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Fault textures in volcanic debris-avalanche deposits and transformations into lahars: the Pichu Pichu thrust lobes in south Peru compared to worldwide avalanche deposits.

Karine Bernard¹. Benjamin van Wyk de Vries¹. Jean-Claude Thouret¹.

1. Laboratoire Magmas et Volcans LMV UMR6524 CNRS, OPGC and IRD UR 163, Université Clermont-Auvergne, 6 avenue Blaise Pascal, Campus les Cézeaux, 63178 Aubière, France.

*Corresponding author. Tel.: Phone: +33 4 73 34 67 74

E-mail address: kbernard@opgc.univ-bpclermont.fr (K. Bernard)

1 1. Introduction

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Volcanic debris avalanches are a large-scale volcanic hazard, which can have volumes of many cubic 3 kilometers and long run outs (up to 100m/s and 50-100 km; Siebert, 1984). To model such rapid mass 4 movements, analysis of internal fault structures is necessary to explain how breccia textures have recorded the 5 dynamic fragmentation during rheological variations from spreading to final avalanche emplacement. Such 6 information can be found in the cataclastic breccias along fault zones of the volcanic debris-avalanche deposits 7 8 (DAD), which are formed from the original volcanic units and transformed as the volcanic landslide moves and finally comes to rest. During this transport, different parts of the gravitational mass-flow, often being units 9 10 inherited from the volcano, move with respect to each other separated by fault zones. In all areas textures reflect this emplacement history. 11

Thus structural and sedimentological analyses contribute to the understanding of volcanic debris-avalanche 12 emplacement, and help to distinguishing the different collapse structures, to determining original stratigraphic 13 and lithologic elements and their evolution. Our understanding of emplacement is improved by studying 14 features such as proximal tilted blocks showing the initial lithostratigraphy, longitudinal ridges parallel to 15 strike-slip faults, hummocky structures due to extensive spreading and disaggregation that produce blocks and 16 17 mixed lithofacies (e.g., Mt. St-Helens, Glicken, 1986; Socompa, van Wyk de Vries et al., 2001; Mont-Dore, Bernard et al., 2009; Iriga, Paguican et al., 2012, 2014; Tutupaca, Valderama et al., 2016, 2018; El Misti, 18 19 Bernard et al., 2017). Syn-emplacement structures have been studied in relation to granular segregation, dynamic fragmentation, collisional and frictional processes (Capra and Macías, 2002; Clavero et al., 2002; 20 21 Davies and Mc Savenney, 2006, 2009; Roverato et al., 2014). A granular disaggregation can appear with runout distance showing decreasing megablocks and block-rich lithofacies (<30% matrix) together with increasing 22 matrix-rich lithofacies (Glicken, 1986), that is not always present (e.g., Chimborazo, Bernard et al., 2008). 23 Equally pseudotachylites with fault gouge found in the base and at the frontal lobes of deposits contribute to 24 correlate the splitting conditions related to frictional response along the DAD fault sole during kinematic 25 transition (Legros et al., 2000; Bernard and van Wyk de Vries, 2017). The distal lithofacies contains evidence 26 27 of water concentration and the transformation into lahar deposits. Thus, deposit morphology, structure and avalanche textures provide partial information on internal kinematic and dynamic processes, especially related 28 to the transformation and remobilization into lahars and debris flows. Further systematic studies are needed in 29 order to provide the necessary semi-quantitative analysis that can aid the delineation of DAD-prone hazard 30 31 zones.

To study structures and textures of a debris avalanche, we closely look at the voluminous DAD thrust lobe below the Pichu Pichu volcano in south Peru (Fig. 1). At a distance of 28 km from the extinct compound volcano, this deposit is the thrust frontal part of a major avalanche. The DAD frontal thrust came on to low slopes of the Arequipa basin, where it compressed in a series of thrusts and then re-extended on graben

structures. Previous work has described the basal pseudotachylite generated during the kinematic transition 36 from long-runout spreading to deceleration and emplacement of DAD thrust lobe with a 40 Ar/ 39 Ar age of ~2.42 37 Ma (Legros et al., 2000). Sedimentary methods allow us to characterize the fragmentation and the 38 transformation of two defined structural units. We describe the grain-size reduction, termed cataclastic gradient 39 that has been produced and the granular segregation that has sorted materials. The aim of this study is to 40 conduct a semi-quantitative analysis of the sedimentological characteristics related to syn-emplacement 41 brecciation with matrix transformations in order to: (1) compare the well preserved structural units, and to (2) 42 43 differentiate the in-avalanche structural controls on the precursory stages of the transformation into lahars from the syn-sedimentary emplacement features preserved in the matrix. Statistical results are subsequently 44 compared to other DADs worldwide such as those emplaced around Mt. St-Helens (Glicken, 1986), Nevado de 45 Colima (Capra and Macías, 2002), Chimborazo (Bernard, 2008), Mt. Ruapehu (Keigler et al., 2011), and 46 Meager (Guthrie et al., 2012), in order to correlate the sedimentological characteristics of debris-avalanche 47 structural units with runout distance and matrix transformations into lahar deposits. 48

