Journal of Volcanology and Geothermal Research 176 (2008) 36–43

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

# The Chimborazo sector collapse and debris avalanche: Deposit characteristics as evidence of emplacement mechanisms

Benjamin Bernard [a,*], Benjamin van Wyk de Vries [a], Diego Barba [b], Hervé Leyrit [c], Claude Robin [d], Samantha Alcaraz [c], Pablo Samaniego [b]

[a] Laboratoire Magmas et Volcans, CNRS UMR 6524, 5 rue Kessler, 63038 Clermont-Ferrand, France
[b] Departamento de Geofísica, Escuela Politécnica Nacional, A. P. 17-2759, Quito, Ecuador
[c] Institut Polytechnique Lasalle Beauvais, Département Géosciences (ex-IGAL), 13 bd. de l'Hautil, 95092 Cergy-Pontoise, France
[d] Institut de Recherche pour le Développement, Laboratoire Magmas et Volcans, IRD UMR 163, 5 rue Kessler, 63038 Clermont-Ferrand, France

ARTICLE INFO

Available online 28 March 2008

*Keywords:*
Chimborazo
debris avalanche deposit
block facies
mixed facies
structures
emplacement

ABSTRACT

Chimborazo is a Late Pleistocene to Holocene stratovolcano located at the southwest end of the main Ecuadorian volcanic arc. It experienced a large sector collapse and debris avalanche (DA) of the initial edifice (CH-I). This left a 4 km wide scar, removing 8.0±0.5 km$^3$ of the edifice. The debris avalanche deposit (DAD) is abundantly exposed throughout the Riobamba Basin to the Río Chambo, more than 35 km southeast of the volcano. The DAD averages a thickness of 40 m, covers about 280 km$^2$, and has a volume of >11 km$^3$. Two main DAD facies are recognized: block and mixed facies. The block facies is derived predominantly from edifice lava and forms >80 vol.% of the DAD, with a probable volume increase of 15–25 vol.%. The mixed facies was essentially created by mixing brecciated edifice rock with substratum and is found mainly in distal and marginal areas. The DAD has clear surface ridges and hummocks, and internal structures such as jigsaw cracks, injections, and shear-zone features are widespread. Structures such as stretched blocks along the base contact indicate high basal shear. Substratum incorporation is directly observed at the base and is inferred from the presence of substratum-derived material in the DAD body. Based on the facies and structural interpretation, we propose an emplacement model of a lava-rich avalanche strongly cataclased before and/or during failure initiation. The flow mobilises and incorporates significant substrata (10–14 vol.%) while developing a fine lubricating basal layer. The substrata-dominated mixed facies is transported to the DAD interior and top in dykes invading previously-formed fractures.



## 1. Introduction

### 1.1. Sector collapses

In Ecuador, several of the largest cities, including Quito (1.6 million people), are built near active volcanoes such as Guagua Pichincha, Tungurahua, Cotopaxi, and Chimborazo, all of which have been, and may still be, affected by major flank collapse. Debris avalanches (DAs) issuing form such collapses are major volcanic hazards and are highly destructive phenomena (Leyrit, 2000). Their initiation phases and triggering mechanisms are well studied (Siebert et al., 1987; McGuire, 1996; Voight and Elsworth, 1997; van Wyk de Vries et al., 2001), whereas the understanding of DA timing and emplacement processes is still poorly constrained (Francis and Wells, 1988; Siebe et al., 1992; Cleary and Campbell, 1993; Ui et al., 2000; Legros et al., 2000).

Chimborazo volcano has been active in the Holocene (Barba et al., 2006 and this volume). The present stratocone is clearly asymmetric and glacial erosion has increased its slopes, which are typical factors of instability (McGuire, 1996). Today more than 130 000 inhabitants live on top of the Chimborazo debris avalanche deposit (DAD), which is one of the most voluminous and best exposed examples in Ecuador. Previous studies have described and mapped the DAD (Clapperton, 1990; Alcaraz, 2002; Bernard et al., 2006). Based on the excellent exposure provided in numerous quarries dug in the deposit we have re-estimated the event magnitude and facies distribution through thickness measurement and facies mapping. Structural and textural investigation of outcrops provides evidence of the avalanche emplacement mechanism.

