Pyroclastic deposits and lava flows from the 1759–1774 eruption of El Jorullo, México: aspects of 'violent Strombolian' activity and comparison with Parícutin

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Abstract: The eruption of El Jorullo (1759–1774) in Guanajuato, Mexico, generated substantial (100–300 m high) pyroclastic cones, an extensive ash blanket and a flow field of thick lavas. The cones have the aspect of scoria cones that result from Strombolian eruptions, but the ash blankets consist predominantly of sub millimetre-sized particles (comprising ≥80 wt% beyond 1 km from the vent). This combination of cones, fine deposit grain size, and moderate dispersal area has previously been attributed to 'violent Strombolian' eruptions. The ash blanket at El Jorullo comprises *c*. 40% of the erupted volume and contains hundreds of strictly parallel laminae, evidence for deposition by fallout from a great number of explosions such as those observed during the eruption of nearby Parícutin volcano (1943–1952). The high degree of fragmentation could have resulted from hydromagmatic activity, but the deposit mostly lacks evidence for significant involvement of external water. We consider that the predominantly fine grain size was probably produced by a combination of a high yield strength and viscosity of the erupting magmas, possibly high juvenile water content, and recycling and milling of pyroclasts within the vent. The lava flow field at El Jorullo constitutes *c*. 40% of the erupted volume. Eight major flows vary from 10 to 50 m thick. Flow thickness and yield strength (calculated from flow profiles) increased with time from *c*. 30 000 Pa for the earliest flows to *c*. 200 000 Pa for the latest.

The Michoacán–Guanajuato monogenetic volcano field (Fig. 1) contains almost 1000 youthful vents, most of which are basaltic andesite or basalt pyroclastic cones, with associated lava flow fields (Hasenaka & Carmichael 1985). This field geographically fills a gap in the Mexican volcanic chain between Colima and Nevado Toluca stratovolcanoes. It is one of a number of monogenetic fields in Mexico (Fig. 1).

The majority of pyroclastic cones in the Michoacán–Guanajuato monogenetic field have the morphology of scoria cones such as those typically produced by normal Strombolian explosivity activity. However, some of them consist predominantly of ash instead of scoria, lapilli and bombs, and the pyroclastic blankets around them are more extensive and ash-rich than those produced by Strombolian eruptions. Two of these ash-rich cones in the southern part of the Michoacán–Guanajuato monogenetic field are El Jorullo, which erupted from 1759 to 1774, and Parícutin, which erupted from 1943 to 1952. Only a few accounts of the El Jorullo eruption have been published, whereas almost all of the Parícutin eruption was observed by geologists and described in considerable detail (e.g. Luhr & Simkin 1993). Of particular significance to our study are the more explosive episodes of eruptive activity at Parícutin, termed 'violent Strombolian' by Macdonald (1972).

El Jorullo, at 19.03°N, 101.67°W, formed in what is now the Mexican state of Michoacán, and is approximately 300 km west of Mexico City. Access is relatively easy; the nearest large town is La Huacana, 1–2 h away. Rough dirt roads provide access to the lava flow field from the west and north, and to the pyroclastic cones from the north

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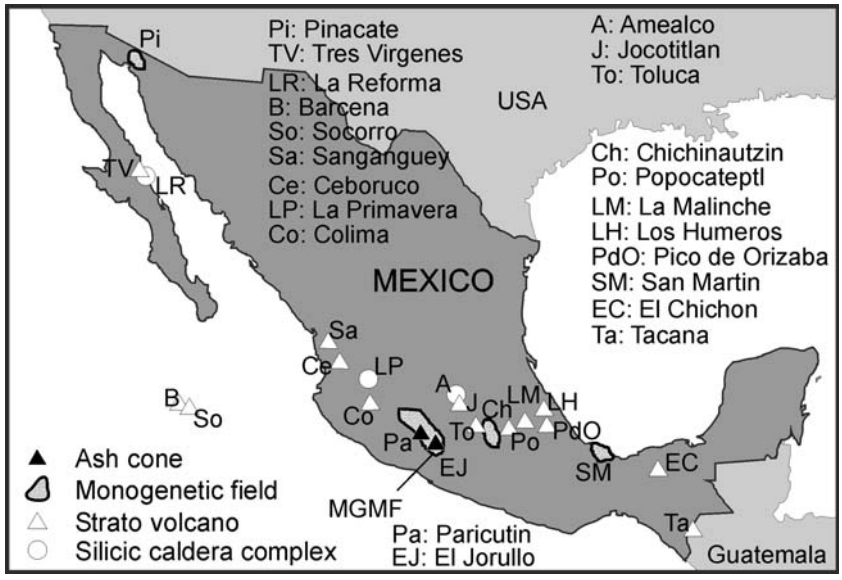

Fig. 1. Map of Mexico showing locations of large strato volcanoes (open triangles), silicic caldera complexes (open circles), and monogenetic fields (stippled). El Jorullo (EJ) and Parícutin (P; filled triangles) are shown within the Michoacán–Guanajuato monogenetic field (MGMF).

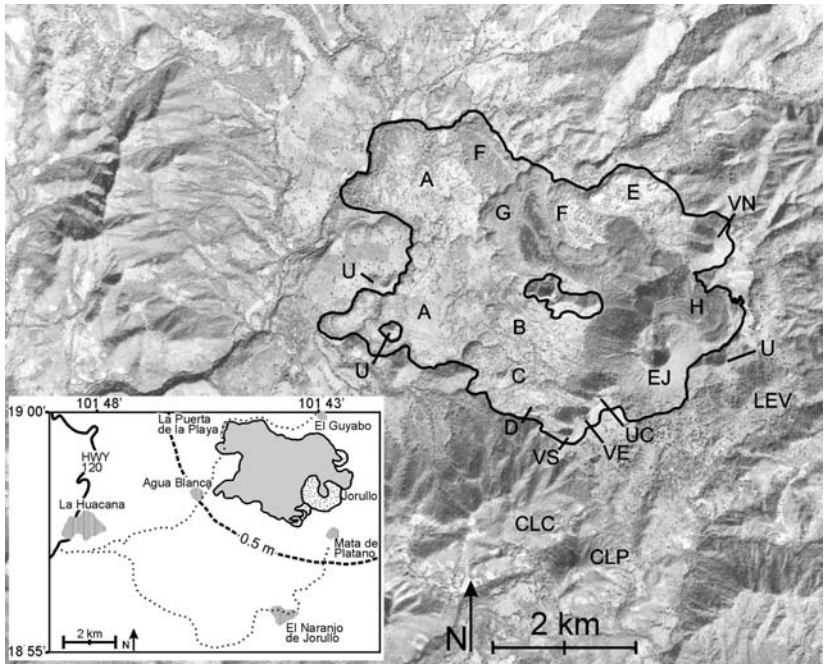

Fig. 2. Portion of an aerial photo showing the El Jorullo cones, flow field, and surrounding region. Cones of the El Jorullo eruption, are, from south to north, VS (Volcán del Sur), VE (Volcán Enmedio), UC (an unnamed cone), EJ (the main El Jorullo cone) and VN (Volcán del Norte). Letters A–H are the eight major lava flow units (see text and Fig. 11). Pre-1759 volcanic features include Cerro La Pilita (CLP), Cerro Las Cuevas (CLC), Loma el Volcancit (LEV) and three unnamed cones (U). Inset (after Luhr & Carmichael 1985) shows location of El Jorullo cones (stippled), flow field (grey), and we have superimposed on it the 0.5 m pyroclastic isopach (dotted line).

and south (Fig. 2). The small villages of Agua Blanca, La Puerta de la Playa, El Guayabo and Mata de Platano sit at the periphery of the El Jorullo cones and lava flows. The El Jorullo eruption took place in an area of hilly open-forested ranchland and farmland. Other youthful volcanic features nearby are Loma el Volcancito (1.5 km ESE), Cerro La Pilita (3 km SSW; Luhr & Carmichael 1985), Cerro Las Cuevas (3 km SW) and two un-named scoria cones 1 km east and NE of Agua Blanca, respectively. El Jorullo is underlain by deeply weathered cenozoic granites and granodiorites (Luhr & Carmichael 1985).

The El Jorullo fissure broke out in September 1759 at an elevation of *c*. 850 m, on the western bank of Cuitinga brook (Gadow 1930), a small stream that flowed south, which is roughly perpendicular to the *c*. 2° westward slope of the region. Rainfall in the area averages about 100 cm per year, concentrated strongly in a wet season from June to September that is commonly characterized by brief, heavy afternoon showers (Gadow 1930; Segerstrom 1950).

Previous work and eruption chronology

El Jorullo was known to nineteenth-century geologists because of its citation by Humboldt (1858) as an example of a volcano that grew endogenously, or as he put it, a 'Crater of Elevation'. This claim relied heavily on a perceived convex profile of the lava flow field and on the interpretation that ash layers that mantled the steep flow field margins had been pushed up from below. Hans Gadow, a vertebrate morphologist from Cambridge University, visited the region in 1908 specifically to study the recovery of fauna and flora following the eruption. His report (Gadow 1930) contains the most complete description of the pre-, syn- and post-eruption geology of El Jorullo. Importantly, he translated and summarized a number of eyewitness accounts of the eruption, as well as accounts of visits to the area shortly after the eruption. Commenting on Humboldt's ideas, Gadow pointed out that the flow field is not convex, but instead thickens in a stepwise manner toward the eruptive vents. He also observed that, in many locations, exposed flow margins make it clear that lava flowed on the surface (i.e. exogenously) and that steeply dipping ash layers mantled the flow field after it was emplaced, as opposed to having been pushed up from below.

The eruption chronology provided by Gadow (1930) is the most detailed, and it has been summarized by Bullard (1962), Luhr & Carmichael (1985), Luhr & Simkin (1993) and others. In Table 1 we present only a few details from Gadow's chronology, concentrating on those that are pertinent to the nature of the explosive activity and the eruption of the lava flows. Note that there was considerable discussion of water, flowing and falling mud, heavy rain and flooding during the first 2 weeks of the eruption, but that after that the falling ash was

Table 1. *El Jorullo eruption chronology*

End of June 1759	Subterranean noises
September 17	Noises that sounded like cannon shots, earthquakes crack chapel walls
September 27	Returning guava pickers found ash on their hats
September 29	Several sharp tremors, eruption of thick dark steam and lava fountains, falling mud, sulfurous smell
October 1	Muddy water issued out of the foot of a hill south of the new volcano, pyroclastic flow(?) erupted: 'a mass of sand rose to the outlet of the volcano, which at that time was little more than a cleft, and flowed into the bed of the Cuitinga brook; but this sand was dry and so hot that it set on fire everything in its path; having followed and filled up the brook for about half a mile, the water underneath exploded at several places, throwing torn sods high into the air' (Gadow 1930)
October 2–4	Strong earthquakes, many new springs, ash-clogged streams cause flooding, erupting material described as 'sand' rather than mud, and considerable fall of pyroclastics extending at least 10 km west
October 5–6	Considerable flooding, either new springs or release of water when temporary pyroclastic dams broke (Wilcoxson, 1967)
October 8	Pyroclastics become coarser and glassy
October 9	Sharp shocks, rain, ash and ox-sized incandescent bombs
October 12	Two hour-long steam eruption, accompanied by flood of water
October 14 (or 16?)	New springs gone, only dry ash reported falling (as opposed to mud) from this time onward, but accompanied by rain
November 13	Cone 250 m high, area abandoned because of eruption damage, no lava flows yet
1760–1764	Violent explosions continuing, lava flows emplaced(?)
1775	Activity waning

specifically described as being dry. Also, by the time the region was abandoned, *c.* 1.5 months after the start of the eruption, the main El Jorullo cone was already *c.* 250 m high, but apparently none of the lava flows had yet erupted. After the well-documented first month and a half, no detailed descriptions exist of the subsequent 16 years of activity. Gadow (1930) suggests that the lava flows were emplaced in 1764, when somewhat vague references were made about the eruption briefly gaining intensity, based on reports of ash falling in Quereto, some 125 km away.