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50 2. Terminology

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The terminology used in this study concerns the distinction between DADs associated with the primary pyroclastic and lahar deposits, the DAD hybrid lithofacies and its transformation into lahar deposits. From the textural and sedimentological characteristics of 288 DADs from 210 volcanoes worldwide (Siebert et al., 1987; Dufresne, 2009), we discriminate various categories of the debris-avalanche lithofacies as follows (Table 1).

(1) Syn-eruptive DADs with juvenile material, often termed the Bezymianny-type deposits (Siebert et al., 1987; 56 Belousov et al., 2007), are interstratified with syn-eruptive deposits, which include lateral blast deposits, 57 pumiceous pyroclastic flows and tephra fallout as described in the Mt. St-Helens, Shiveluch and Tutupaca 58 volcano case studies (Glicken, 1986; Belousov et al., 1999; Valderama et al., 2016, 2018). Slope failures for 59 such types are produced by deformations induced by magma intrusions, dome collapse occurred during phreatic 60 61 eruptions followed by decompression of the collapsed edifices. A thermal effect is likely to be present, with temperature varying from 70 to 200°C during avalanche emplacement (Siebert et al., 1987; Belousov et al., 62 2007). The distal avalanche deposits are overtaken by blast pyroclastic deposits as observed on the Tutupaca 63 DAD in south Peru (Samaniego et al., 2015; Valderama et al., 2016). Bezymianny- and Bandai-type deposits 64 are commonly associated with lahars generated by snow melted by the blast and pyroclastic deposits, and also 65 by dewatering and DAD transformations (e.g., at Mt. St-Helens and Mt. Rainier; Major and Voight, 1986; Scott 66 67 et al., 1995).

68 (2) The hybrid DADs (Table 1) are formed of water saturated, reworked and interstratified primary edifice 69 deposits and are a transition between avalanche breccias and lahar deposits. Examples are at Nevado de Colima (Capra and Macías, 2002), and the middle unit of the Ruapehu deposits (Keigler et al., 2011), showing poorly sorted, cataclastic breccias with a coarse stratification and collisional textures. Inherited megaclasts are observed with jigsaw-fractured breccias. (3) DADs transformed into lahar deposits show inherited jigsawfractured breccias in finer-grained matrix (Table 1; Citlaltepetl, Carrasco-Núñez et al., 1993; Mt. Rainier, Scott et al., 1995; Scott et al., 2001; El Misti, Bernard et al., 2017). The DAD dam-breakout deposits, transformed into debris-flow deposits, are differentiated from other deposits by $Md <-1 \Phi$, <50% matrix, and variations of the fine grain-size fractions (Mt. Shasta, Crandell et al., 1984; Mt. St-Helens, Major and Voight, 1986; and

77 Nevado de Colima, Capra and Macias, 2002; Capra, 2007).

The DAD lithofacies have been distinguished along three zones according to the distance away from the 78 collapse scar as follows. (1) In the debris avalanche proximal area (as far as 8 km from the source), three 79 lithofacies encompass: (i) megablocks showing inherited stratification; (ii) block-rich lithofacies with ~30 wt% 80 of matrix (≤ 2 mm); and (iii) cataclastic breccias with large megaclasts (>1 m) are dispersed in the matrix. (2) 81 In the median area (between 8 and 15 km from the source), two lithofacies appear: (i) a mixed matrix 82 lithofacies with polylithological distribution (similar to the B-type hummock described by Glicken in 1986). 83 (ii) The sheared contacts show clastic and fluidized matrix injected along fault structures or bulked with 84 85 bedrock, generating "bulldozer facies" (Belousov et al., 1999). (3) In the distal area, at a distance of 28 km from the extinct compound volcano, three lithofacies include (i) the matrix-rich lithofacies with clastic 86 87 fragments (clasts <1 m). The deposits showing this matrix-rich lithofacies are overlain by thrust lava-rich breccias. (ii) Along fault zones, the basal matrix-rich DAD shows secondary cataclastic gradient along 88 89 frictional faulted deposits such as lava sheared sigmoids, together with (iii) crushed clast-rich lithofacies showing fault gouge and pseudotachylite (Legros et al., 2000; Bernard and van Wyk de Vries, 2017). An 90 91 increasing matrix with a bimodal distribution is produced during syn-transport granular disaggregation. (4) In the distal zones and beyond the front of the DAD lobe deposits, we observe transformed deposits. These 92 93 deposits show two lithofacies. (i) The hybrid matrix lithofacies, portions with matrix and clast-rich matrix lithofacies (Roverato et al., 2014), are generally overlain by coarse debris-flow deposits with reverse grading. 94 The matrix of hybrid lithofacies is mixed and transformed into lahar deposits. (ii) Lahar or volcanic debris-95 flow deposits are associated with hyperconcentrated flow deposits produced by dilution down valley. 96

