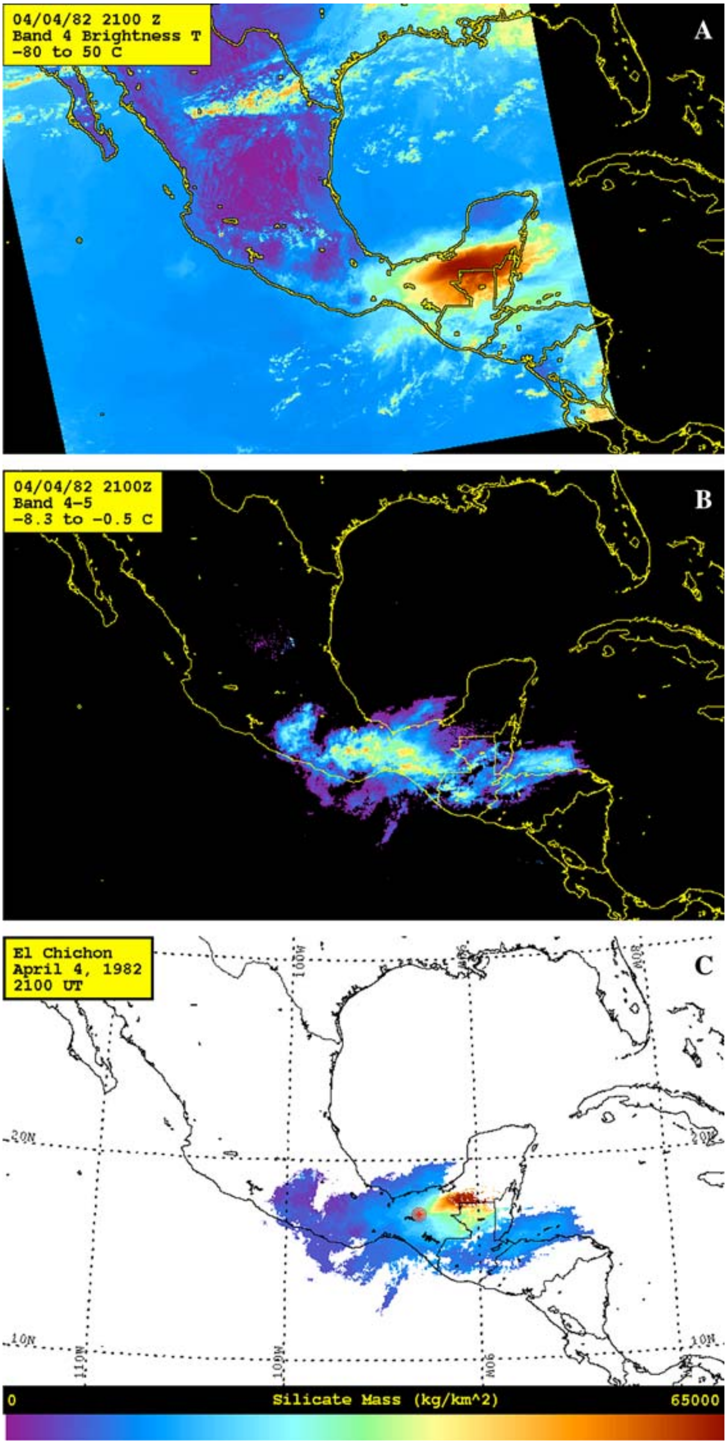

04/04/82 2100 Z
Band 4 Brightness T
-80 to 50 C
A
04/04/82 2100Z
Band 4-5
-8.3 to -0.5 C
B
El Chichon
April 4, 1982
2100 UT
C
100W
90W
80W
20N
10N
110W
0
Silicate Mass (kg/km^2)
65000

Fig. 5 Grain size distributions of ashfall samples from El Chichón's B and C eruptions, April 4, 1982. All ▶ samples were determined with Microtrac laser diffraction particle size analyzer and are displayed using Gradistat software (Blott and Pye 2001). Samples are roughly arranged by distance downwind from top to bottom. Note that the GSDs generally become finer with distance