Humboldt (1858) describes innumerable hornitos dotting the surface of the flow, west of the main cone, but his description of them is somewhat difficult to interpret. He states: 'Each of the numerous hornitos is composed of weathered basalt spheres, with fragments separated like concentric shells; I was frequently able to count from 24 to 28 such shells. The balls are flattened into a somewhat spheroidal form, and are usually 15–18 inches in diameter, but vary from 1 to 3 feet'. According to Gadow (1930), many of these features consist of concentric rings of indurated ash, in places surrounding a hollow cavity. Segerstrom (1950) suggested that preferential induration of ash occurred over fumaroles on the flows and that differential erosion removed most of the non-indurated ash to leave them high-standing. Luhr & Carmichael (1985) did not mention the hornitos.

Other high-standing mounds were reported by Gadow (1930) to resemble true hornitos more closely and A. Hoskuldsson, in his review of this paper, suggests that they might comprise a rootless cone field. Unfortunately, we did not attempt to locate any of these hornitos nor can we find any in the aerial photographs.

The general relationship of El Jorullo to the Michoacán–Guanajuato monogenetic field was documented by Williams (1950) as well as Hasenaka & Carmichael (1985). In a study of erosion at Parícutin, Segerstrom (1950) discussed the pyroclastic materials of El Jorullo briefly. He included a photograph of a sequence of thin-bedded fine-grained ash, and a table comparing many aspects of the Parícutin and El Jorullo eruptions. Luhr & Carmichael (1985) presented a detailed geologic, petrographic and geochemical study of El Jorullo, and showed, based on whole-rock analyses, that earlier-erupted lava flows are basaltic (*c.* 52 wt% SiO_2) and later-erupted flows are quartz-normative basaltic andesite (*c.* 54.5 wt% SiO_2). All of their samples have <0.5 wt% water based on bulk rock analyses. They also commented on the fine nature of the ash layers, and the fact that some of these layers mantle even steep lava surfaces, indicating that they must have been cohesive when deposited, and perhaps baked and lithified by heat from the lava. Luhr and Carmichael (1985) also compared the El Jorullo and Parícutin eruptions, particularly with respect to changes in eruptive chemistry and the inclusion of basement rock xenoliths in the lavas. An excellent summary of many El Jorullo studies can be found in Luhr & Simkin (1993).

Rubin *et al.* (2004, 2006, 2007) revised previous lava flow maps and calculated lava flow volumes, confirmed the compositional shift from early to late eruptive products and considered that this shift was due at least partly to increasing contamination of erupting magma by crustal material during the eruption. Johnson *et al.* (2004, 2006, 2008) measured high volatile concentrations in El Jorullo olivine phenocrysts and noted that the uppermost tephras have a SiO_2 content lower than that of the last lavas. They suggest that ash production must therefore have ended prior to eruption of the late lavas. Their data also suggest that the magmas underwent at least two stages of crystallization during ascent.

Violent Strombolian eruptions

Explosive eruptions were originally classified by mostly qualitative descriptions of the violence of the activity, sometimes combined with estimates of the rheology of the erupting magma (e.g. Macdonald 1972). Cas and Wright (1988) note that pyroclastic nomenclature is less than ideal, and that terms developed from eruptions that were witnessed may not correspond directly with terms describing deposits. Of the many eruption types that have been defined, three that are pertinent to the El Jorullo and Parícutin eruptions are Strombolian, violent Strombolian and Surtseyan (or hydromagmatic). Strombolian and Surtseyan are terms that have been used for many years, whereas 'violent Strombolian' was coined by Macdonald (1972) to describe brief periods of unusually explosive activity at Stromboli and Parícutin.

It is beyond the scope of this paper to discuss all the issues surrounding explosive eruption definitions other than to point out, as did Cas and Wright (1988), that George Walker made the first serious attempt to classify eruptions based on quantitative aspects of their associated pyroclastic fall deposits (Walker 1973). Such a system is especially useful because it can be applied to eruptions that were not witnessed. Walker used position on a graph of indices of dispersal v. fragmentation as a way to differentiate eruption types based on measurable parameters of deposits (Fig. 3a). He defined T_{max} as the maximum pyroclastic deposit thickness (usually at the vent), and noted that it could either be measured or extrapolated from graphs of thickness v. distance from the vent. Dispersal (D) was defined as the area (in km^2) enclosed by the 0.01 T_{max} isopach. Fragmentation (F) was defined as

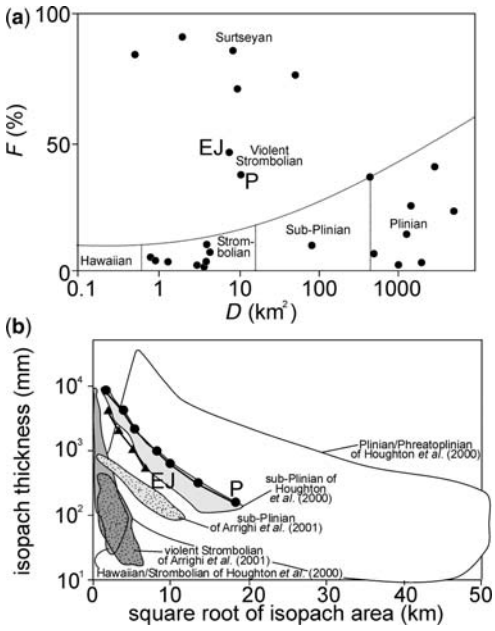

Fig. 3. Graphs illustrating pyroclastic deposit characterizations. A combines data from figures 5 and 6 of Walker (1973), plotting dispersal (D) v. fragmentation (F), and showing eruption-type fields. Note the positions of Parícutin (P) and El Jorullo (EJ; data from the present study) between the fields of Strombolian and Surtseyan eruptions. B utilizes the isopach thickness and area square root axes of Pyle (1989), and shows the fields defined by Houghton *et al*. (2000). The Vesuvius data of Arrighi *et al*. (2001) are indicated by *stippled* fields. P indicates Parícutin data (circles; Houghton *et al*. 2000), and EJ indicates El Jorullo data (triangles; this study).

the percentage of the deposit finer than 1 mm at the location where the 0.1 T_{max} deposit isopach intersects the deposit's dispersal axis. In this scheme, Hawaiian and Strombolian deposits have similarly low F values, and Walker selected a D value of 0.05 km^2 to separate deposits from these two eruption styles (Fig. 3a).

On an F v. D plot, Strombolian and Surtseyan deposits have similar D values, ranging from *c*. 0.5 to *c*. 10 km^2, but Strombolian deposits have F values of $<15\%$ whereas Surtseyan deposits have F values of *c*. 70–80%. Walker (1973) included one Parícutin data point, and it had a D value similar to those of both Strombolian and Surtseyan deposits, but an F value intermediate between the two; he defined this as the field for 'violent Strombolian' eruptions.

Pyle (1989) presented graphs of the square root of isopach area v. isopach thickness, and used these to calculate deposit volumes. Houghton *et al.* (2000) utilized these graphs to classify deposits from different types of eruptions (Fig. 3b). On such a plot Hawaiian and Strombolian deposits occupy a field with a steep negative slope close to the y-axis, indicating that they thin significantly away from the vent. Relative to the Hawaiian and Strombolian deposits, isopachs of sub-Plinian eruptions cover a larger area, and the overall distribution has less of a negative slope, indicating more gradual deposit thinning away from the vent. Plinian and phreato-Plinian deposits occupy a large field, and indicate even less thinning with distance from the vent. Houghton *et al.* (2000) included isopach data for the whole of the Parícutin pyroclastic deposit (although the data are labelled 1944–1945; B. Houghton pers. commun. 2008). The Parícutin data define the higher dispersal (more explosive) boundary of the sub-Plinian field in their classification (Fig. 3b).

Arrighi *et al.* (2001) studied all the post-1631 eruptions of Vesuvius, and classified their explosive deposits based on reported column height, bulk erupted volume, mass discharge rate (MDR), and lithologic characteristics of the deposits. Using an MDR of 10^6 kg s^{-1} as a boundary, they classified two of the post-1631 Vesuvius eruptions as sub-Plinian and the remainder as violent Strombolian. However, when the isopach thickness and area square root are plotted, these two sub-Plinian Vesuvius deposits are intermediate between the sub-Plinian and Hawaiian/Strombolian fields of Houghton *et al.* (2000), and all the violent Strombolian Vesuvius deposits occupy the low-volume portion of the Hawaiian/Strombolian field. In their discussion of eruption styles, they noted 'a certain ambiguity in the volcanology literature as to which physical parameters should be used to define classes' of eruptions other than the most explosive (Plinian) cases.

Pioli *et al*. (2008) provide a very comprehensive analysis of the Parícutin eruption with respect to both the products that were erupted and the processes that occurred. Among the observations pertinent to our El Jorullo study, they noted the bimodal nature of erupted products (fine-grained pyroclasts and lava flows), the overall fine-grained nature of the pyroclasts, the laminations in the pyroclastic deposits and the lack of evidence for interaction with external water. They also describe tan scoria clasts that are more vesicular, more irregular in shape, and contain a lower amount of plagioclase microphenocrysts, as well as black scoria, which is less vesicular, somewhat rounded and contains more microphenocrysts. Erlund *et al.* (2006) suggest that the tan scoria probably ascended more rapidly from depth. Pioli *et al.* (2008) consider that the tan scoria formed from magma in which gas had accumulated and the black scoria formed from magma that had been partially degassed. They noted that there is a decrease in the relative

proportion of tan scoria upwards in the Parícutin deposit, and that this indicates that degassing became more efficient as the eruption continued. A third, less common clast type at Parícutin consists of larger, fluidal, flattened, clasts with a relatively intact glassy outer skin; these have been termed 'pajaritos' by Pioli *et al.* (2008).

Walker (1973) speculated that, although violent Strombolian deposits plot in a position intermediate between those produced by (dry) Strombolian and (wet) Surtseyan eruptions, the involvement of water was not the only explanation for this relationship, and that if water was involved it was to a smaller degree than in Surtseyan eruptions. Other possible explanations for a greater degree of fragmentation include more viscous magma than that involved in typical Strombolian eruptions, or clogging of the erupted vent by loose already-erupted pyroclasts that are recycled and fragmented into finer and finer particles that are eventually erupted. Riedel *et al.* (2003) and Valentine *et al.* (2005) discuss the dispersal of the finer particles in violent Strombolian deposits and consider that they indicate the presence of a sustained pyroclastic jet during these eruptions, in addition to (or at times instead of) ballistic emplacement of large clasts. Recently, Cashman & Rosi (2004) and Cashman *et al.* (2004) studied the role of juvenile volatiles and bubbles in non-steady activity, with particular application to the nature of violent Strombolian activity. They and Johnson *et al.* (2008) and Pioli *et al.* (2008) noted that at Parícutin and El Jorullo, melt inclusions within olivines in some of the early-erupted pyroclasts contained 4–5 wt% H_2O, values that are much higher than typically found in mafic magmas. This gas likely provided the high degree of explosivity compared with typical mafic eruptions.

Lava flow fields

El Jorullo and Parícutin both erupted significant lava flow fields. The lavas have extremely rough surfaces and steep high margins, and can be characterized as transitional between aa and block lava. The areas occupied by lava flows are known locally as *malpaís* (bad lands), and are typically not cultivated, even though they are more than 200 years old and mostly overlain by ash.

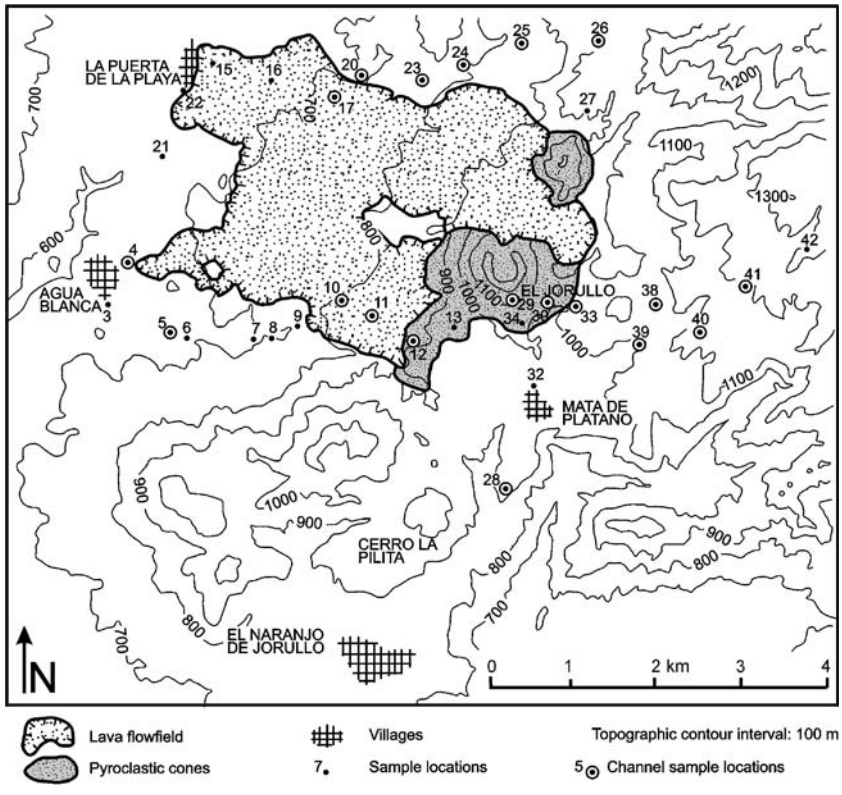

Fig. 4. Map showing locations where ash blanket thickness was measured, and samples collected for granulometric analyses.