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98 2. Analytical methods

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From field observations on the DAD units, we have described the textural variations of the lithofacies assemblages and assessed their relationships to observed structural features, such as fault zones. Sampling of the avalanche matrix contributed to a semi-quantitative, sedimentological analysis to determine grain-size distributions. This has enabled us to establish a cataclastic gradient along the transition from primary to 104 transformed volcanic avalanche deposits and a sedimentological classification of a large number of avalanche 105 lithofacies.

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107 2.1. Outcrop analysis

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109 From field observations and Google Earth imagery, the mapped DAD units were identified related to their geomorphological context and the ratio of the vertical drop with runout distance (H/L). The main outcrops 110 111 chosen for study are at the front of the Pichu Pichu thrust lobe at the eastern margin of the WNW-ESE-trending 112 pull-apart basin of Arequipa. The internal structures and DAD lithofacies of the Pichu Pichu thrust lobe have been studied at two sites: the Alto Jesus open-pit guarry located ~5 km East of Areguipa, and ~3 km of the 113 114 SSW-NNE talus slope along the road section of Pampa Blanca (Fig. 1). Textural and sedimentological characteristics of lithostratigraphic units were correlated for each site, particularly the fracturing patterns such 115 as eleven jigsaw-fractured lithofacies and two lava sheared sigmoids units. 116

Image analysis of outcrop faces was used to calculate the grain-size distributions with the inertia and intercepts methods of the Shape Preferred Orientation 2003 software (SPO, Launeau, 2004) applied to quantify clast shape parameters, such as the a/b ratio (largest axis/ minor axis), and ellipse values (see Robin, 2002; Launeau, 2004 for mathematical definitions). The software was also applied to analyze the preferred orientations of the largest axis from as many as 9193 clasts in Alto Jesus outcrops and 4134 clasts along the Pampa Blanca sections in lava-rich breccias. Several statistical regressions (Eqs. 1-16 in Figs. 7-14) were established in order to determine the cataclastic gradient and to determine a textural classification of faulted DADs.

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125 2.2. Laboratory analysis

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Eighteen, non-cohesive samples from the DAD matrix were collected and sieved at one- Φ interval between the >-5 and <5 Φ size range. Six matrix samples from the sheared lava sigmoids in the Alto Jesus pit quarry, five samples from matrix collected in jigsaw-fractured breccias and seven samples from distal matrix-rich deposits along a 7 m-long transect in the Pampa Blanca site were analyzed.

131 Grain-size distributions were processed using the Gradistat v8 software in Excel (from decimeter-size clasts to 132 matrix ≤ 2 mm; Blott and Pye, 2001) to differentiate the cataclastic and transformed matrix related to lava-rich breccias in sheared sigmoids and jigsaw fracture zones. Each grain-size fraction was compared with cumulative 133 curves to define where the granular segregation together with cataclasis occurred along sheared lava sigmoid at 134 135 Alto Jesus and inside the transformed matrix of lithofacies within the Pampa Blanca graben. Fractal D-values were calculated from exponent h of the power regressions of cumulative frequency on double-logarithmic 136 137 graphs (Suzuki-Kamata et al., 2009) to compare cataclastic processes acting on each grain-size fraction. We 138 have computed the percentage of matrix (≤ 2 mm), the sand-sized matrix-gravel ratio and the following statistical parameters (Folk and Ward, 1957) such as: median diameter, sorting index, skewness and kurtosis.
These values were used to differentiate the primary fracturing of breccias related to transport processes, the
secondary cataclastic lithofacies produced during emplacement, and the transformation into lahars.