4 Size distribution of distal ashfall from B and C

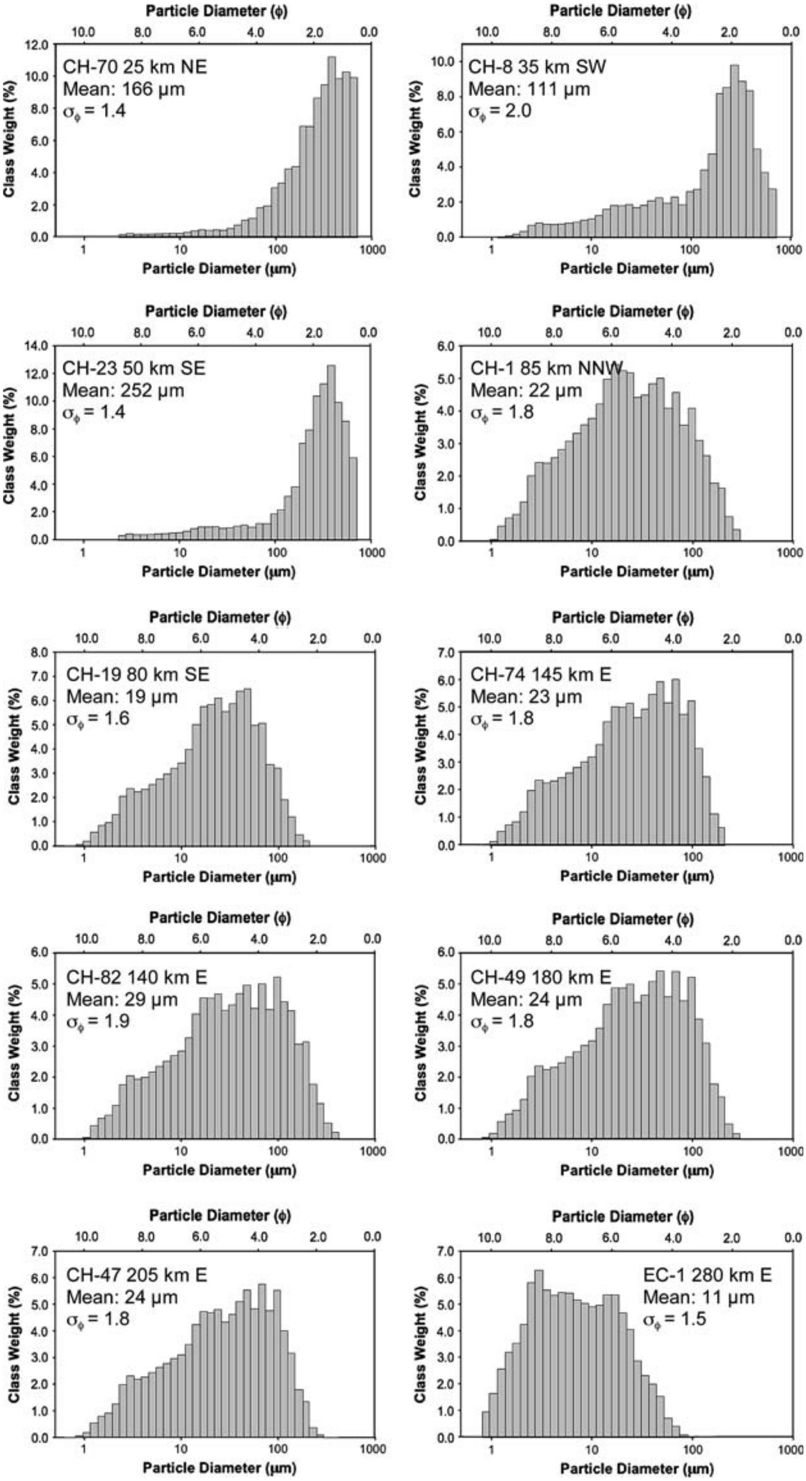
Since Varekamp et al. (1984) emphasized the importance of fine ash in the El Chichon fallout, and because laser diffraction determinations of the ashfall were not done, we obtained samples of the more distal ashfall to characterize the fine particles and tried to estimate the overall fine fraction produced in the eruption. We obtained samples from the collected materials of Jim Luhr and Joop Varekamp, and also one distal sample collected by Peter Gates at Santa Emelia camp in the Guatemalan Peten, about 280 km east of the volcano. We determined the grain size using a Microtrac SRA (Standard range analyzer) 9210-1-10-1 laser particle analyzer to obtain size distributions of the ash samples in bins of 1/4 phi from 0.82 to 704 μm (Fig. 5). Grain-size distributions were analyzed using Gradistat software (Blott and Pye 2001). Representative size distributions are shown in Fig. 5. These results strongly reinforce the conclusions of Varekamp et al. (1984) who pointed out the dominance of fine ash proportions. Even though they could not measure the specific size distributions for samples, they estimated that beyond 50 km from the vent overall more than 50% of the mass of ash consisted of particles finer than 63 μm in diameter (>4Φ). Our measurements show the predominance of fines clearly, with particles <22 μm becoming important at distances greater than about 70 km (Fig. 6). It is very likely that the volumes of "missing" ashfall, inferred by Carey and Sigurdsson (1986) from the physical volcanology, had size distributions similar to the more distal samples shown in Fig. 5. The high proportions of fine particles in fall materials that fell out in distances of no more than a few hundred kilometers resembles other eruptions such as Pinatubo (Dartevelle et al. 2002) and Mount St Helens (Durant et al. 2007a, b), with large ash inputs coming from elutriation of co-erupted pyroclastic flows. Due to the prominence of pryoclastic flows and surges in the B and C events at El Chichón, we infer that pyroclastic flows contributed greatly to the fallout ash and especially to the fine fraction.