Data and methods

Data and observations from El Jorullo constitute the majority of the present study. We visited El Jorullo in January 1991, July 2001 and July 2006 to characterize violent Strombolian deposits better and investigate reasons for the fine grain size. We sampled the ash blanket in 27 outcrops, all within 6 km of the main cone (Fig. 4). At each outcrop we measured the deposit thickness (Th), the average diameter of the three largest scoria clasts (MP), the average diameter of the three largest lithic clasts (ML) and collected 110 samples for granulometric study.

At most outcrops we sampled both the coarsest and finest-looking beds. We also collected channel samples by excavating into a bag the material from a narrow channel cut vertically across the whole exposed thickness of deposit, striving to make the channel uniform in width and depth in order to produce a sample representative of the entire deposit at that point. At the two most proximal locations, the channel samples were collected only from the ash blanket, and not from the underlying coarse agglutinated spatter and scoria.

The El Jorullo ashes are not lithified, and we made grain-size analyses using a set of sieves with a one-ϕ aperture spacing. Following the method of Walker (1971) and Cas and Wright (1988), we plotted the data on probability graph paper and derived the grain-size parameters median ϕ (Md_ϕ, the grainsize at which 50 wt% of the clasts are finer and 50 wt% are coarser) and σ_ϕ (the graphical standard deviation of the grainsize distribution). We also determined the wt% of sub-millimeter and sub-1/16 mm grains. Table 2 lists the granulometric parameters of all the channel samples.

We mapped the El Jorullo lava flows using aerial photographs, topographic maps, and field measurements of flow margin height. We visited Parícutin in July 2001 and also present previously unpublished granulometric data from the ash-blanket deposits of Parícutin collected by GPLW and Basil Booth.

El Jorullo eruptive products

Pyroclastic cones

The El Jorullo eruption generated a line of six pyroclastic cones along a 3.4 km-long fissure striking roughly NNE–SSW (Fig. 2). Gadow (1930) and Luhr and Carmichael (1985) considered that there were five cones. However, the main El Jorullo cone possesses a distinct lump on its north flank (Fig. 5) with a lava surface. Two of the major El Jorullo flow units lead upflow to this lump (flows

Table 2. *Granulometric data from channel samples*

Sample	Location	Distance from El Jorullo cone (m)	Md_ϕ	σ_ϕ	wt% < 1 mm	wt% < $\frac{1}{16}$ mm
4A	W of vent, just off flow margin	4263	2.95	1.5	97.4	52.5
5A	WSW of vent	3840	3.5	1.55	97.2	59.3
10A	WSW of vent, on flow	1879	2.05	2.03	82.5	34.7
11A	WSW of vent, on flow	1603	2.6	1.8	89.7	43.2
12AB	SW of vent, on S-most cone	1346	2.9	1.7	93.4	47.2
17AB	NW of cone, on flow	2749	1.55	1.95	80.9	23.7
20A	W of vent, just off flow margin	2752	1.8	1.9	85.9	27.2
21B	WNW of vent	4114	1.75	1.55	99.2	32.1
23AB	NW of cone	2360	1.8	1.9	87.4	30.6
24D	NNW of vent	2412	1.8	1.85	88.4	27.6
25C	N of vent	2667	2.4	1.7	93.5	34.9
26C	NNE of vent	2954	1.25	1.6	81.7	16.3
28B	S of vent	2580	3.6	2.35	98.6	63.2
29	Near S rim of cone, overlying spatter	384	−1.9	1.7	18.6	5.4
30B	Half-way up SE flank of cone	590	0.8	2.15	69.2	21.0
38A	E of vent	1738	1.3	1.85	80.2	20.1
39A	ESE of vent	1717	1.55	2.0	82.5	26.7
40A	ESE of vent	2285	1.6	1.85	86.1	24.7
41A	E of vent	2725	1.85	1.95	86.9	29.0

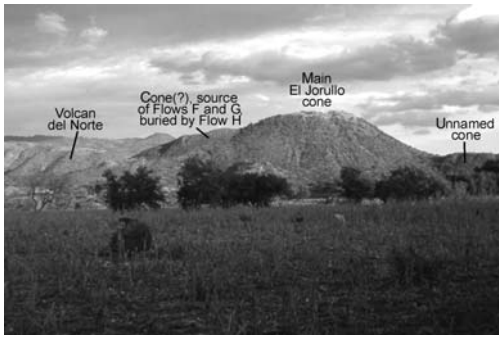

Fig. 5. Photo (looking east) toward the El Jorullo pyroclastic cone group. The buried cone was the source for flows F and G (see Figs 2 & 11).

F and G; Fig. 2), and we interpret it to be a sixth cone. From north to south the cones are Volcancito del Norte, the now-buried cone, Volcán El Jorullo (the main El Jorullo cone), an un-named cone, Volcancito Enmedio and Volcancito del Sur. All but the main El Jorullo cone and the buried cone are breached to the west, the direction that most of the flows travelled.

The summit of the main El Jorullo cone is 1136 m above sea level and about 330 m above its base. The other cones average only about 100 m high. All but one cone produced lava flows, and the main El Jorullo cone appears to have erupted both the earliest and latest flows.

The crater of the main El Jorullo cone is 410 by 510 m in rim diameter, and 160 m deep (Fig. 6; Segerstrom 1950). The crater rim is coated with large spatter bombs, some of which were obviously fluid when they landed. Others resemble the clinkers that occur on aa lava flows. A number of lava terraces cling to the upper part of the inner crater wall (Fig. 6). Some terraces are down dropped along inward-dipping grooved normal faults. Others are separated from the crater wall by outwardly dipping clefts that are large enough to crawl into. Lower on the crater wall are patches of lava veneer with scrape marks aligned toward the bottom of the crater (Fig. 6).

Fig. 6. Photo of the crater in the main El Jorullo cone, viewed toward the south. Note the multiple ledges, which indicate previous levels of lava within the crater. Some of these have been highlighted by dashed lines. The two people at right (arrows) are standing on one such ledge. At left, areas surrounded by dotted lines are occurrences of prominent scrape marks that formed as a solid crust scraped past semi-plastic lava adhered to the crater wall.

The crater rim is deeply notched on the north side. Rubbly aa lava forms a well-defined outflow from the notch and there are terrace-like levees adhering to the notch. This is the lava that buried the cone immediately north of the main El Jorullo cone. One lobe of this flow is completely without ash cover, and it stands out because of this and because of a near-complete lack of vegetation (Fig. 5).

The ash blanket

A pyroclastic blanket surrounds El Jorullo, and Segerstrom (1950) notes that ash is obvious on the ground and in creek beds as far as 8 km from the main cone. Because our thickness measurements at each outcrop include many tens of fine layers, the derived isopach map (Fig. 7) is the integrated sum of the dispersal of many beds. The isopachs indicate dispersal in all directions around El Jorullo with only a slight preference toward the NW (Fig. 7a). Contours of Md_{ϕ}, wt% < 1 mm, and wt% $< \frac{1}{16}$ mm (Fig. 7b–d) all show more of a westerly dispersal than that of the isopachs, although these are similarly indistinct. Scattered accretionary lapilli occur, but in none of the outcrops that we visited did they ever constitute more than a few per cent of any one layer.

Most of the deposit consists of thin-bedded ash layers, with some minor scoria layers, and overall the deposit is fine grained. At least 80 wt% of every channel sample collected more than 1 km from the main El Jorullo vent is finer than 1 mm, and at least 20 wt% is finer than $\frac{1}{16}$ mm (Fig. 7e).

At all size fractions, the pyroclasts form a bimodal population with respect to colour, vesicularity and crystallinity (Fig. 8). Those in one group (defined here as type 1) are sub-angular to fluidal in shape and olive-green to tan in colour. Their surfaces commonly consist of exposed vesicle interiors. Those in the other group (type 2) are sub-rounded, dark grey to black in colour, and their surfaces are smoother (Fig. 8a). Both groups are glassy. The surfaces of the finest grains, for example, $\frac{1}{16}$ mm, appear to be almost wholly planar or curvi-planar (Fig. 8b). Photomicrographs show that type 1 clasts are mostly clear to slightly brown glass, and contain many round vesicles and

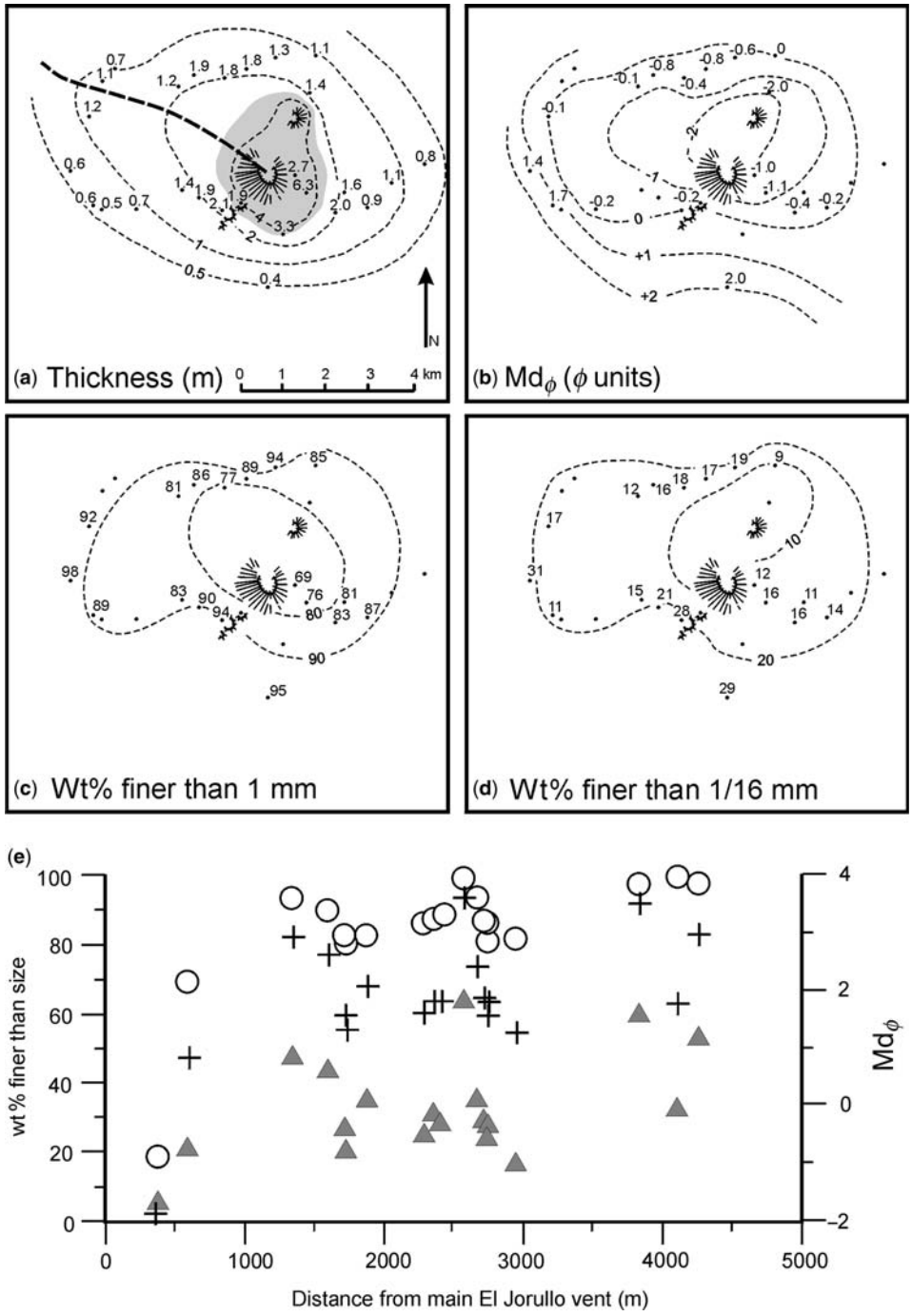

Fig. 7. Data from thickness and granulometric analyses at El Jorullo. (**a**) Isopachs of total ash blanket thickness, and indicates a subtle dispersal axis to the NW (heavy dashed line). (**b**) Contours of median grain size (Md$_\phi$) of the coarsest bed at each location. These contours suggest a more westerly orientation of the dispersal axis. (**c**, **d**) Contours of wt% of channel samples finer than 1 mm and finer than $\frac{1}{16}$ mm, respectively. These likewise suggest a more westerly dispersal. (**e**) The wt% finer than 1 mm (circles) and $\frac{1}{16}$ mm (triangles), and Md$_\phi$ (crosses) v. distance from the main El Jorullo vent for all channel samples. Note that all three parameters show a distinct fining of the deposit within the first 1000 m from the vent, and maintain relatively constant values beyond this.