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143 2.3. Comparison of sedimentological results

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145 Statistical and shape parameters were compared with those from other structural DAD units in the Central Andean Volcanic Zone (CAVZ) such as the thrust lobes of El Misti deposits, and the Tutupaca ridge DAD (50 146 sieved samples, SPO from 6746 clasts, Launeau, 2004; Bernard, 2015; Valderrama et al., 2016; Bernard et al., 147 148 2017). These sedimentological datasets were correlated to other structural DAD units, such as lateral levees and frontal thrust deposits of Mont-Dore in the French Massif Central, the debris-flow facies deposits observed in 149 the front of the Meager DAD in Canada (156 sieved matrix samples, SPO from 30,342 clasts, Bernard, 2015) 150 and other DADs such as Nevado de Colima in Mexico (Capra and Macías, 2002), Taapaca in Chile, Ticsani in 151 152 Peru and Chimborazo in Ecuador (Bernard, 2008). Fractal h and D values of 150 sieved samples of avalanche matrix were calculated (Suzuki-Kamata et al., 2009; Bernard, 2015). This method contributes to defining the 153 154 in-motion controls related to the dynamic fragmentation of clasts during the sedimentary emplacement that 155 generates the sheared matrix components within the transformed and mixed matrix lithofacies (Table 1).

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158 **3. Geological context of the study area**

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160 3.1. El Misti and Pichu Pichu volcanoes and their debris-avalanche deposits

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As many as 75% of Andean volcanoes have large scale collapses due to fault systems (Francis, 1994; van Wyk 162 163 de Vries and Francis, 1997; McGuire, 2003). In southern Peru, Pleistocene volcanoes such as Coropuna, Ampato-Sabancaya, Misti, Ubinas, Huaynaputina, Ticsani, Tutupaca and Yucamane are aligned along N130°E 164 165 strike-slip faults along the Western Cordillera (Fig. 1A, Table 2; Thouret et al., 2001). Recurrent avalanche deposits have been studied and differentiated from associated deposits, such as Ticsani (H/L = 0.13, Bernard, 166 2008), Tutupaca with associated pyroclastic deposits (H/L = 0.12, Samaniego et al., 2015; Valderama et al., 167 2016, 2018) and El Misti with transformation into lahar deposits (H/L = 0.11-0.24, Bernard et al., 2017). The 168 Huanca N130°E strike-slip fault, together with conjugate, normal, N25-N70°E faults form a transtensional 169 170 system in the Arequipa ignimbrite basin (13 Ma, Thouret et al., 2001; Finizola et al., 2004; Paquereau-Lebti et al., 2006, 2007, 2008). 171

The WNW-ESE oriented Arequipa pull-apart basin is filled by no fewer than five DADs $\sim 100 \text{ km}^2$ (Fig. 1). The subdued DAD coming from the eastern flank collapse of Misti 1 $\sim 833-112$ ka (DAD0 in Fig. 1A; Thouret et al., 2001) is incised along N20E thrust lobes in the Quebrada San Lazaro valley and to the NE of the city of Arequipa with $H/L \sim 0.24$ (Table 2, Bernard et al., 2017). The Río Chili DAD blocks at Misti are tilted along normal N20E faults with $H/L \sim 0.1$ (DAD1 in Fig. 1A; Table 2) and overlain by Estribo lava-rich breccias (0.908-0.694 Ma, Aguilar et al., 2015). A thrust DAD coming from the extinct Pichu Pichu compound volcano at ~5510 m above sea level (a.s.l.) is well exposed to the East of Arequipa with $H/L \sim 0.1$. Its age is about 2.42