5 SEM examinations

Figure 7 shows selected SEM views of the distal fall materials of the B and C events. The pyroclasts are highly angular and are dominated by shard-like shapes. Phenocrysts are larger in size than the smaller pyroclasts, and do not fragment as readily as the bubbly glass. Thus glass is more abundant in finer samples. Overall, this ash is similar to many plinian ashfalls (Heiken and Wohletz 1985).

6 Total grain-size distributions

Although there is much uncertainty about the amounts and distribution of distal fall materials from the B and C events, we estimated the total grain-size distribution (TGSD) by weighting the individual analyses according to isopach volume following the


Particle Diameter (ϕ)
Class Weight (%)
Particle Diameter (μm)
CH-70 25 km NE
Mean: 166 μm
σϕ = 1.4
CH-8 35 km SW
Mean: 111 μm
σϕ = 2.0
CH-23 50 km SE
Mean: 252 μm
σϕ = 1.4
CH-1 85 km NNW
Mean: 22 μm
σϕ = 1.8
CH-19 80 km SE
Mean: 19 μm
σϕ = 1.6
CH-74 145 km E
Mean: 23 μm
σϕ = 1.8
CH-82 140 km E
Mean: 29 μm
σϕ = 1.9
CH-49 180 km E
Mean: 24 μm
σϕ = 1.8
CH-47 205 km E
Mean: 24 μm
σϕ = 1.8
EC-1 280 km E
Mean: 11 μm
σϕ = 1.5

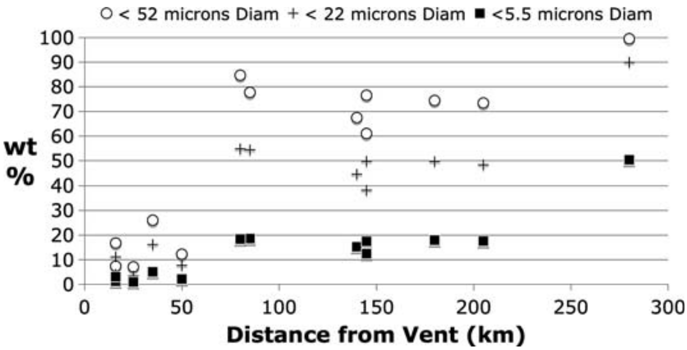


Fig. 6 Plot of the proportions of fine particles as a function of distance from the vent. Most samples beyond 70 km had a majority of their mass made up of particles less than about 25 μm in diameter