### 1.2. Geological setting

Located 150 km south-southwest of Quito and 28 km northwest of Riobamba, ice-capped Chimborazo is the highest (6 268 m a.s.l.; Lat. 1°28′S, Long. 78°49′W) volcano in Ecuador. The Ecuadorian Andes consist of two parallel cordilleras (Western and Eastern Cordilleras) separated by the Interandean Valley (Fig. 1). Chimborazo is built on Western Cordillera basement (Cretaceous to Palaeogene sediments and volcanics) and Neogene rocks of the continental volcanic arc

* Corresponding author. Tel.: +33 4 73 34 67 21; fax: +33 4 73 34 67 44.
*E-mail address:* b.bernard@opgc.univ-bpclermont.fr (B. Bernard).

0377-0273/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2008.03.012

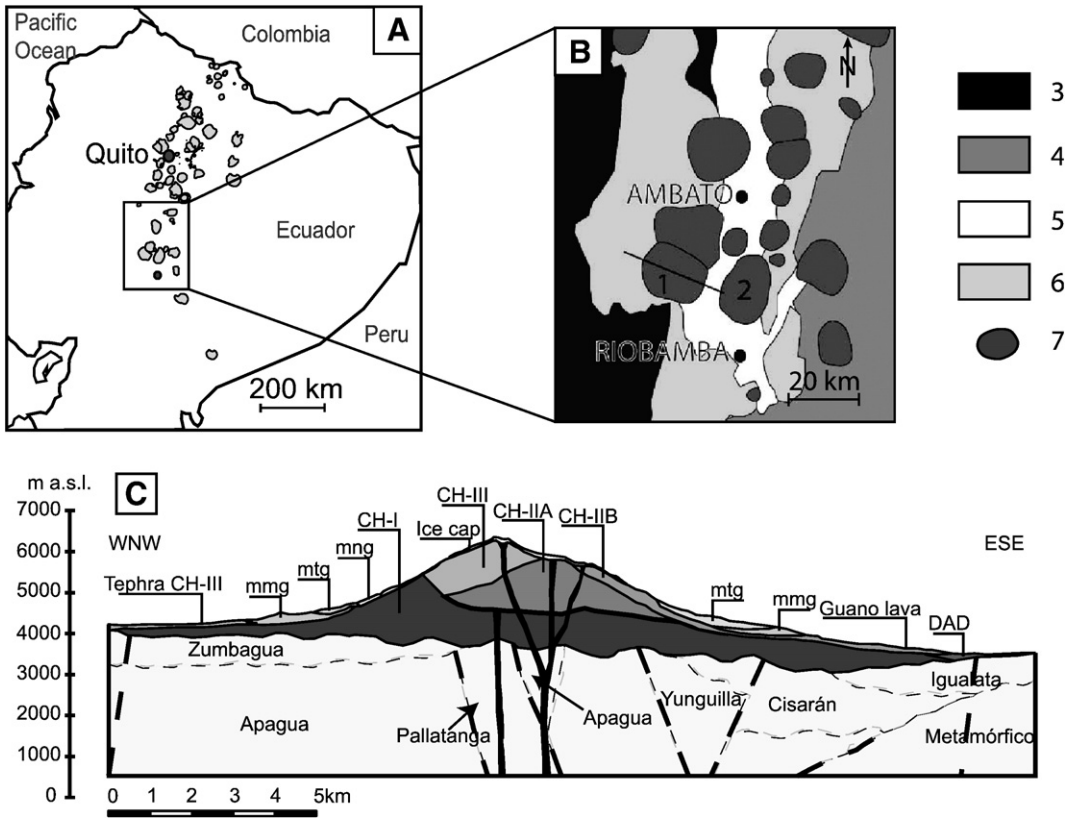


**Fig. 1.** (A) Map of Ecuadorian Quaternary volcanoes (Monzier et al., 1999; modified), (B) geological setting of Chimborazo (Barberi et al., 1988; modified), and (C) profile across the edifice (Barba et al., 2006). 1: Chimborazo volcano and location of profile; 2: Igualata volcano; 3: Western Cordillera; 4: Cordillera Real; 5: Interandean Valley; 6: Miocene to Quaternary volcanism; 7: Quaternary volcanoes; mmg: maxi-glacial moraines (>33—14 ka $^{14}$C BP); mtg: tardi-glacial moraines (12—10 ka $^{14}$C BP); mng: neo-glacial moraines (5 ka $^{14}$C BP to present).