- ± 0.11 Ma based on 40 Ar/39 Ar analysis (Legros et al., 2000).
- Using Google Earth imagery, this western flank collapse of the extinct Pichu Pichu volcano shows at the 180 181 summit, a composite scar about ~15 km in length with several landsliding segments modified by glacial erosion 182 around 5510 m a.s.l. Three DAD structures are observed with H/L between 0.14 and 0.22 (Fig. 1A, Table 2; Siebert, 1984; Bernard, 2008). Sliding lava-flow lobes with $H/L \sim 0.2$ have been mapped from horseshoe-183 184 shaped scar \sim 3 km in length around 5155 m a.s.l. (L = 8 km, no. 1 in Fig. 1A). Lateral levee of channeled ashrich deposits with $H/L \sim 0.19$ are distinguished from U-shaped scar ~ 8.14 km in length at 5416 m a.s.l. (L = 10185 km, no. 3 in Fig. 1A, Table 2). A DAD to the south with $H/L \sim 0.17$ has developed from a horseshoe-shaped scar 186 ~4.36 km in length at about 5371 m a.s.l. (L = 12.7 km; no. 2 in Fig. 1A, Table 2). The south DAD presents 187 several transverse megablocks between 3325-3975 m a.s.l., with extensional faults along the 10-km long runout 188 189 distance at 3308 m a.s.l., and transformed deposits downstream. A north DAD with H/L ~0.22 extending from a 5 km-long U-shaped scar around 5247 m a.s.l. is characterized by a series of stretched lobes (L = 10 km, no. 5 190 in Fig. 1A; Table 2). The front lobes are thrust against the topographic obstacle of El Misti lava flows along the 191 192 left bank of the Río Andamayo valley.
- 193
- 194 *3.2. Syn-emplacement avalanche structures*
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196 The largest Pichu Pichu DAD is associated with five nested scars forming an erosional amphitheater ~10.8 km in length around 5425 m a.s.l. It has an H/L of ~0.09 with a length L = 28 km (no. 4 in Fig. 1A, 1 Ma), its area 197 is <100 km², and its volume <10 km³ (Legros et al., 2000; Thouret et al., 2001). Similar H/L ratios have been 198 computed for the DADs of Mt. St-Helens (Glicken, 1986) and Socompa (van Wyk de Vries et al., 2001; 199 200 Kelfoun et al., 2008). Asymmetric spreading structures on the southern margin of the deposits are observed to the north of the granodiorite and ignimbritic basement in paleo-valleys (Paquereau-Lebti et al., 2006). A north-201 northeast depression ~5.3 km in width between 3229-3714 m a.s.l. (Fig. 1A) is characterized by an ablation 202 area located at a distance of ~8.1 km from the large and curved scar of the Pichu Pichu compound volcano. The 203 Arequipa Airport Ignimbrite (AAI, 1.65 Ma, Fig. 1A; Paquereau-Lebti et al., 2006, 2007, 2008) has been 204 205 incorporated into lava-rich breccias in the north part of the DAD thrust lobe. The distal front thrust shows inverted extensional faults with horst-graben structures and the transformation into lahar deposits along the 206 11.85 km-long runout distance. The matrix-rich DAD to the south shows several N20E thrust lobes against the 207 granodiorite horst, a 7.85 km-long topographic obstacle along the N100E valley (Molebaya, Chiguata, Fig. 1A) 208

209 generating frictionite, injections dikes and transformations into lahar deposits (Legros et al., 2000; Bernard, 2015).

211 At a distance of 28 km from Pichu Pichu, a DAD thrust lobe on the east side of the WNW-ESE oriented pull-212 apart basin has been filled by fluvial and volcanoclastic deposits as a result of streams obstructed by DADs, that became diverted to the north inside the Quebrada Guarangal valley and to the south inside the Río 213 214 Andamayo valley (Fig. 1B). The distal DAD unit is channelized into lobate structures, which are eroded on the west front along N80-N110 lineaments with the debris-avalanche basal contact of the underlying basement. 215 216 Along the upstream upper part of the DAD lobes, thin layered ignimbrite deposits in the N40E outcrop (AAI in 217 Fig. 1B; Paquereau-Lebti et al., 2006, 2007, 2008) are overlain by thick ash-rich debris-flow deposits. At ~5 218 km east of the city of Arequipa, lava block-rich facies (LB in Fig. 1B; Thouret et al., 2001) are thrust and 219 incised along N130-N160 lineaments, parallel to the sinistral strike-slip fault named Huanca, with a rotational 220 shear ~2 km downstream of the thrust front lobe. Injection structures and mixed lithofacies (M in Fig. 1B) are observed in inverted extensional faults of the tilted front lobe. At 1 km NE of Arequipa, N30E graben structures 221 222 are filled by the mixed DAD matrix overlain by coarse- to medium-grained debris-flow deposits (DF in Fig. 223 1B). The hyperconcentrated flow deposits (HF in Fig. 1B) are preserved in backward frontal thrusts. Landslide 224 scars located in frontal lobes can be reactivated by retrogressive erosion generating lahars of reworked material forming deposits in the city of Arequipa during heavy rainfall episodes such as the 8 February 2013 in the 225 226 Quebrada Venezuela (124.5 mm within 3 h, Ettinger et al., 2015).

