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1 Plate tephra: Preserved bubble walls from large slug bursts
2 during violent Strombolian eruptions

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8 **ABSTRACT**

9 Unusual “plate tephra” are described and provide key information about rarely
10 observed processes occurring during volcanic eruptions. The tephra formed during the
11 2008–2009 eruption of Llaima volcano, Chile and dispersed as far as 9 km from the vent.
12 The plates are angular clasts of vesicular basaltic-andesite ranging in size from 1 to 14
13 cm and in thickness from 2 to 5 mm. External features such as ridges, varying degrees of
14 curvature, and adhered material are present. Internal textures include strong crystal
15 alignment and deformed enclaves. We propose that the plates are wall fragments formed
16 during the rupture of large gas slugs associated with unsteady fire fountaining during the
17 violent Strombolian phase of the eruption. The presence of plate tephra may be a
18 diagnostic feature of highly unsteady activity where slug rupture is concurrent with the
19 formation of a sustained eruption column.

20 **INTRODUCTION**

21 Distinct vesicular, basaltic andesite plates produced during the violent
22 Strombolian opening phase of the 2008–2009 eruption of Llaima volcano, Chile, are

investigated. These clasts are part of the juvenile tephra that also included a bimodal scoria population, characterized by brown and black scoria of low and high density, respectively. The plates share morphological characteristics with other unusual tephra such as pajaritos (Foshag and González, 1956), lava flakes (Maleyev and Vande-Kirkov, 1983), and limu o Pele (Schipper and White, 2010). Here we characterize the Llaima plate tephra, investigate their origin, and present a formation model that explains their morphological, textural, and dispersal characteristics. These plates represent an overlooked fragmentation product in the context of violent Strombolian eruptions, yet their generation has important implications for both conduit and plume processes.

2008–2009 ERUPTION OF LLAIMA

Llaima is a basaltic andesite stratovolcano (3125 m a.s.l. [above sea level]) located in the Southern Volcanic Zone of the Chilean Andes (Fig. 1), which erupted on average every 5–6 yr over the past 400 yr (Dzierma and Wehrmann, 2010). The latest eruption began on 1 January 2008 with violent Strombolian activity producing a sustained eruption column 3.5–11 km in height. A tephra blanket was deposited to the east-southeast, with thicknesses up to 11 cm (Smithsonian Institution, 2013a). The opening phase lasted 13.5 h, and lower level activity continued occasionally until 21 February 2008. Periodic low-level Strombolian activity persisted until July 2008 and waned by the end of April 2009 (Smithsonian Institution, 2013b).

DEPOSIT DESCRIPTION

Isopleth and isopach maps were produced for the tephra deposit (Fig. 2). For both scoria, the isopleth dispersal axis is due east of the vent, whereas the plate isopleths mark a more constrained zone to the east-southeast of the vent. Plate dimensions range from

major axis diameters of ~14 cm (6 km from the vent) to 1 cm (9 km from the vent). Over the same area, black scoria range in size from 8 to 5 cm and the brown scoria from 7 to 3 cm (see the GSA Data Repository¹). Plate abundance is estimated at <1% of the deposit by volume. It was not possible to distinguish whether they occupied a specific stratigraphic position.

The average plate density is 813 kg m^{-3} , whereas black and brown scoria densities are 583 kg m^{-3} , and 340 kg m^{-3} , respectively (Fig. 2a-c, insets). Eruption parameters were calculated as follows: the deposit volume is $\sim 1.31 \times 10^6 \text{ m}^3$ after Bonadonna and Costa (2012); and assuming a deposit density of 583 kg m^{-3} , the mass eruption rate (MER) for the opening 13 h, 36 min, is $\sim 1.6 \times 10^4 \text{ kg s}^{-1}$ after Pioli et al. (2008).

TEPHRA CHARACTERISTICS

Hand Sample Textures

Plate shapes are oblate to bladed based on the Zingg shape parameter (Zingg, 1935; Wilson and Huang, 1979) (Fig. 3a) (Table 1). Minor axis dimensions are relatively constant (~4 mm), irrespective of plate size. By contrast, both scoria are generally equant to prolate. Approximately 90% of the 120 plates collected show curvature (Figs. 3b and 3c), but ~5% are folded with the edges tacked together. Scoria fragments are found adhered to either surface. Major-axis parallel ridges and tension cracks are present on the plate surfaces, occasionally on both sides.

Microscopic Textures

Thin sections show contrasting vesicularity and crystallinity for the three clast types (see the Data Repository, Fig. 4). Vesicularity in the black scoria is moderate to high with a few large, convolute vesicles whereas the brown scoria has very high

69 vesicularity with abundant smaller, more homogeneous and rounded vesicles. In the
70 plates, vesicles are convolute (with roughness from impinging crystals) to rounded and
71 are well connected, often forming long trains of bubbles parallel to the major plane.