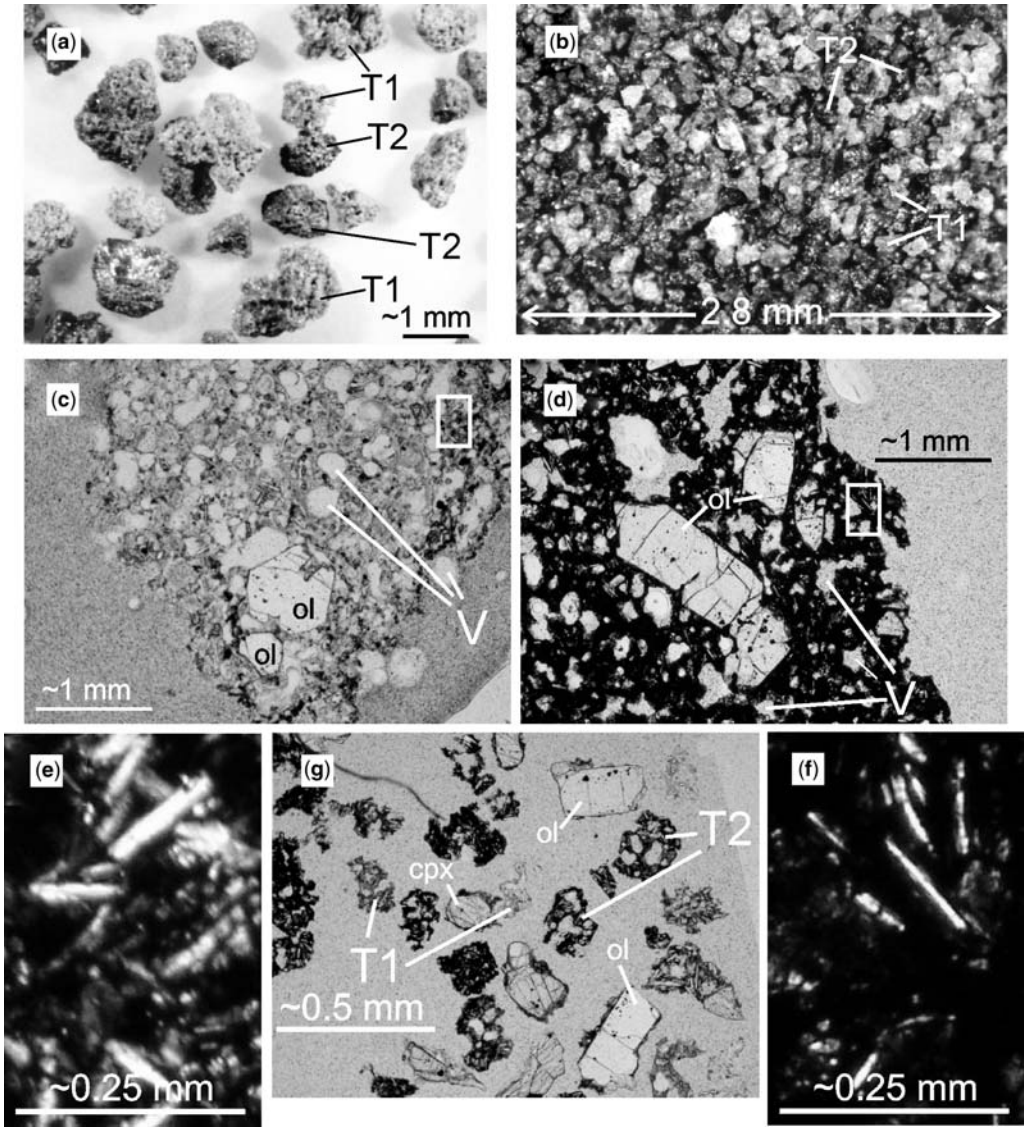

Fig. 8. Photographs and photomicrographs of pyroclasts from the El Jorullo ash blanket illustrating the bimodal nature of the clasts. In all images, ol and cpx are olivine and clinopyroxene, respectively, and T1 and T2 indicate type 1 and type 2 clasts. (**a**) shows some of a 1 mm ($\phi = 0$) sieve separate. Note the more ragged shapes and lighter tone of the type 1 clasts. (**b**) Close-up of part of the $\frac{1}{16}$ mm ($\phi = +4$) sieve separate. Note that, at this size, most of the particles have planar or curviplanar fracture-like surfaces. (**c**) Photomicrograph in plane light of part of a type 1 clast from the 4 mm ($\phi = -2$) sieve separate. Note the translucence of the glass and the abundance of microlites and round vesicles (v). Box indicates location of image (e). (**d**) Photomicrograph in plane light of part of a type 2 clast from the same 4 mm sieve separate. Note the opacity of the glass and the irregular shape of the vesicles (v). Box indicates location of image (f). (**e**) Close-up of part of the type 1 clast shown in (b) (under crossed polars), showing the abundance of plagioclase microlites. (**f**) Close-up of part of the type 2 clast shown in (d) (under crossed polars) showing that plagioclase microlites tend to be thinner and less abundant. (**g**) Photomicrograph (in plane light) of part of a 0.25 mm ($\phi = +2$) sieve separate. Note that both type 1 and type 2 clasts are identifiable, and that there is an abundance of free and nearly free crystals.

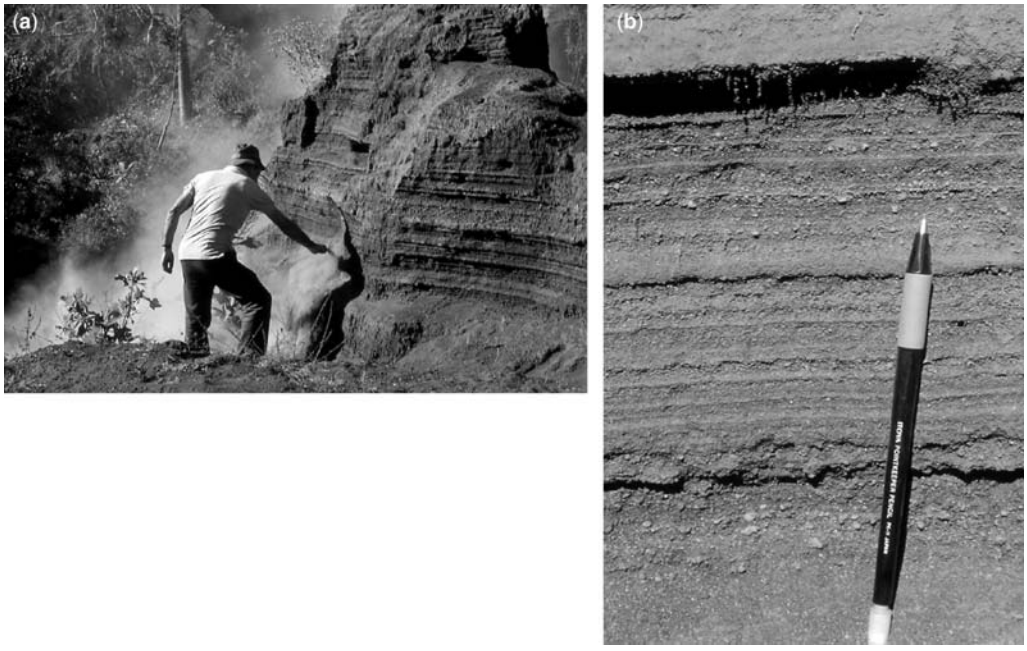

Fig. 9. Photos of location 33, approximately 1 km south of the main El Jorullo crater (Fig. 4). In (**a**), G.P.L.W. is 'cleaning' the outcrop. Note the high percentage of fine material being remobilized. Note also the continuous, planar nature of the ash layers. In (**b**), the finely laminated nature of the deposit is evident.

plagioclase microphenocrysts (Fig. 8c & e). Type 2 clasts consist of opaque glass, contain fewer and more irregularly shaped vesicles, and also contain fewer, thinner plagioclase microphenocrysts (Fig. 8d & f). In sieve separates of finer grains, e.g. *c*. 0.25 mm, some of the grains have vaguely planar surfaces, and single crystals are common (Fig. 8g).

At the SE foot of the main El Jorullo cone is location 33 (Fig. 4), where we found the thickest exposure of the ash blanket deposit. The minimum thickness here is 6 m, as the base is not exposed. The deposit contains more than 600 individual beds. Across the width of the outcrop (as at other locations) each bed is uniform in thickness and grainsize. The deposit is dominated by beds of fine ash, many of which are laminated (Fig. 9). We collected a number of channel samples from the lower, middle and upper parts of the deposit, and also collected samples from 35 individual beds. We measured MP, ML and Md_ϕ of these channel samples and individual beds (Fig. 10). Md_ϕ values for the coarser beds range from 1 to 2 mm (0 to $-1\ \phi$), whereas those in the finer beds range from $\frac{1}{2}$ to $\frac{1}{16}$ mm ($1-4\ \phi$). Md_ϕ values for the channel samples range from slightly smaller than 1 mm ($-0.3\ \phi$) to slightly larger than $\frac{1}{8}$ mm ($2.8\ \phi$). Most of the layers at location 33 lack large scoria clasts so we have only a few MP values. These cluster at around 16 mm in size. Lithics are even rarer, and we were able to identify them in only five of the layers; ML values are around 8 mm.

Accretionary lapilli are rare at location 33, occurring in only four individual beds. We found no signs of dune-bedding or cross-bedding, nor did we find surge bedforms. A few minor unconformities occur locally occur within the deposit, however, where the ash was gullied during the eruption.

What we have interpreted as a *c*. 1 m thick pyroclastic flow deposit occurs near the base of the bedded ash layers at the SE foot of the main El Jorullo cone at our sample locality 34 (Fig. 4), which is about 1 km north of Mata de Platano village. It contains rounded cauliflower bombs of dense juvenile lava with slightly glassy surfaces as well as pieces of clinker-like material in a sandy and ashy matrix. Also included are some dense oxidized clasts. This deposit is crudely reverse-graded. The event of 1 October 1759 (Table 1) may be describing emplacement of this deposit.