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229 **4. Results**

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231 4.1. Lithofacies assemblages with structural control

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233 Lithostratigraphic and textural variations in the Pichu Pichu thrust lobe help to distinguish the different stages 234 of the cataclastic gradient in the avalanche breccias. We first consider the Alto Jesus open-pit quarry (Fig. 2A) 235 that shows the DAD thrust lobe, which is located at the confluence of the paleo-riverbeds. The distal front shows horst and graben fault blocks, equally distributed along the ~8 km road section of Pampa Blanca (Fig. 236 2B). From SPO analysis, the quantitative sedimentary comparisons contribute to distinguish the lithofacies 237 238 variations with syn-emplacement structures, to define the conditions generating the mixed and transformed 239 deposits (Table 1) in an extensional context. The mixed unit within the graben has enabled us to identify the 240 precursory stages of the cataclastic transformations of the avalanche matrix into lahar deposits.

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242 4.1.1. Stratigraphy of the thrust DAD in Alto Jesus

Eight lithostratigraphic sections in the Alto Jesus open-pit quarry (sections 1-8 in Fig. 3A) have been described,

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244 and textural variations have been correlated to granular segregations along the sheared contacts between lithofacies assemblages. The basal matrix-rich DAD (MD), overlain by lava block-rich facies (LB), is under-245 thrust at the back front (section 1 in Fig. 3A). Along the sheared contacts, the interlayered sandy matrix (M2-3), 246 from 20 cm to 2 mm in thickness, consists of cohesive and brecciated beds with muddy matrix (>3-5% clay-size 247 sediments), and contains few centimeter-sized fragments of subrounded lava clasts and stretched pumices 248 249 (section 2 in Fig. 3A). Along the thrust front, the breccias are partially mixed (MD+LB, section 2 in Fig. 3A.B) within the matrix lithofacies (M1). The overlying debris-flow deposit (DF) is discontinuous (sections 3-5 and 7 250 251 in Fig. 3A.B). These units are faulted by the frontal thrust downstream and mixed with the matrix (M) in the 252 basal lithofacies.

253 At the N80E downstream thrust section, a condensed succession (M and bC, section 6 in Fig. 3A.B) has been reworked and is unconformably overlain by a steeply dipping matrix unit. The matrix (M) and mixed 254 lithofacies with lava breccias (LB+M2, Fig. 3B) are interstratified and cataclased along the sheared contacts. 255 The overlying ash-rich pumice layers (I, Fig. 3A.B) are discontinuous and interlayered between the matrix and 256 mixed DAD lithofacies containing striations of frictional contact showing recrystallized of original pumiceous 257 258 material along slickensides. Along the SE horst and graben structures, the upper lava-rich breccias are tilted 259 (LB, sections 7-8 in Fig. 3A.B) and partially mixed within the extruded avalanche matrix (MD+LB, section 8 in Fig. 3A.B) along the N120 basal thrust contact. In the NE-SW direction, the clay and ash-rich layers (bC, 260 sections 1-6 in Fig. 3A.B) are stretched and intercalated with lava-rich breccias because of shearing along the 261 262 cataclastic contacts.

More than eleven mesoscale structures have been studied with the SPO analysis from 812 clasts in the thrust 263 264 lobe (Fig. 3C). Fractured lava block-rich facies (LB) show unimodal clast distributions (sections 1-5 in Fig. 3C) with *a/b* values increasing from 1.48 to 1.74. A polymodal clast distribution includes basal blocks with jigsaw 265 266 fractures and sigmoidal jigsaw-breccias in gLB tilted in mixed M matrix showing a/b values decreasing from 1.48 to 1.16 (SPO from 93 clasts, sections 1 and 3 in Fig. 3C). Cataclastic shear bands of thrust lava-rich 267 268 breccias (LB, sections 1-2 in Fig. 3C) are associated with "flame structures" and boudinage of stretched and mixed layers with dips ~14-33° towards the NE. The granular sorting decreases along sheared contacts (M2, 269 270 sections 1-2 in Fig. 3C). The tension cracks are filled by M2 matrix with bimodal clast distributions (section 2 271 in Fig. 3C).

At the thrust section, lava breccias show injections of M2 matrix in the extensional fractures (section 4 in Fig. 4A). Along the N80-N160E rotational shear, several cataclastic shear bands occurred in the S1 and S2 basal lava sigmoids (section 4 in Fig. 4B; Bernard, 2015). The sheared lava-rich breccias and the cataclastic matrix exhibit bimodal clast distributions with 67% of the clast-size fractions (SPO from 622 clasts). The mixed matrix inside the jigsaw-fit breccias shows a polymodal clast distribution with a/b ratio decreasing from 1.47 to 1.36 (SPO from 222 clasts) link with the clastic sorting. Along the thrust lobe front, the avalanche units are tilted in half-horsts bounded by inverted extensional fault (sections 5-8 in Fig. 3C). Jigsaw-fractured clay clasts

are stretched in the rotated matrix and in extruded matrix mixed with lava-rich breccias (sections 6-7 in Fig.4B).