72 The black scoria are highly crystalline (~50%–60%; tachylite), whereas the brown
73 scoria has lower crystallinity (~10%–15%; sideromelane). Some brown scoria contain
74 clots of higher crystallinity magma which are similar to the black scoria. Crystallinity of
75 the plates ranges from 40 to 50 vol%, similar to that observed in the black scoria. The
76 black and brown scoria are texturally akin to the “high porphyricity” (HP) and “low
77 porphyricity” (LP) scoria at Stromboli, respectively (Francalanci et al., 2004).

78 In all tephra, the mineralogy is mostly plagioclase with minor olivine (Fig. 4a and
79 4b). Plagioclase phenocrysts are 10–15 vol% of the overall crystal population, are
80 euhedral to subhedral, sieve textured with growth rims, and occasionally occur as
81 glomerocrysts. Olivine represent ~1 vol% of the total crystal population are subhedral to
82 anhedral with visible melt inclusions. The groundmass for all tephra is mostly plagioclase
83 microlites. Minor amounts of pyroxene and Fe-Ti spinel (<10 µm) are present in the
84 black scoria and plates.

85 A striking internal textural feature unique to the plates is the ubiquitous alignment
86 of crystals (Fig. 4c). Plagioclase and olivine phenocrysts and plagioclase microlites are
87 parallel to subparallel to the plate-parallel plane. Relatively large, dark enclaves, with
88 high Fe-Ti spinel and pyroxene content, are also present (Figs. 4a and 4b). The enclaves
89 are aligned relative to the major plane and show pinch-and-swell features. Neighboring
90 crystals and spinel-rich bands bend around the enclaves and glomerocrysts where present.

91 **SIMILAR TEPHRA FROM ELSEWHERE**

Similar tephra have been found elsewhere including pajaritos from Parícutin, Mexico (Foshag and González, 1956; Pioli et al., 2008) and lava flakes from Tolbachik, Russia (Maleyev and Vande-Kirkov, 1983). Pajaritos are microvesicular sideromelane plates, centimeteres in diameter that show partial folding, and have external millimeter size ridges (Pioli et al., 2008). Lava flakes are 5–20 cm diameter, 1–3 mm thick, slightly vesicular, and show deformation (Maleyev and Vande-Kirkov, 1983). Only Maleyev and Vande-Kirkov (1983) proposed that the plates represented ruptured bubbles walls, but both studies associated these clasts with violent, pulsating, Strombolian activity.

Small (millimeter size) glassy, non-vesicular plates, termed limu o Pele, are observed at lava flow ocean entries and in submarine deposits, notably at Lo’ihi volcano, Hawaii (Schipper and White, 2010). Again, formation models involve the inflation and rupture of basalt bubbles produced by either trapped super-heated seawater (Clague et al., 2000), and/or from magmatic gases associated with Strombolian eruptions (Clague et al., 2003).

CONCEPTUAL MODEL OF FORMATION

We suggest that pajaritos, lava flakes, and the Llaima plates are formed by the same mechanism and recommend the umbrella term “plate tephra” be used to describe similar clasts in the future. Our model elaborates on the basic model invoked by Maleyev and Vande-Kirkov (1983) and accounts for a number of common features of these clasts.

We interpret the distinct shape of the plates, as well as internal textures, as caused by extensional thinning of a magma film originating as walls of large slugs (several to tens of meters in diameter) (Fig. 5a). In this model, expanding bubbles, near or above the vent, experience film thinning, ductile deformation, and then undergo a primary phase of

115 inertial fragmentation, generating large, possibly sheet-shaped tatters of magma. During
116 flight, these ductile tatters are subject to chaotic rotation, torsion, and tension, as well as
117 cooling. Upon cooling to the glass transition temperature and thinning to a critical film
118 thickness of ~4 mm, they fragment brittly forming the observed angular plates. The
119 plates, instead of being ejected ballistically, were entrained into the eruption column and
120 dispersed according to their interaction with the wind field.

121 Strong crystal alignment during bubble expansion has been reproduced
122 experimentally (Yu et al., 2008). Furthermore, the near perfect crystal alignment with the
123 plate-parallel plane is typically formed in pure shear conditions associated with thinning
124 and extension (Manga, 1998). The observed pinch-and-swell enclaves and flow banding
125 are characteristics inherited at this stage. We infer that initial fragmentation of the bubble
126 film produces fluidal ejecta (on the basis of video observations), so primary
127 fragmentation is inertial, rather than brittle, in nature (Namiki and Manga, 2008).
128 Possible film retraction and additional plastic deformation of these plate parent particles
129 is evident in the form of the surface ridges (i.e., wrinkles, see Debrégeas et al., 1998),
130 variable curvature, tacked edges, and adhered material. The observed cracks are
131 interpreted as tension fracturing of a cooler, brittle crust covering ductile interior. Finally,
132 the abrupt selvages and lack of thinning at the edge of individual plates imply a
133 secondary brittle fragmentation event, probably occurring in the eruption column.