Lava flows

We mapped eight major flows at El Jorullo (Fig. 11, Table 3), but note that detailed field mapping might subdivide these into a larger number. In fact, samples from the northern and southern margins of flow A have different chemical compositions

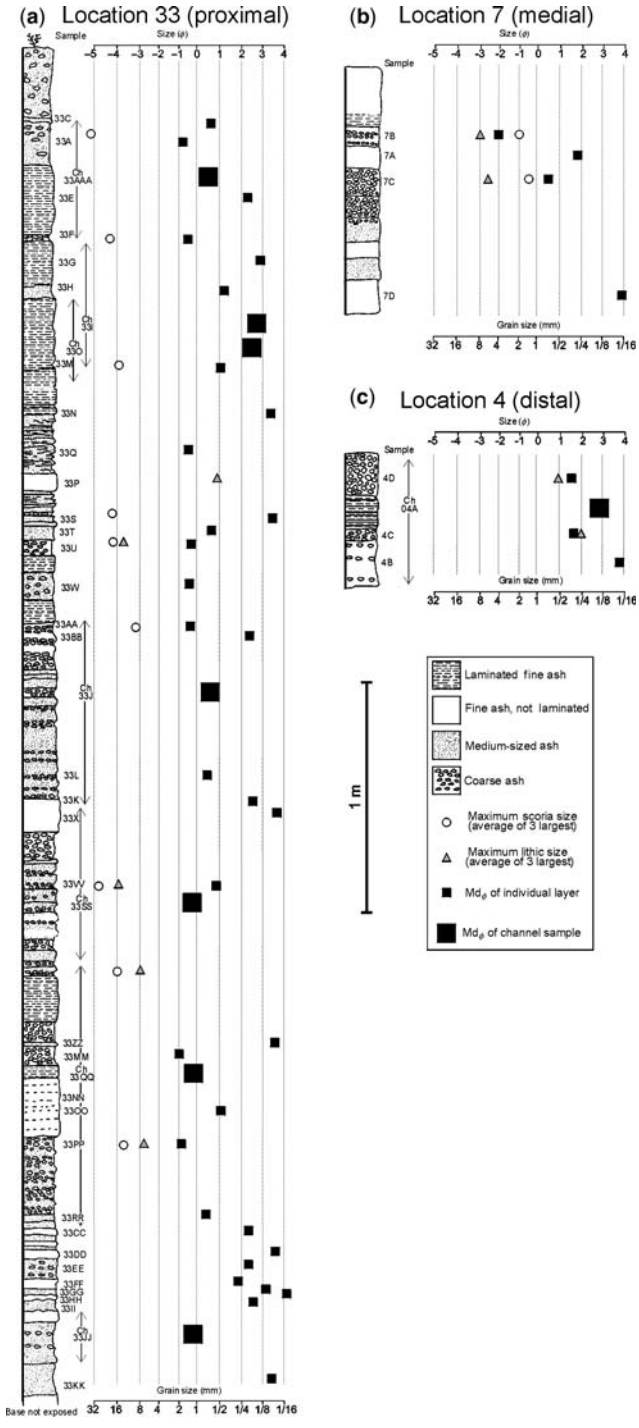

Fig. 10. Diagrammatic section of proximal, medial and distal ash beds (locations 33, 7 and 4, respectively). The variability of the deposit means that there are no beds that can be correlated from one location to another and that this particular medial example is coarser overall than both the proximal and distal examples. At the proximal location, the fine-grained nature of the deposit can be seen by the clustering of median grain sizes (squares) at sizes <2 mm ($\phi = -1$). Note also the paucity of lithics (triangles). Arrows indicate extent of channel samples.

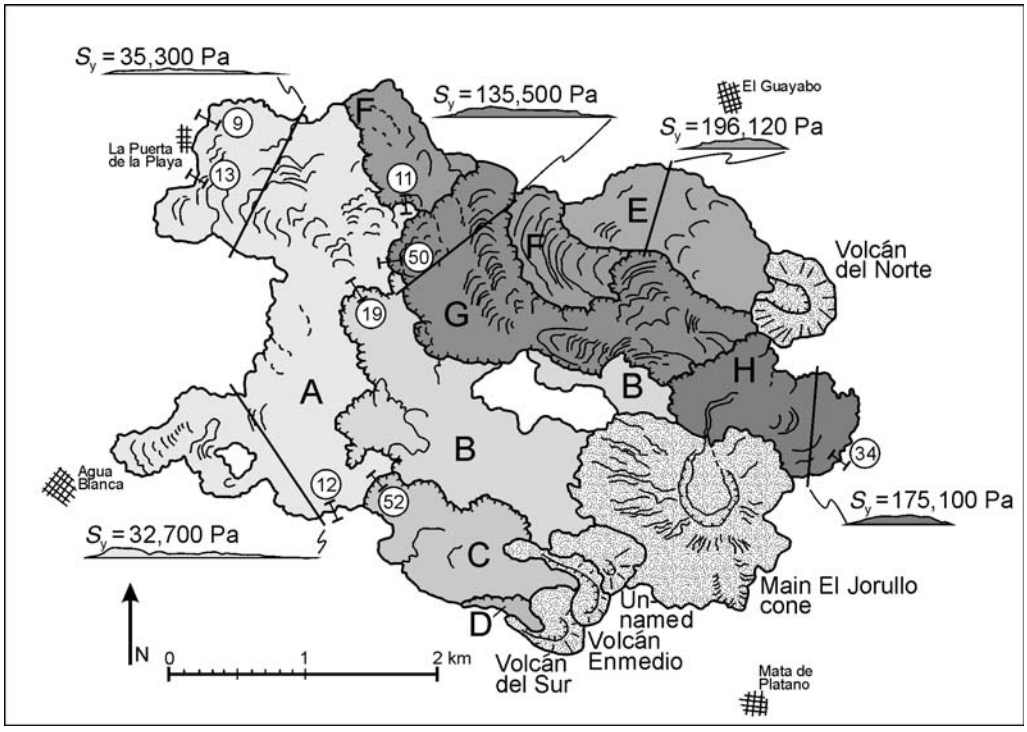

Fig. 11. Map showing the El Jorullo lava flow field subdivided into eight major units (A–H), and source cones (stippled). Tick marks occur on overlying flows. Note that tracing flows F and G upflow leads to a source covered by part of flow H (see Fig. 5). Lines within flows are major pressure ridges. Cross-flow topographic profiles are drawn with no vertical exaggeration from a published topographic map, and yield strength (S_y) determinations based on these profiles are indicated. Circled numbers are field-derived flow-front and flow-margin thicknesses (in metres).

(K. Rubin, pers. commun. 2007). Additionally, other flows may be buried. Except for one lobe of the very last flow, all the lava flows travelled westward, i.e. down the pre-eruption regional slope. All the El Jorullo lava flows almost completely lack macroscopic vesicles except at the flow front of flow A, the earliest flow.

The main El Jorullo cone produced the first, second and last flows (A, B and H, respectively, in Fig. 11). Flows A and B cover the largest areas (*c.* 6.8 and *c.* 2.9 km^2, respectively), and have the thinnest margins (Table 3). Two lobes of flow A reach *c.* 4.5 km NW and west from the main El Jorullo cone and, particularly near their distal

Table 3. *El Jorullo lava flows*

Flow	Length (km)	Maximum width (km)	Margin thickness (m)	Area (km^2)	Volume (km^3)	Yield strength (Pa)	wt% SiO_2 (Rubin *et al.* 2004)
A	4.4	3.1	11[a]	6.8	0.074	33 000–36 000	53.6[a]
B	2.6	1.4	19	2.9	0.054		54.1
C	1.8	1.2	52	0.8	0.043		54.3
D	0.6	0.2	*c.* 20	0.06	0.001		53.9[a]
E	1.9	0.7	50	0.9	0.047	196 000	53.8
F	3.8	0.6	11	2.0	0.021		54.0[a]
G	3.0	1.2	50	2.1	0.105	153 000	55.2[a]
H	1.2	0.6	34	0.8	0.027	175 000	55.8[a]
Total	—	—	—	10.8	0.364	—	—

[a]Average of two or more measurements.

ends, both of these lobes have numerous, large arcuate ridges that are convex in a down-flow direction. We interpret flow B to have once been almost as wide as flow A (its north margin is now buried), but it reaches only *c*. 3 km from the main El Jorullo cone. Flow C issued from Volcán Enmedio, is almost 2 km long, and covers an area of *c*. 0.8 km^2. It had the thickest flow front that we measured (52 m). Flow D erupted from Volcán del Sur, and is by far the smallest, with a length of *c*. 0.6 km and an area of <0.1 km^2. Flow E issued from Volcán del Norte, is almost 2 km long, and covers an area of *c*. 0.9 km^2. Two flows (F and G) issued from the now-buried cone immediately north of the main El Jorullo cone. They are *c*. 4 and *c*. 3 km long, respectively, and both cover areas of *c*. 2 km^2. Both flows F and G display numerous prominent pressure ridges, and we measured flow front thicknesses of 11 m on flow F and 50 m on flow G. Some parts of Flow G are essentially free of a pyroclastic cover (Fig. 2). Flow H (*c*. 0.8 km^2) issued out of the notch in the north rim of the main El Jorullo cone, buried the cone associated with flows F and G, and divided into two lobes, one of which flowed west and the other east. The eastern lobe evidently formed entirely after cessation of explosive activity because it lacks an ash cover (Figs 2 & 5; Luhr & Carmichael 1985).

Overlapping relationships (Fig. 11) indicate that flows A–D are in order of decreasing relative age. Flow E issued from Volcán del Norte and we interpret that it is younger than flows A and B, although no contacts between them are exposed. Additionally, we cannot relate it temporally to flows C and D. Flow F overlies flows E and A, and probably also flow B. Flow G overlies flows A, B, E and F. Flow H overlies flows B and G. Our interpreted order of emplacement is therefore A, B, C + D + E, F, G and H (Table 3).

Flow volumes (Fig. 12a) are calculated by multiplying flow margin heights by flow areas, a technique that we acknowledge is prone to errors due to flow thickness variations and unknown pre-eruption topography (e.g. Murray 1990; Stevens *et al.* 1999; Murray & Stevens 2000). The volume estimates are therefore only approximate. Additionally, we have not made corrections for void spaces within the lava. With these uncertainties in mind, our data show an overall decline in volume from flow A to flow H with the exception of flow G, which is the most voluminous of all.

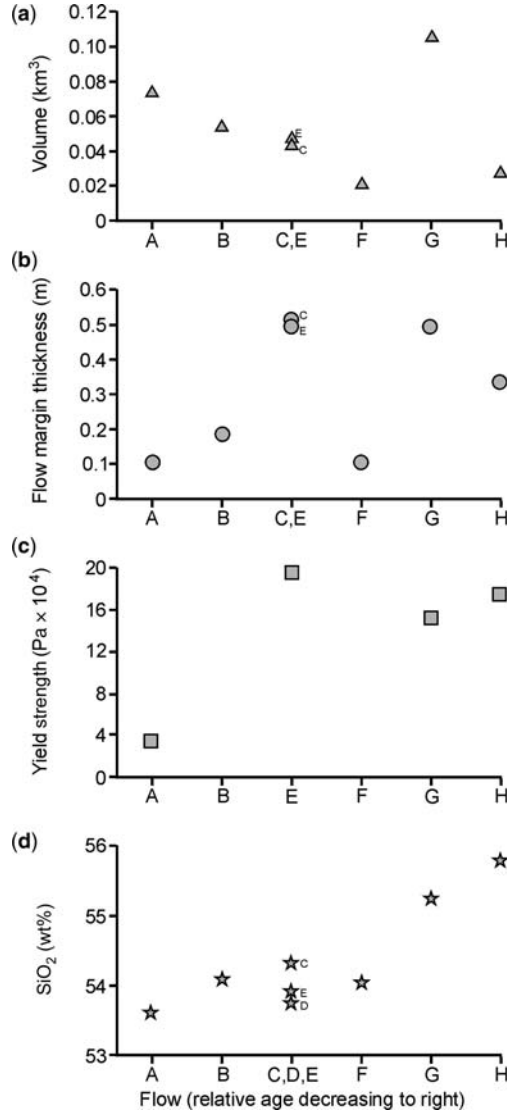

Fig. 12. Graphs of (**a**) flow volume, (**b**) flow margin thickness, (**c**) yield strength and (**d**) SiO_2 wt% (from Rubin *et al.* 2004). These parameters are all plotted against relative flow age. Note that volume decreases with time whereas the thickness, yield strength and SiO_2 increase (although some of these data are sparse and show considerable scatter).

Discussion

Character of the fine ash blanket

The first month of the El Jorullo eruption produced considerable ash, most of the main cone and water-flood deposits. This was followed by many years of eruption during which hundreds of thin-bedded ash layers were deposited. Some time during this latter period, the lava flow field was emplaced so that at least some ash layers are found on top of all but one of the flows. The impression from the historic accounts, previous work and our data is of an eruption that started

with strong explosions and considerable interaction with both surface water and groundwater. The main cones built rapidly, and the historic accounts note that the water interactions ended about a month after the eruption started. Presumably it was at this point that the thin ash beds began to accumulate. The overall result was a set of prominent pyroclastic cones, a lava flow field, and a blanket of fine ash layers. Our discussion of 'violent Strombolian' activity is concerned mainly with the ash blanket.