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4.1.2. Structural evolution of the frontal DAD in inverted extensional faults

Along the ~8 km road section of Pampa Blanca, lithostratigraphy and textural correlations with structures 283 284 reveal that the frontal lobe can be sub-divided into four structural units (sections 9 to 16 in Fig. 5). (1) The thrust lobe exposes the faulted lava-rich breccias (LB, sections 9-10 in Fig. 5A), which are thrust between thin 285 286 and non-cohesive, ash-rich layers (A1-2, Fig. 5A). These are overlain by brown clay-rich layers (bC) with the 287 thrust ignimbrite (I, Fig. 5A). (2) The back-thrust lobe mainly exposes steeply dipping layers of lowermost 288 lava-rich breccias and the overlying mixed lithofacies (LB+A2, section 11 in Fig. 5A). These are partly covered 289 by a fine-grained cohesive debris-flow deposit with subrounded blocks reworked along the basal contact (DF, Fig. 5A). (3) The frontal lobe is tilted in horsts and grabens (sections 12-14 in Fig. 5A.B). Lava-rich breccias in 290 half-horst are cut out by NE-dipping normal faults. The grabens are filled by layered and transformed matrix, 291 292 and unconformably overlain by a debris-flow deposit partly mixed with ignimbrite I unit (I+DF, Fig. 5A). The 293 initial lithofacies assemblage disappears at the frontal thrust due to the mixture between LB, A2, bC and I 294 deposits from bottom to top. (4) At the front lobe, these mixed lithofacies (I+DF, A1+rLB, gLB+A2+bC, sections 15-16 in Fig. 5A.B) are transformed into the laminar hyperconcentrated flow deposits. Rafted, oriented 295 296 and subrounded blocks characterize the top eroded surface.

297 Outcrop-scale deformation structures are well preserved in lava rich-breccias showing a basal thrust fault of the DAD lobe. Lava rich-breccias have undulating and sheared contacts (sections 9-10 in Fig. 5C) and vertical 298 299 injection structures at the base of the graben with granular readjustments (sections 11-14 in Fig. 5C). The long axes of 2445 clasts are sub-horizontal, with a conjugate inclination of ~52-70°W to the fault plane (Bernard, 300 301 2015). Along N105E fault contacts, a cataclastic gradient in lava breccias is characterized by increasing *a/b* values from 1.2 to 1.55 within the polymodal clast distributions in the downstream thrust section (SPO from 302 303 422 clasts, sections 11-14 in Fig. 5C). We attribute this cataclastic gradient to an increasing brecciated matrix 304 and mixed lithofacies in which clasts have a lower (1.08) a/b ratio. Fault breccias (sections 15-16 in Fig. 5C) 305 occur along faulting between horsts and grabens. In the downstream graben, the mixed unit presents reverse 306 graded beds with sub-horizontal long-axes of 1490 clasts in matrix deduced from SPO analysis (Fig. 6A). This matrix-rich DAD is unconformably overlain by coarse-grained debris-flow deposits. Inherited jigsaw-fractured 307 breccias have been studied in the clastic matrix (Fig. 6B) for the quantitative sedimentary comparisons with 308 mixed and transformed lithofacies to define the conditions generating the precursory stages of the avalanche 309 transformations. Cataclastic mixing and longitudinal sorting have been characterized in an extensional context 310 over the distance of a few meters. 311

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313 4.2. Sedimentological features and clast-shape evolution

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In the Alto Jesus open-pit quarry, six non-cohesive samples were collected from two lava sheared sigmoids to define the structurally controlled syn-emplacement processes generating secondary cataclasis of matrix in lava rich-breccias. Along the Pampa Blanca graben, five samples of the matrix in jigsaw-fractured breccias have been compared to seven samples of matrix from mixed and transformed deposits collected along a 10 m-long transect (black and grey triangles in Fig. 6A).

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321 4.2.1. Cataclastic gradient

Each grain-size fraction was compared to distinguish the sandy-gravel textures of the bimodal matrix-supported jigsaw breccias (M_z -2.52 ϕ , Table 3, Fig. 7A), and the polymodal and mixed matrix (M_z -0.39 ϕ), which is very poorly to poorly sorted in the graben. From 1 to 4 m along the transect, the coarse gravel fractions of mixed lithofacies decrease from 50 to 10%, while the medium gravel and sand fractions increase from 49 to 92% (see Supplemental File 1). The sandy-gravel textures become sandy. From 5 to 7 m along transect, the values of mixed lithofacies tend towards similar grain-size distributions from 19 to 23% of sand and gravel fractions while the coarse sand fractions decrease.