134 Online videos of the eruption show highly unsteady fire fountaining punctuated
135 by discrete slug bursts occurring tens to hundreds of meters above the vent (Fig. 5a).
136 Illustrative screen shots of footage from 23:00 on 1 January 2008–04:00 on 2 January
137 2008 (local time) (Figs. 5b and 5c) shows the continued advance and expansion of a

fragmentation front populated by large sheets and clots of lava from a recently ruptured slug. In the video, fire fountaining resumes shortly after this particular slug rupture.

IMPLICATIONS

Material Behavior

The plate tephra experience significant rheological changes during the entire formation process. Their complex deformation and fragmentation history is determined by both cooling-related and strain-rate dependent behavior of magma. The limu o Pele have distinctive features (see Schipper and White, 2010), which unlike those of the subaerial plates, are determined by rapid quenching ($10^{5.31} \text{ K s}^{-1}$; Potuzak et al., 2008) before fragmentation (i.e., quench granulation; Maicher et al., 2000; Schipper et al., 2013). Calculated minimum quench rates for the Llaima plate tephra range from 2 to 5 K s^{-1} (see the Data Repository), about six orders of magnitude slower than limu o Pele. Thus, initial fragmentation occurs prior to the completion of cooling, allowing for post-fragmentation melt relaxation, plastic deformation, and material adhesion during flight. Assuming the estimated quench rate and an eruption temperature of 1050 °C, the glass transition temperature (700 °C; Gregg and Zimbelman, 2000) could be reached in ~1–3 min, allowing for secondary brittle fragmentation to occur during flight.

Conduit Flow

Magma provenance is inferred from internal textures in the tephra. The high crystallinity and density of the plates and black scoria suggests this magma may have originated near the conduit walls (e.g., Cimarelli et al., 2010), and/or that vesicle collapse occurred during film thinning. The high vesicularity and low crystallinity of the brown

scoria suggests a hotter, more volatile-rich magma, that ascended from depth up the center of the conduit.

Video observations indicate highly unsteady eruptive behavior, with intensity and gas decoupling varying on minute to second time scales. The fire fountaining and resultant scoria represent relatively high intensity and either limited gas decoupling (for foam fragmentation), or complete decoupling (if an annular flow regime is achieved). The plates and large slugs indicate periods of relatively low intensity with significant gas decoupling. Rapidly fluctuating behavior is possible due to nonlinear coupling and decoupling of ascending phases (i.e., magma and gas) (Darteville and Valentine, 2007), which may be enhanced by viscosity variations in the conduit. According to Pioli et al. (2009), the estimated MER of 10^4 kg s^{-1} implies limited gas decoupling and the development of a sustained column, which corresponds with plume observations (Smithsonian Institution, 2013a). Since MER is an eruption-averaged value, finer scale variations in conduit flow behavior are not captured. In this context plates can be a useful diagnostic feature of highly unsteady violent Strombolian eruptions.

Plume Conditions

Based on their planar shape and similar densities to the scoria, we infer the plates had a lower fall velocity, as a function of increased surface drag and chaotic fall behavior (e.g., tumbling and fluttering) (Foshag and González, 1956; Wilson and Huang, 1979; Andersen et al., 2005; Pioli et al., 2008). This would have allowed increased transport of the plates, with respect to the scoria, which is reflected in the factor of 2.5 difference in the clast diameters at the same distance (Figs. 2a-2c). Further, the cross-wind distribution of plates in the deposit was evidently limited with respect to the scoria; this likely relates

to the complex interaction of the plates with the wind field, such as possibly the decoupling from the plume at lower heights.

CONCLUSIONS

We characterize an uncommonly reported type of plate-shaped tephra produced during a violent Strombolian eruption at Llaima volcano. From morphological, textural and video observations we infer the plates are formed by thinning and extension of a magma film, followed by inertial fragmentation as large gas slugs emanate from the conduit and rupture above the vent. The primary fragmentation results in thin sheets that continue to deform in flight, eventually cooling and undergoing secondary, brittle fragmentation to form the observed plates. They are formed during highly unsteady flow where the bursting of discrete gas slugs punctuates the more sustained fire fountaining. The plates are entrained into the eruption column, yet their distinct aerodynamic properties result in slightly modified dispersal features with respect to the scoria. Finally, this class of tephra although not common, is also not unique, and has been briefly described previously under a variety of nomenclature. We propose that these should collectively be termed plate tephra and suggest that they are an important diagnostic feature of the highly unsteady flow conditions common in some violent Strombolian eruptions.