The ash layers forming the blanket are fine-grained, with most channel samples containing more than 80 wt% material finer than 1 mm, and more than 20 wt% material finer than $\frac{1}{16}$ mm (Table 2, Fig. 7). The average Md_ϕ for all samples farther than 1 km from the vent is 2.1. All the samples are probably even finer because at most outcrops some of the finest fraction was lost to the wind during sampling (Fig. 9a).

Using the height of the main cone (330 m) as T_{max} yields values of 3.3 m for $0.01\,T_{max}$, and 33 m for $0.1\,T_{max}$. The 3.3 m isopach encloses an area of *c.* 7 km^2, defining the *D* value (Walker 1973) for El Jorullo (Fig. 3a). Because of the lack of a distinct dispersal axis, determination of the *F* value is much less straightforward. What dispersal axis there is in the isopach data extends to the NW (Fig. 7a), and a sample near the NW foot of the cone would be ideal. Unfortunately, we do not have any samples from this area. The closest to this are from locations 29 and 30, and very different percentages of these samples are finer than 1 mm: 19 and 69 wt%, respectively. Location 29 is a little closer to the dispersal axis but it is too close to the vent (i.e. well inside the $0.1\,T_{max}$ isopach), whereas location 30 has an appropriate deposit thickness but it is farther from the dispersal axis. We therefore averaged these two <1 mm wt% values to produce an *F* value of 44 (Fig. 3a). This combination of *D* and *F* values places the El Jorullo deposit near to that of Parícutin in the classification scheme of Walker (1973; Fig. 3a).

On a graph of isopach thickness v. the square root of isopach area, the El Jorullo data plot near to those reported for Parícutin by Houghton *et al.* (2000; Fig. 3b). Together the Parícutin and El Jorullo data correspond respectively to the most and least explosive boundaries of the sub-Plinian field of Houghton *et al.* (2000).

Comparison with hydromagmatic ashes

With their predominantly fine-grained constitution, the ashes of El Jorullo and Parícutin resemble hydromagmatic ashes, which typically also have a high degree of fragmentation and abundant fine ash. Other common (although not ubiquitous) indicators of the involvement of external water are accretionary lapilli, vesicular ash, rain splash microbedding, high proportions of lithic fragments and cross-beds from dilute density currents (e.g. Moore *et al.* 1966; Walker & Croasdale 1972; Lorenz 1985). All of these are distinctly rare at El Jorullo. For example, only four of 600 individual layers at our most carefully studied locality (location 33) contain accretionary lapilli. This same locality, although only 1 km from the main vent, lacks any features indicative of turbulent, sub-horizontal deposition. The lack, or near lack, of any one of the features commonly associated with hydromagmatic activity does not rule out the possibility that such activity occurred. For example, most of the Keanakakoi deposit of Kilauea almost certainly involved hydromagmatic activity (e.g. Decker & Christiansen 1984; McPhie *et al.* 1990), yet it is possible to find finely laminated, near-horizontal ash beds within 1–2 km of the probable vent.

Heiken (1972) provides descriptions of the shapes of pyroclasts from different styles of eruptive activity. Those from hydromagmatic eruptions commonly have planar or curviplanar fracture surfaces that tend to give individual pyroclasts blocky or angular shapes. El Jorullo pyroclasts larger than 1 mm do not resemble those produced by hydromagmatic activity because neither the type 1 nor type 2 clasts have obvious fracture surfaces. Instead, many of the larger type 1 clasts appear to have been fluid when quenched, and many others appear to have been rounded and possibly abraded (Fig. 8a). This abrasion has exposed vesicles and vesicle interiors. Large type 2 clasts tend to have pitted and more rounded surfaces than those of type 1. In the smaller size fractions, however, the grains commonly have planar or curved fracture surfaces (Fig. 8b), which suggests that these may have fragmented before expanding volatiles within them could disrupt the magma, possibly due to contact with external water. An alternative possibility, which we favour, is that these finer grains are fragments of larger clasts. These fragments broke off, probably during fall back and recycling within the vent. Thus, grain morphology suggests that magmatic gases and surface tension controlled the fragmentation and shapes of the larger clasts, but that some other mechanism produced the smaller size fraction.

Walker & Croasdale (1972) sieved single-bed samples, and found that on a plot of Md_ϕ v. σ_ϕ, Strombolian and Surtseyan pyroclastic deposits occupy two fairly distinct fields with little overlap. Surtseyan deposits were shown to be more poorly sorted (i.e. higher σ_ϕ) than typical Strombolian deposits and somewhat finer, although the Md_ϕ ranges of the two fields overlap. Figure 13 shows single-bed samples of El Jorullo and Parícutin on such a plot, along with the Surtseyan and normal

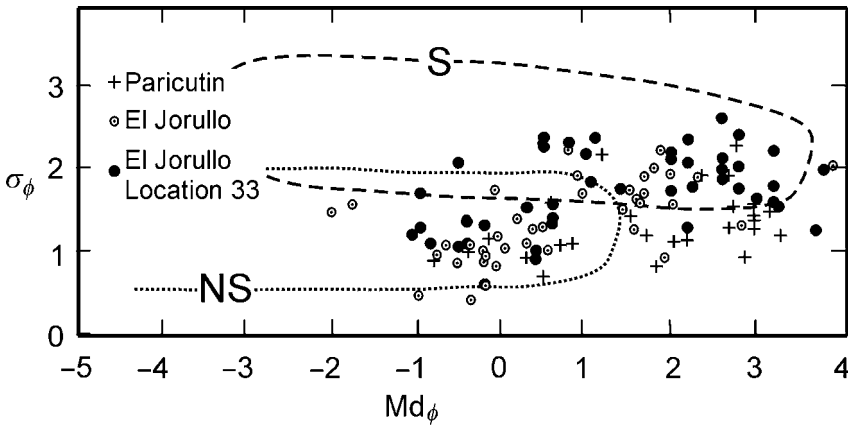

Fig. 13. Graph of Md_ϕ v. σ_ϕ (after Walker & Croasdale 1972) for channel samples and individual bed samples at El Jorullo and Parícutin. S and NS indicate the Surtseyan and normal Strombolian fields of Walker and Croasdale (1972).

Strombolian fields of Walker & Croasdale (1972). Individual-bed samples from both El Jorullo and Parícutin define a field that extends from the fine-grained end of the normal Strombolian field to the fine-grained end of the Surtseyan field, but corresponding closely with neither.

Although we consider that there is a paucity of strong evidence for hydromagmatic interactions in the El Jorullo ash blanket (other than with respect to grainsize), the historic accounts of the earliest part of the eruption (Table 1) contain clear descriptions of the interaction between magma and groundwater, including the appearance of new springs that yielded enough water to cause flooding. Wilcoxson (1967), however, suggested that some of this surface flooding could have happened when temporary pyroclastic dams on streams failed. It is probable that the streams were carrying a lot of water because the eruption started shortly after the end of the rainy season and the groundwater table would probably have been high for the same reason. Regardless of whether or not the floods issued from springs or dammed streams, much of the early explosive activity, including extremely heavy falls of mud, obviously involved interactions between erupting magma and external water.

All of the eruption–water interactions described in the historic accounts occurred during the first 2–3 weeks of the eruption, and the character of erupted products was distinctly described as being 'dry' from that time onward. The rare, scattered accretionary lapilli suggest that sufficient water was occasionally present in the eruptive cloud, possibly due to external water entering the vent. Likewise, the partial overlap of the El Jorullo data with the hydromagmatic field of Walker & Croasdale (1972; Fig. 13) indicates that water may have occasionally entered the vent. In general, however, we conclude that the majority of the ash blanket at El Jorullo, which formed after the first month of activity, did not involve external water mixing with the erupting magma. Pioli *et al.* (2008) came to a similar conclusion regarding the activity at Parícutin based on the lack of lithic fragments, accretionary lapilli and surge deposits, as well as the vesicular nature of the great majority of pyroclasts.

Comparison with 'normal' Strombolian pyroclastic deposits

Basaltic cones consisting of coarse scoria are common in many monogenetic volcano fields (e.g. Auckland, New Zealand; Searle 1962) and also occur as parasitic cones on shield and stratovolcanoes (e.g. Etna; Rittmann 1963; Riedel *et. al.* 2003). Dynamics of eruptions that generate them are understood well (McGetchin *et al.* 1974; Self *et al.* 1974; Blackburn *et al.* 1976; Head & Wilson 1989; Riedel *et al.* 2003). The cones of El Jorullo and Parícutin are morphologically similar to cones produced by normal Strombolian activity, but the blanket deposits around them are much more extensive and consist predominantly of ash instead of coarse scoria. Lathrop Wells volcano (Nevada, USA) and numerous other examples show basically the same cone and blanket pattern (Valentine *et al.* 2005, and references therein).

The pyroclasts in normal Strombolian cones tend to be very vesicular due to a high exsolved gas content upon eruption. They are also typically coarse and ragged in shape due to tearing. Many have forms that result from surface tension of the still-fluid lava during flight. The ashes at El Jorullo include some low-vesicularity clasts but in general

both type 1 and type 2 are highly vesicular. The type 1 clasts are similar to the tan clasts described from Parícutin by Erlund *et al.* (2006) and Pioli *et al.* (2008) with respect to colour and higher vesicularity. The high content of round vesicles in these clasts suggests expansion of magmatic gases as a probable driver of explosions. Similarly, the type 2 clasts from El Jorullo resemble the black clasts of Erlund *et al.* (2006) and Pioli *et al.* (2008) with respect to colour and lower vesicularity. The lower content of irregular vesicles suggests some bubble coalescence and a greater resistance to the surface tension of bubbles that become deformed, which in turn suggests a more viscous magma. With respect to microcrystallinity, however, the clasts from the two volcanoes differ. Specifically, the type 1 (tan) clasts at El Jorullo contain a higher amount of, and larger, plagioclase microphenocrysts than the type 2 (dark) clasts (Fig. 8d & e). This vesicularity–crystallinity relationship is opposite to that described for the tan and black Parícutin ashes of Erlund *et al.* (2006) and Pioli *et al.* (2008).

At El Jorullo, isopleths of the largest pyroclasts (MP) occur at about the same distance from the vent as in normal Strombolian deposits (Fig. 14). For example, where it intersects the dispersal axis, the 20 mm isopleth can be found at 4.2, 3.5, 5 and 6 km from the vent for El Jorullo, Parícutin, Carvao and Serra Gorda, respectively (the latter two are Strombolian cones on Sao Miguel, Azores; Booth *et al.* 1978). Although the data are sparse, we can also examine the wt% of ash finer than 1 mm at these locations. We find that, at El Jorullo and Parícutin, the 20 mm isopleth corresponds roughly with the contour of 90 wt% finer than 1 mm, whereas at Carvao and Serra Gorda, the 20 mm isopleth corresponds with a contour value of 30 wt% finer than 1 mm (Fig. 14). The differences are particularly clear when MP is plotted against wt% finer than 1 mm (Fig. 15). Thus in Strombolian deposits, the coarsest clasts at any one location do not differ greatly from the typical clasts at that location, whereas at El Jorullo and Parícutin, the coarsest clasts are both rarer and much larger than the majority of the deposit. These relationships imply that at El Jorullo the eruptive power ejecting the largest clasts was similar to that of Strombolian eruptions, but each explosion carried mostly fine ash and only a small proportion of large clasts.

Most of the clasts in normal Strombolian eruptions, being coarse, fall out before reaching the top of the plume, and that top (which extends much higher than the lava fountain proper) tends to consist mainly of volatiles, and is hence light-toned during an eruption. In contrast, if a much larger percentage of fine ash occurs within the erupting plume it will have a dark tone due to this heavier load of fine ash. This is exactly what was observed during most of the Parícutin eruption (see numerous photos in Luhr & Simkin 1993). Additionally, the greater amount of fine ash will produce a thick, mostly fine blanket deposit as opposed to a thin, mostly coarse deposit (Fig. 16). Riedel *et al.* (2003) consider that the fine-grained ash blankets indicate sedimentation from a sustained jet, although we note that the high number of thin ash beds at El Jorullo suggests that the jets were not sustained for long periods of time.