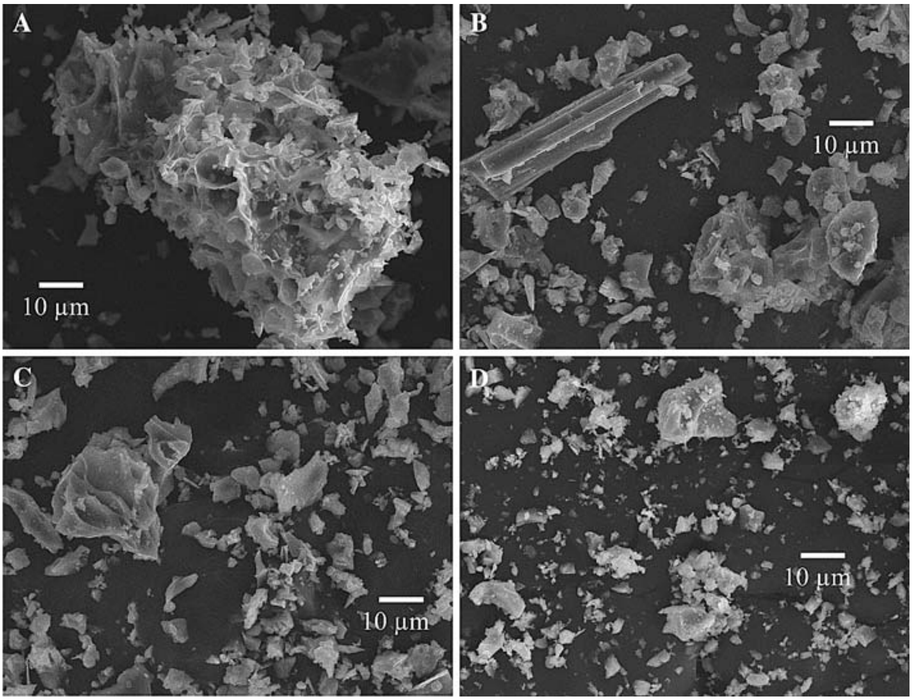


Fig. 7 SEM views of distal ashfall materials from El Chichón's B and C eruptions. (**a**) Pumicious pyroclast from CH-1, which fell 85 km NNW of the volcano. Note the bubbly shapes and sharp edges of the glass. (**b**) Angular sharp-edged shards and one elongated, cleaved amphibole crystal from ashfall sample CH-19, which fell 80 km SE of the volcano. (**c**) Glassy, sharp-edged pyroclasts dominate CH-19. Glassy materials are dominant in the fine fractions of the El Chichón ash. (**d**) Glassy shards of EC-1, which fell at Santa Emelia, 280 km east of the volcano. This sample is the most distal studied, and is dominated by glassy pyroclasts

approach of Murrow et al. (1980) (Fig. 8). In this estimate, and based on the assertion of Carey and Sigurdsson (1986), it is our conjecture that the proportion of distal fallout in previous analyses was underestimated (this assumption stems from the analysis of the intensity of the eruption determined from physical sedimentology of the proximal fall deposit). In order to investigate the importance of the fine fraction, we performed a sensitivity analysis of the TGSD to the assumed fraction of distal fallout. We used our new laser diffraction data on distal fall grain-size distributions, along with the data of Carey and Sigurdsson (1986) for proximal samples, to estimate a range of TGSDs which realistically bracket the true values (Fig. 8). Here, volume fractions of 5, 25, and 50 wt.% of fine material outside the 1 mm isopach were investigated. The calculated distribution is similar to the TGSD determined for the Mount St. Helens May 18, 1980 eruption by Durant et al. (2007a, b).