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296 **FIGURE CAPTIONS**

297 Figure 1. A: Location map of Llaima volcano, Chile. B: Southeast view of the eruption
298 plume (~3–5 km above the vent) produced on 15 January 2008. Courtesy of Juan Enrique
299 Llona.

300

301 Figure 2. Simplified isopleth maps for plate tephra (A), black (B), and brown (C) scoria.
302 Black dots denote sample locations. Average diameter (cm) was calculated from three
303 measured dimensions of the ten largest clasts at each location, where possible. For the
304 plates, the parenthetical values are the average diameter calculated from the major and
305 intermediate axes only, for easier comparison with scoria isopleths. The insets are the
306 density histograms for each tephra type. Density determined after Houghton and Wilson
307 (1989). D: Deposit isopach map with contours in centimeters.

308

309 Figure 3. A: Plot of axial ratios of plates and scoria, the tephra after Wilson and Huang
310 (1979). Note that the plates and scoria fall in separate fields. B: Assorted plates with
311 varied curvature and size. C: Image of curved plate tephra and the major-axis parallel
312 ridges.

313

314 Figure 4. A: Thin section image shown parallel to major axis of a plate exhibiting aligned
315 plagioclase and deformed enclaves. B: Backscattered electron (BSE) image of the
316 enclave in A. The plagioclases align around the enclave, which exhibits more Fe-Ti
317 spinel and pyroxene. Image obtained using a SU-70 Hitachi SEM at University at
318 Buffalo, New York, USA. C: Rose diagrams of the main mineral phases. Data plotted in

the northwest quadrant of the rose diagram were projected into the southeast quadrant to obtain the true average orientation. The horizontal axis is 0°. Axial ratios calculated using CSDSlice (Morgan and Jerram, 2006). Additional thin section images are shown in the Data Repository (see footnote 1).

Figure 5. A: Model for plate formation illustrating the relationship between conduit flow and resultant tephra type. B,C: Screen shots of the video at 1:33–1:35. Note, silhouette in the foreground right, corresponds to tree branches. B: Fragmentation front captured after a slug burst. C: Expanding fragmentation front of the same large ruptured slug as in B. Dashed lines in this image show the location of the fragmentation front in B.

¹GSA Data Repository item 2013xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. DIMENSION DATA FOR 2008–2009 TEPHRA

	n	Average Major Axis (cm)	Average Intermediate Axis (cm)	Average Minor Axis (cm)	Zingg (b/a) (intermediate/major)	Zingg (c/b) (minor/intermediate)
Plates	424	4.5 (±2.4)	3.3 (±1.8)	0.4 (±0.2)	0.7	0.1
Black scoria	1009	3.6 (±1.4)	2.5 (±1.2)	1.6 (±1.1)	0.7	0.6
Brown scoria	1025	2.9 (±1.3)	2.0 (±1.1)	1.3 (±0.8)	0.7	0.7

Note: Numbers in parentheses are 1σ standard deviation and n is number of clasts measured.

Figure 1

Figure 2

Figure 4

Figure 5

SUPPLEMENTAL MATERIALS

Quench rate calculation

Quench rates were estimated using the following equation (Xu and Zhang, 2002):

$$q=(T_{ae}-T_{ff})h/\rho C_p L$$

where T_{ae} is the apparent equilibrium temperature, T_{ff} is the glass transition temperature, h is the heat transfer coefficient, ρ is material density, C_p is the heat capacity of basalt, and L is the effective half thickness of the object (volume/surface area). We assumed an equilibrium temperature of 1450 K, a glass transition temperature of 1000 K (Gregg and Zimbelman, 2000), a heat transfer coefficient of $50 \text{ W m}^{-2} \text{ K}^{-1}$ (Robertson, 1988), a density of 2750 kg m^{-3} , and heat capacity of $1200 \text{ J kg}^{-1} \text{ K}^{-1}$ (Greg and Zimbelman, 2000). To determine L , we assumed the plate shapes were rectangular prisms with the dimensions reported in Table 1.

Figures and Video

Back scattered electron images of the brown and black scoria are provided for reference (Fig. S1). Additional thin sections are provided to show the range of textures observed within the plate tephra (Fig. S2).

Observations of one fragmenting slug concurrent with fire fountaining were conducted on video provided by Patricio Oberg.

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27 **FIGURE CAPTION**

28 Figure S1. Back-scattered electron images of brown scoria (A) and black scoria (B). Note that
29 images were collected at the same scale.

30 Figure S2. An assortment of plate tephra in thin section. All tephra are at approximately the
31 same scale. Note the ubiquitously aligned plagioclase crystals, the presence of flow banding and
32 wide range of vesicularity.

33

~3 cm

Figure S2