The outstanding difference between the El Jorullo (and Parícutin) deposits and normal Strombolian deposits is thus the overall finer grainsize and dominance of fine ash at El Jorullo, as well as the abraded shape of most of the larger El Jorullo ash particles. These differences indicate a much higher degree of fragmentation of the magmas during pyroclastic activity at the vent.

The roles of magma rheology and high juvenile water contents

We consider that the fine grain-size of the El Jorullo ash deposit was at least in part produced by high-viscosity, high-yield-strength magmas that may also have had relatively high juvenile water contents. A high viscosity and yield strength could have had two effects. First, degassed plugs of magma could have developed in the conduit, allowing pressures beneath them to build significantly before the plugs ruptured. Cashman & Rosi (2004), Cashman *et al.* (2004) and Pioli *et al.* (2008) consider that both Strombolian and violent Strombolian activity involves two-phase (gas and magma) flow regimes, and that the transition from Strombolian to violent Strombolian activity may be due to a change from slugs of gas passing through slower-rising magma, to more continuous upward flow of a gas-rich spray surrounded by an annulus of degassed magma. Both the plug and two-phase flow models may help explain the bimodal nature of the pyroclasts, with the type 2 (black, lower vesicularity) clasts comprising either the plugs or the slower-rising magma, and the type 1 (tan, higher vesicularity) clasts comprising either the magma trapped beneath the plugs or the gas-rich spray. A second effect is that bubble growth may have been hindered by the yield strength and viscosity to the point that considerably greater bubble pressures were able to develop, leading to more powerful explosions.

Finally, we consider the role that high dissolved gas contents can play in increased explosivity. Johnson *et al.* (2004, 2006, 2008) studied melt inclusions in olivines found in the El Jorullo ash deposit, and Pioli *et al.* (2008) discuss similar inclusions at Parícutin. Inclusions in olivines in the early-erupted ashes have as much as 5.3 wt%

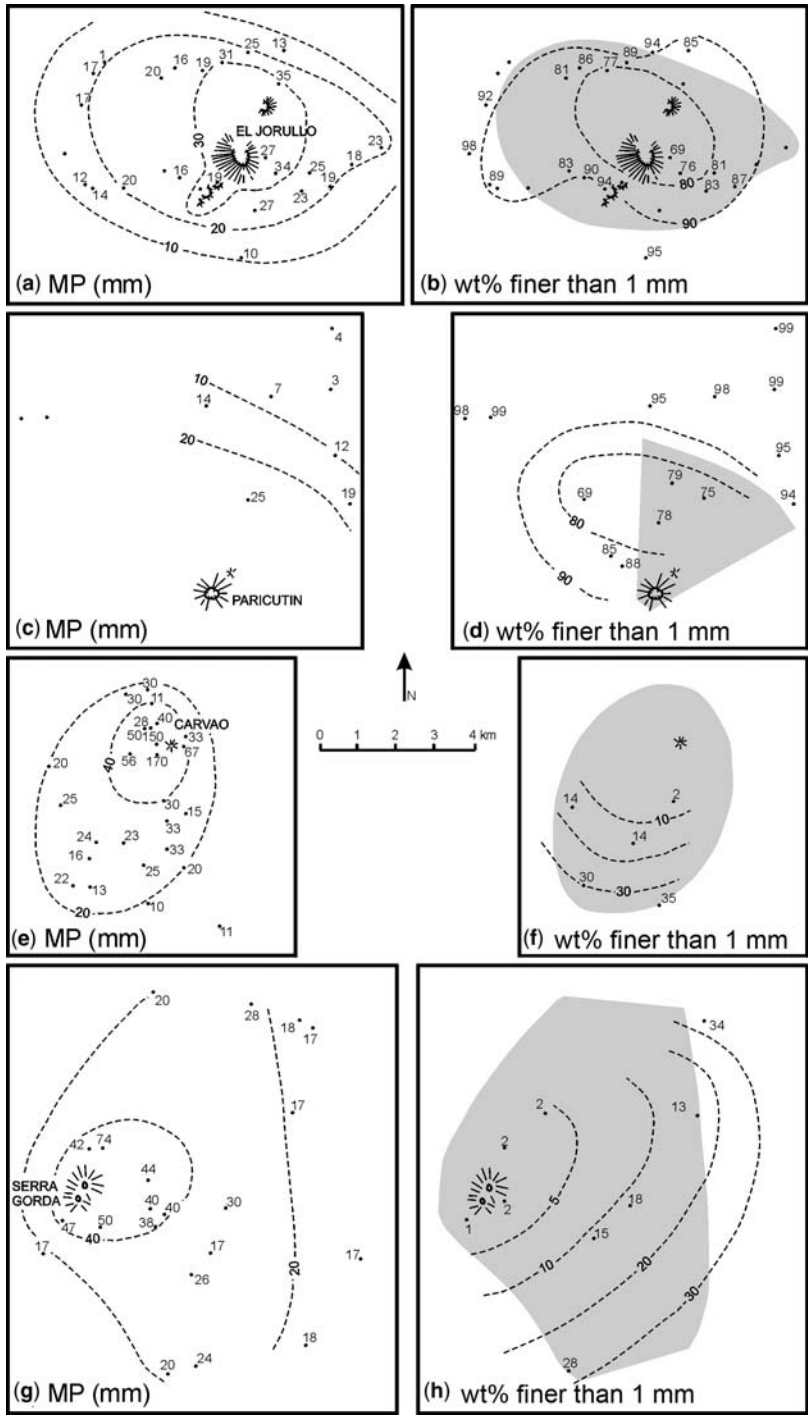

Fig. 14. Maps comparing maximum pumice sizes (MP; the average of the three largest at each outcrop) and wt% finer than 1 mm for violent Strombolian deposits (El Jorullo and Paricutin; this study) and normal Strombolian deposits (Carvao and Serra Gorda, Azores; Booth *et al*. 1978). (**a**, **c**, **e** & **g**) MP isopleths; (**b**, **d**, **f** & **h**) contours of wt% finer than 1 mm, with the area enclosed by the 20 mm isopleths shown in grey. Note that the 20 mm isopleth of the violent Strombolian deposits corresponds to samples that are 80–90% finer than 1 mm, whereas the 20 mm isopleth of the normal Strombolian deposits corresponds to samples that are only 20–30% finer than 1 mm.

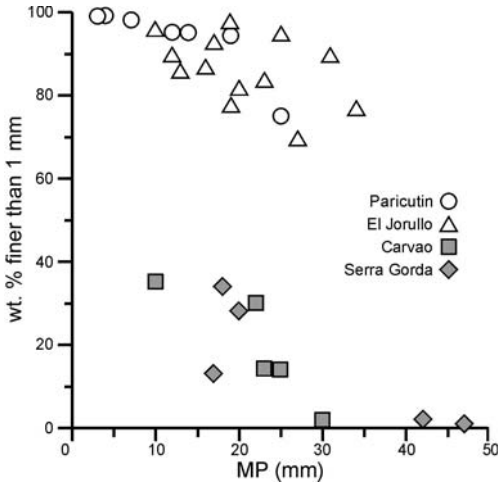

Fig. 15. Graph of MP v. wt% finer than 1 mm for violent Strombolian deposits (El Jorullo and Paricutin; this study) and normal Strombolian deposits (Carvao and Serra Gorda, Azores; Booth *et al.* 1978).

H_2O and 1000 ppm CO_2, whereas those in later ashes have 0.2–1.4 wt% H_2O and no detectable CO_2. Whole-rock analyses (Luhr & Carmichael 1985) of the lavas indicate H_2O contents that are mostly <0.5 wt%, so significant degassing must have occurred, although how much of this took place within the vent and how much took place as the lavas flowed is not clear. Certainly, the combination of a high dissolved gas content with a frequently plugged vent and/or rheology-induced impedance to bubble growth could have produced excess explosivity in these basaltic magmas, leading in turn to high degrees of fragmentation.

Comparison with Parícutin

Similar to El Jorullo, Parícutin produced a significant pyroclastic cone, an extensive ash blanket and thick lava flows. Details of the eruptions were undoubtedly different, but the similarities are sufficient that useful information can be gleaned from a comparison of the two.

At both locations the ash was dispersed in all directions from the vent as the wind varied with seasons over the multi-year durations of the eruptions. One consequence of this is that analysis

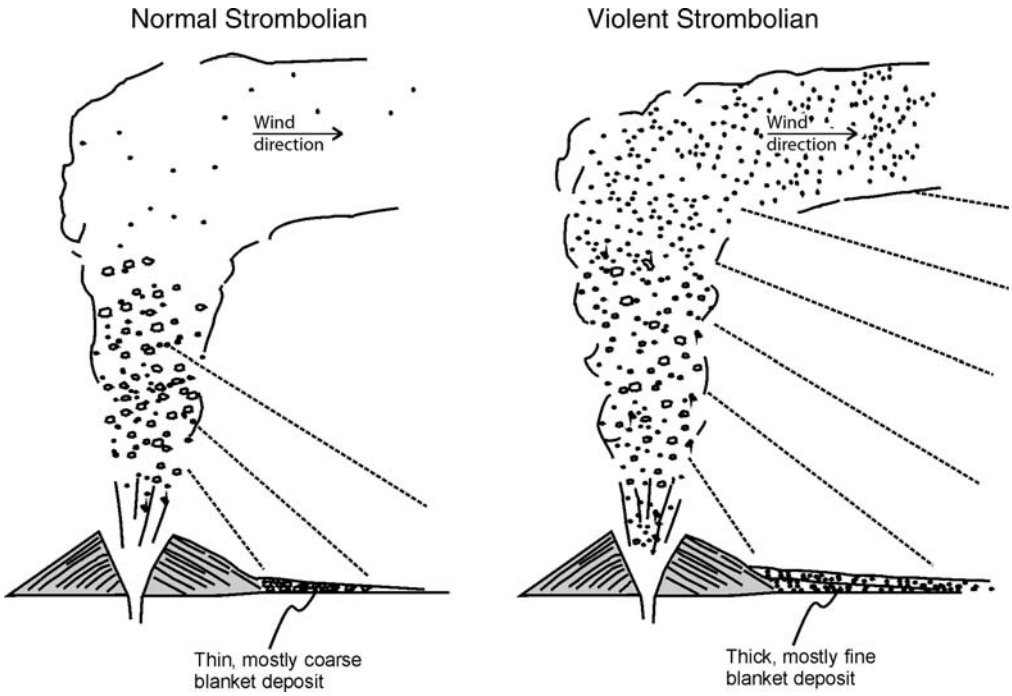

Fig. 16. Schematic diagrams showing eruption clouds of normal and violent Strombolian eruptions. In both cases the larger pyroclasts (ovals) are ejected to the same height and thus are deposited the same distance from the vent. The increased percentage of fine material (dots) in the violent Strombolian case produces a much more significant ash blanket even though the eruption clouds have the same height.

of the eruption dynamics following Carey and Sparks (1986) would be problematic. From the isopach maps and following the method of Pyle (1989), we calculated bulk (i.e. not corrected for vesicularity) ash blanket volumes at El Jorullo and Parícutin of 0.38 and 0.64 km^3, respectively. Estimated cone volumes for El Jorullo by Luhr & Carmichael (1985) and for Parícutin by Fries (1953) are 0.16 and 0.25 km^3, respectively. The blanket deposits therefore comprise 42 and 40% of the total erupted bulk volumes (including lava), and 70 and 72% of the explosive ejecta bulk volumes at El Jorullo and Parícutin, respectively (Table 4). At El Jorullo, the actual ash blanket percentage is probably even higher because some of the ash has been eroded away, some is concealed by lava flows, and not all outcrops reach the base of the deposit.

In both deposits, isopleths of the maximum clast size enclose very similar areas, suggesting that the eruptions had similar peak intensities. In March 1943 the Parícutin column rose to more than 6 km above the cone (Foshag & Gonzalez 1956), and at its peak the El Jorullo column probably would have had a similar height. An eruptive column 6 km high would imply a magma discharge rate of *c.* 100 $m^3\ s^{-1}$, assuming efficient energy transfer from magma particles to entrained air (Wilson *et al.* 1980). The overall accumulation rate of the Parícutin ashes averaged over the whole 9 years of the eruption was *c.* 3 $m^3\ s^{-1}$, and would have been about a third of that at El Jorullo (*c.* 1 $m^3\ s^{-1}$) where a smaller total volume accumulated over 15 years. At Parícutin (and by analogy at El Jorullo), the typical eruption rate was about 2 orders of magnitude less than the peak eruption rate.