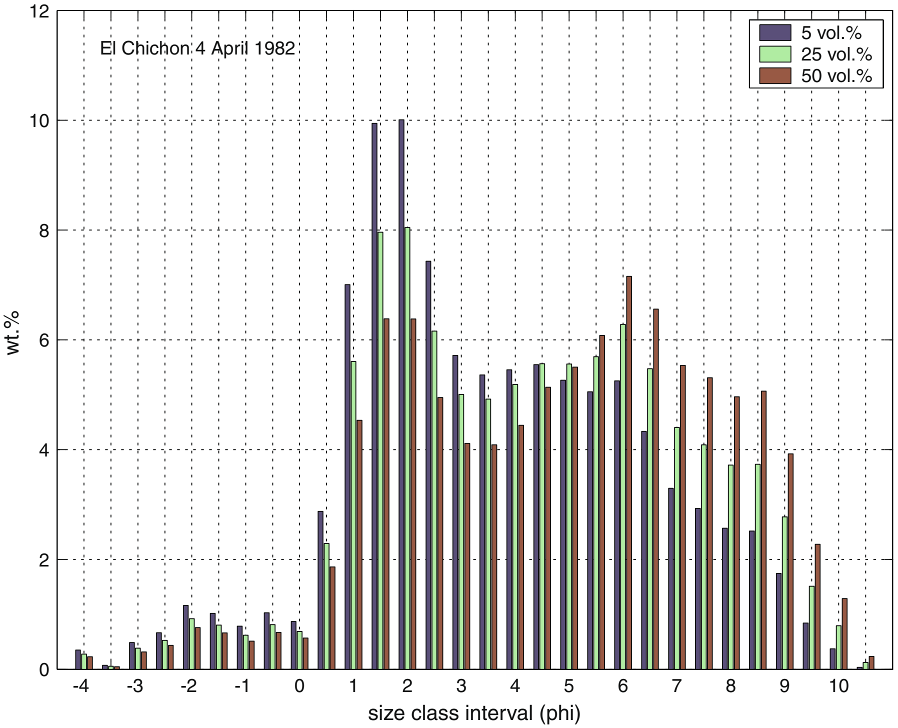
7 Discussion

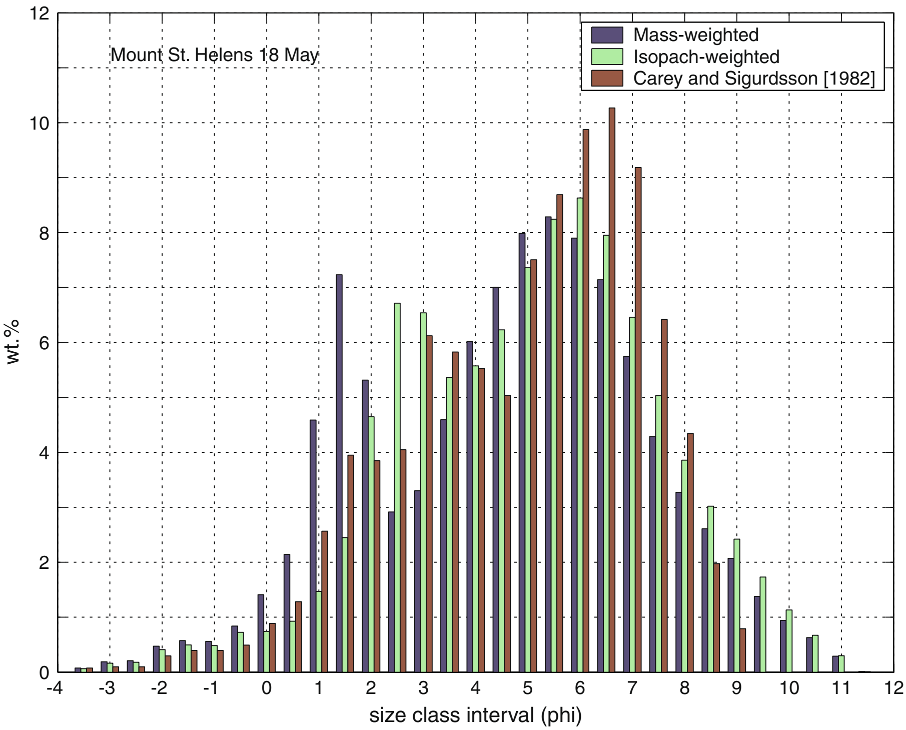
There is some uncertainty associated with the dispersal and physical characteristics of the deposit generated by the April 4, 1982 eruption of El Chichón due to a paucity of ground-based observations immediately after the eruption. However, nearly all of the volcanic ash erupted during the eruption was transported in the convective volcanic cloud to the east and settled to the ground level within a day. This is remarkable because the dominance of small particle sizes (Figs. 5, 6) implies a significantly longer residence time, if the ash settles as simple particles due to gravity. It is clear that the fine ash was removed rapidly from the drifting clouds, which is supported by remote sensing observations (Fig. 3). Observations of high silicate particle loading in the El Chichón clouds at or above the stratosphere (Fig. 4) lend support to the hypothesis that much of the fine ash nucleated ice, which enhanced sedimentation by increasing particle terminal velocities and coalescence (Durant et al. 2007a), and that ice- and ash-fall was coeval, as in the case of the 1991 Pinatubo volcanic cloud (Guo et al. 2004a, b); Schneider et al. (1999) have shown that a disperse ash cloud from the B and C events migrated across Guatemala, transporting particles as far as the Equatorial Pacific. However, the only detectable deposit was found within a few hundred kilometers east in Chiapas, Tabasco, Campeche (all in Mexico), and the northern Peten of Guatemala.