(McCourt et al., 1997). The Pallatanga fault system (NNE) ends at the southern foot of the volcano and may have influenced the development of Chimborazo. There are also NW orientated faults (Fig. 1).

Chimborazo is a large, composite stratovolcano with three main summits oriented WNW–ESE that rise 2200 to 3000 m above its base. Detailed field studies, Ar–Ar ages, and chemical compositions provide ample evidence for the construction of three successive volcanic edifices (Barba et al., 2005, 2006 and this volume; Fig. 1). The basal volcano (CH-I) is a massive, mainly effusive andesitic and dacitic strato-volcano dated between 93 and 60 ka, which produced an ignimbrite and andesitic block-and-ash flow deposits. At least one period of explosive dome growth occurred before CH-I was destroyed by the major sector collapse. The Politécnica and the Nicolás Martínez summits correspond to the remnants of two edifices (respectively CH-IIA and CH-IIB) constructed in the CH-I avalanche caldera (Fig. 1). CH-II is dated between 50(?) and 35 ka. The youngest edifice, CH-III, is the highest summit of the complex (Fig. 1). It is a well-preserved andesitic stratocone (lava flows, pyroclastic flows, surge, and tephra deposits) constructed on CH-I and CH-II lavas. This edifice was active between 35 and 1 ka $^{14}$C BP.

The Riobamba Basin is a segment of the Interandean Valley and is a pull-apart basin bounded by major N22°E strike–slip faults (Monzier et al., 1999). It is delimited by the Western Cordillera to the west, the Cordillera Real to the east and the junction of both to the south. Chimborazo and Igualata volcanoes form the north side (Fig. 2). This basin, about 20 km long and 8 km wide, is the main depocenter for volcaniclastics, epivolcanics, and fluviatile sediments from Chimborazo, erosion of Igualata, and the Western Cordillera. The presence of the Chalupas ignimbrite, a regional stratigraphic marker (211 ka; Hammersley, pers. com.), is observed under more than 15 m of clastic sediments below the DAD base westward from Calpi strombolian cones (Fig. 2).

## 2. Origin and magnitude of the event

### 2.1. The avalanche escarpment

Post-avalanche volcanic activity and glacial erosion have erased most of the scar, making its identification difficult (Fig. 2). Beate and Hall (1989) and Clapperton (1990) proposed that the sector-collapse affected the Politécnica summit and that Nicolás Martínez summit is post-avalanche. Alcaraz (2002) proposed the opposite scenario. Alcaraz et al. (2005) proposed a removed volume of about 9 km$^3$ calculated with the mean expansion (20 vol.%) for debris avalanche deposits (Glicken, 1991). Based on field work and chemical analysis of the present edifice and the DAD, Barba et al. (2006) proposed that the destabilization affected the CH-I edifice and that the three current summits are all post-avalanche. A semi-circular scarp with a diameter of ca. 4 km, rising to 5400 m a.s.l., is partially preserved on the western flank. This structure was first interpreted as a collapse caldera (Kilian, 1987) but no ignimbrite deposits have been found and it is more likely to be the source of the sector collapse. Due to the geometry of the ancient edifice, CH-I probably rose to an elevation of ~6200 m a.s.l., giving a collapse volume of ca. 8.4 km$^3$ (Barba et al., 2006). Taking account of possible geometrical errors of the scar determination, we suggest a volume of 8.0±0.5 km$^3$.

### 2.2. Age of the collapse and triggering mechanism

No dating has been done on the DAD itself. Beate and Hall (1989) found an age older than 35.8 ka $^{14}$C BP for a pyroclastic flow deposit on the DAD top near Cochapamba (Fig. 2).

Barba et al. (2005) dated this deposit at 42.6 ka $^{14}$C BP and estimated the collapse age to be between 60 and 50 ka. Alcaraz