Both El Jorullo and Parícutin erupted significant lava flow fields (Fig. 17), and in both cases the majority of the flows extended in the general direction of the pre-eruption regional slope. At El Jorullo, lava covers 11 km^2 with an estimated volume of 0.4 km^3, and at Parícutin lava covers 25 km^2 with an estimated volume of 0.7 km^3 (Table 4; Fries 1953). Both eruptions produced multiple flows, with at least eight at El Jorullo, and about 40 major flows at Parícutin. The El Jorullo lava flows range in thickness from 10 to 50 m (probably $\pm$5 m), whereas those of Parícutin flows average 10 m. At both locations the lavas are extremely rough-surfaced, blocky aa.

At Parícutin, lava constructed a flow field with a shield-like topographic profile 5 km across, rising 245 m above the pre-1943 surface. The shield extends farthest from the vents on the downslope north and east sides (Fig. 17). Construction of the Parícutin shield was documented by Fries and Gutierrez (1950*a*, *b*, 1951*a*, *b*, 1952*a*, *b*, 1954) and Fries (1953), and an excellent summary diagram of its growth is presented on the inside cover of Luhr & Simkin (1993). At any given time during the eruption, only one to a few flows or flow lobes were active, and they advanced slowly. Lava issued mostly from boccas at the SW and NE foot of the main cone. These boccas presumably lie on a NE-trending fissure similar to, but shorter than, that at El Jorullo. The Parícutin boccas at the NE base grew into a parasitic cone, which was named Sapichu.

Two commonly reported rheological properties of lava flows are viscosity and yield strength. Typically, no attempt is made to indicate which part of the flow is being considered – the liquid (molten rock), the fluid (molten rock + bubbles + crystals) or the bulk lava (fluid + surface skin). Additionally, because viscosity deals with the rate of deformation it is a property best measured while lava is flowing. Indeed, a number of lava viscosity determinations were made at Parícutin during its eruption (see summary by Luhr & Simkin 1993). Near its main bocca, the lava of Parícutin flowed at up to 15 m min^{-1}, but by several kilometres downflow it slowed to 10 m day^{-1} or less. Krauskopf (1948) applied the Jeffreys formula (Jeffreys 1925) to estimate that the viscosity was 10^6–10^7 Pa s, two or three orders of magnitude more viscous than typical Hawaiian pahoehoe lava (e.g. Rowland & Walker 1988).

Yield strength, at least that of the bulk lava, can be determined relatively simply from post-eruption topographic profiles. Thus yield strength turns out to be easier to determine for the El Jorullo lavas because there are fewer of them and because the flow field is much less complex. At the few El Jorullo locations where we were able to measure the thickness of flow margins and where the flows are sufficiently obvious in the topographic map, we calculated bulk yield strength (S_y) from thickness and width data after Hulme (1974): $S_y = \rho\ g\ h^2\ w^{-1}$. In this formula, ρ, h and w are the lava flow density, thickness and width, respectively, and g is gravity.

Table 4. *Volumes, in km^3 and percentage of total, for cones, ash blankets and lava flows*

	Cone	Ash blanket	Lava flows	Total
El Jorullo	0.16 (18%)	0.38 (42%)	0.36 (40%)	0.9
Parícutin	0.25 (16%)	0.64 (40%)	0.7 (44%)	1.6

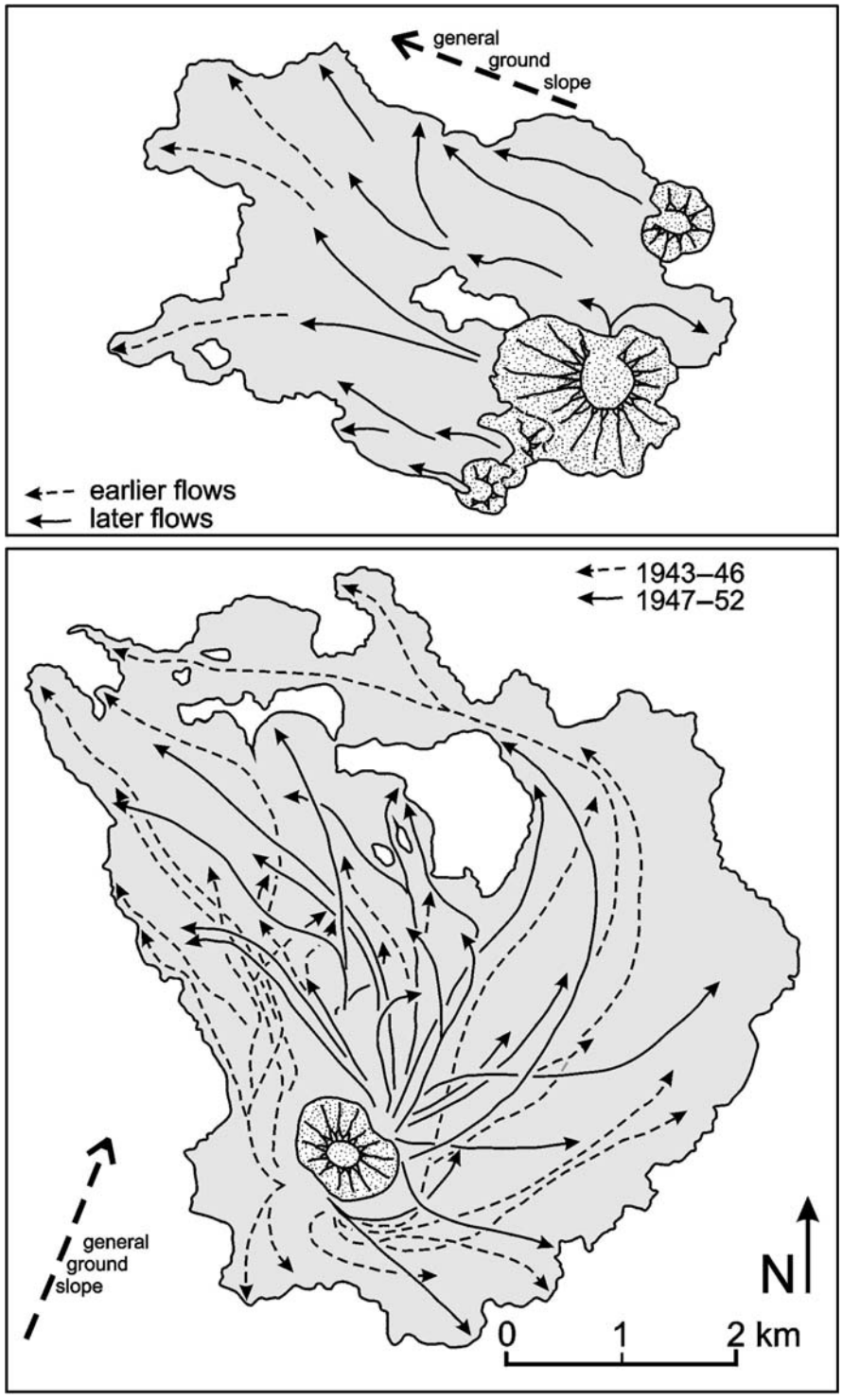

Fig. 17. El Jorullo and Parícutin flow fields drawn at the same scale, showing the flow directions of early- and late-erupted lavas. Note the much larger number of mappable flow units at Parícutin.

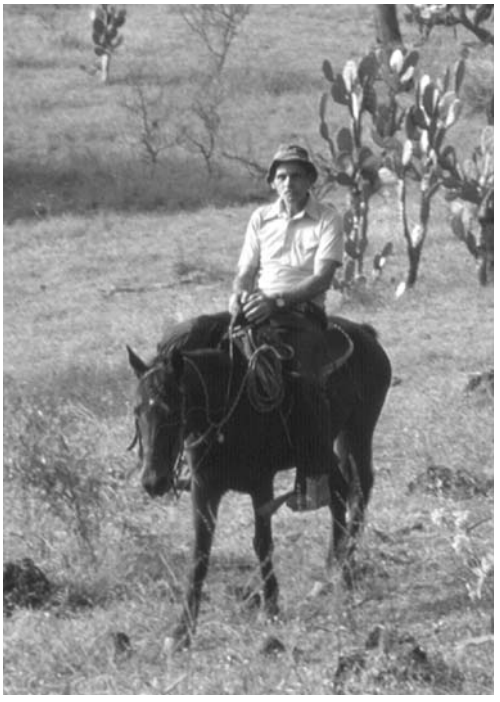

Fig. 18. George Walker at El Jorullo in 1991.

The resulting yield strength values range from slightly more than 30 000 Pa for the earliest flow, to 135 000–200 000 Pa for later flows (Fig. 12, Table 3). This is related directly to the general relationship of the later flows being thicker and narrower than the early flows. The SiO_2 wt% of the later flows is likewise higher (Rubin *et al.* 2004). Given the uncertainty in the thickness measurements and the lack of knowledge regarding the pre-eruption topography, these yield strengths can only be considered order of magnitude estimates.

Thus we have viscosity measurements for Parícutin lavas, and yield strength determinations for El Jorullo lavas, making comparisons less than straightforward. Qualitatively, based on the smaller number of flow units and their overall greater thickness, the El Jorullo lavas appear to have been less fluid than those of Parícutin. This is despite the fact that the El Jorullo lavas range from 53 to 56 wt% SiO_2 (Fig. 12d; Luhr & Carmichael 1985; Rubin *et al.* 2004) and Parícutin lavas range from 55 to 60 wt% SiO_2 (Wilcox 1954).

Conclusions

This chapter documents the nature of pyroclastic deposits and lava flows of El Jorullo, México. The pyroclastic deposit is much finer and more widely dispersed than the products of normal Strombolian activity. Historic accounts indicate that external water was involved in the earliest phases of the El Jorullo eruption but indicators of hydromagmatic activity are mostly lacking in the later-erupted El Jorullo ash blanket. We attribute the fine grain sizes to a higher degree of fragmentation of erupting magma during violent Strombolian activity, and consider a number of mechanisms that may be working together to cause this. We consider that plugs of high-viscosity, high-yield-strength magma in the vent could have allowed large pressures to develop, thus increasing the degree of pyroclastic fragmentation. A high initial water content is also consistent with the high degree of fragmentation, but evidence for this is equivocal in all but the earliest tephras from both eruptions. Finally, it is likely that at least some, if not a great deal, of recycling of clasts within the eruptive vent occurred. This would have abraded the larger clasts to help produce many smaller fragments and, unlike the hydromagmatic and juvenile gas mechanisms, helps to explain why only the smaller fragments appear to have formed by fracturing.

This chapter is dedicated to the memory of our good friend, colleague, and mentor; George P. L. Walker (Fig. 18), who inspired us and left us with a legacy of work such as never was achieved in volcanology before. Had it been up to him alone, he would have published this paper long ago. Instead, he developed several versions of the manuscript with S. K. Rowland and Z. Jurado-Chichay over an extended period, most recently revising it with G. Ernst during stimulating discussions at the 'Boston Tea Party' café at Bristol in 1997–1998 and in 2003. This project was dear to George and, using his last version of the manuscript, we have tried to keep with his vision of the paper. The research reported in this paper was led by George, and most of the crucial observations leading to it were made by him. However, the responsibility for any errors is ours. We would also like to dedicate this chapter to the memory of Jim Luhr, a gentle student of El Jorullo, whose sudden, recent passing was a terrible shock. We thank the people of the El Jorullo area for their kind support, assistance and interest, including the Mayor of La Huacana for writing letters of introduction to the villages we visited. We would particularly like to thank S. and G. Revollar-Cortez of Agua Blanca for making horses available, and our guides R. Chavez Tana and S. Almanza in La Puerto de la Playa, G. Cornejo Harnandez in Mata de Platano and A. Ponce Castillejos in El Guayabo. We are indebted to J. Urrutia-Fucugauchi of the Paleomagnetism Laboratory at the National Autonomous University of Mexico (UNAM), who made possible the loan of a field vehicle. Travel by GPLW was funded from the Jaggar Bequest Fund. S. K. Rowland thanks P. J. Mouginis-Mark for allowing time for travel to Mexico. Z. Jurado-Chichay was supported by a fellowship from UNAM (DGAPA). G. Ernst acknowledges support from a Nuffield Foundation Award at the University of

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