Coeval fallout of ice hydrometeors and ash can occur without obvious sign of ice on the ground because of sublimation and evaporation of the water during fall. Fallout at the ground from the April 4, 1982 eruption was distinctly wet (Varekamp et al. 1984), which is consistent with the melting of ice hydrometeors. The entrainment of moist tropical air in the eruption column promotes the development of a large convective thunderstorm-like clouds, which following the mechanism proposed by Durant et al. (2007a, b), links meteorological factors to enhanced and rapid fallout of pyroclasts.

The proportion and size of fine volcanic ash particles is strongly influenced by the prevalence of pyroclastic flows and surges (Sigurdsson and Carey 1984): milling and elutriation can generate a high proportion of fine particles. The lower occurence of pyroclastic flows led to a reduced abundance of fine particles in the TGSD for El Chichon, as compared to the May 18, 1980 Mount St. Helens eruption (Fig. 8).

The rapid fallout of fine ash in explosive eruptions limits the atmospheric effects following eruptions, because only very small proportions of ash remain in the atmosphere after a few days (Rose et al. 2000). The observations in this article provide insight into the meteorological factors that apparently lead to an efficient and early ashfall of aerodynamically fine particles. Even though the eruption itself produced prolific proportions of fine ash, the ice rich volcanic cloud conditions led to efficient fallout.


El Chichon 4 April 1982
5 vol.%
25 vol.%
50 vol.%
wt.%
size class interval (phi)
0
2
4
6
8
10
12
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10


Mount St. Helens 18 May
Mass-weighted
Isopach-weighted
Carey and Sigurdsson [1982]
wt.%
size class interval (phi)
0
2
4
6
8
10
12
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

◀ **Fig. 8** Total grain size distribution estimates for the El Chichón B and C eruptions of April 4, 1982 (above) based on variable amounts of distal ash fall volumes. We show a size distribution skewed to emphasize the distal ashfall GSD in proportions of 50%, 60%, and 67% of distal GSD, with progressively the GSD shifting in favor of the most distal GSDs as the proportion of distal ash rises. In a complimentary way, the proportion of proximal ash falls from 50% to 40% to 33% as the distal proportion rises. Finally, the lower plot offers a total GSD from the May 18, 1980 eruption of Mount St Helens for comparison, based on the work of Durant et al. (2007a, b)

8 Conclusions

In one of the largest explosive volcanic events of the past three decades, the eruption of El Chichón in 1982 generated about 1 $km^3 \pm 30\%$ DRE of magma, most of which was erupted in two explosive episodes on 4 April. The fraction of fine particles in fallout from the eruption was enhanced by a large contribution from pyroclastic flows. Overall, 50 wt.% of the particles in the tephra fall deposit were <62 μm diameter, which included a larger proportion of particles <10 μm. The dominance of highly angular ash shards increased at greater distances. Fallout of fine particles from the eruption occurred mostly in one day, forming a deposit predominantly within <300 km of the volcano. Satellite- and ground-based observations of the volcanic clouds are consistent with ice being a driver of the volcanic particle fallout.

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