- 329 Along two lava sheared sigmoids of the Alto Jesus thrust lobe, the texture is sandy gravel (Mz -2.03-0.94 Φ , Table 3) with grain-size distributions similar to those of the bimodal lava breccias and the polymodal 330 distributions of jigsaw-fractured breccias. The -4-2 Φ gravel-size fractions decrease (from 41.6 to 17.1%) with 331 332 1-3 Φ sand-size fractions (from 16.9 to 7.4%) in the 4-m long transect, while the 0-1 Φ sand-size fractions 333 increase (from 12 to 42.6%) together with the -5-6 Φ gravel-size fractions (23.4%, Supplemental File 1). 334 Along the 8-m long transect (Table 3), fractal D-values converge around ~2.5-2.6. The mean fractal D-values 335 range from 1.96 in the matrix-supported jigsaw-fractured breccias, to 2.26 in lava sheared sigmoids, and 2.53 in 336 mixed and transformed lithofacies in the graben (Table 3).
- 337 The percentage of matrix (≤ 2 mm) vs. sand-sized matrix/gravel diagram shows a logarithmic regression (Eq. 1) 338 in Fig. 7B), which correlates textural variations in mesoscale structures including an initial dilation of jigsaw-fit 339 texture with <22% matrix and 0.11 to 0.3 matrix/gravel. The primary fracturing with <40% matrix and 0.37 to 340 0.55 matrix/gravel is attributed to the 25-km runout distance with clastic matrix of lava sheared sigmoids along 341 thrust basal contacts (1 in Fig. 7B). The secondary fracturing with 40-50% syn-emplacement breccia matrix and 0.82 to 1.48 matrix/gravel values is observed along fluidized cataclastic matrix of basal sheared sigmoids 342 (2 in Fig. 7A). In the graben, the mixed units contain >50% matrix and sand-sized matrix-gravel ratio >1.5 343 344 associated to the matrix transformations into lahar deposits (3 and 4 in Fig. 7B, Table 3).
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346 4.2.2. Statistical grain-size parameters

Statistical grain-size parameters highlight the granular differences between the syn-emplacement textures observed along the Pichu DAD lobe. The sorting index (σ) vs. median diameter (*Md*) diagram helps to

- The skewness values of lava sheared sigmoids are intermediate (Folk and Ward, 1957; Table 3) and increase 353 354 from -0.28 to 0.58 as the matrix percent and the matrix-gravel ratios decrease from 58.9 to 27.4% and from 1.43 to 0.37, respectively, due to the granular segregations of the very poorly sorted, fine gravel fractions. We 355 356 compare these values to the very platykurtic and mesokurtic values of lava breccias sampled at the Tutupaca 357 ridges. The sorting index and the skewness values of the mixed matrix in graben decrease ($\sigma = 3.13$ to 2.46; $SK_G = -0.3$ to 1.7) along the 2-m long transect, while matrix/gravel increases from 0.55 to 1.31 (Table 3, 358 Supplemental File 1) and to ~3.07 along the 4-m long transect. The sorting index and the skewness values 359 increase downstream (>4 m; $\sigma \sim 2.4$ -2.6; SK_G ~-0.6-0.3), while matrix/gravel decreases down to 1.48. Kurtosis 360 values between 0.64-0.84 indicate a platykurtic distribution associated to the hybrid DADs and the transformed 361 DAD matrix into lahar deposits (Table 3). 362
- The diagram showing ellipse/a/b vs. sand-sized matrix percent (Fig. 8B) helps to distinguish textural variations 363 364 of avalanche lithofacies. (1) The primary fracturing with <33% matrix is localized along avalanche fault zones with ellipse/a/b >1.99 associated to fault cataclasis. In the graben, the matrix-supported jigsaw shows <40% 365 matrix and ellipse/a/b <1.76, which are similar to values on the Tutupaca ridge DAD, implying thermal 366 367 fracturing effect with dilation on subrounded lava clasts during the first stage of mass flow. (2) Lava sheared sigmoids present 40-50% secondary fractured matrix with ellipse/a/b > 2 due to sheared cataclasis; and 50% 368 369 transformed matrix with ellipse/a/b between 1.4 and 2.15 related to fluidal transformations (Fig. 8B). (3) Mixed 370 lithofacies in graben show cataclastic matrix transformations with >50% matrix and thermal fracturing 371 generating clast shapes with ellipse/a/b < 2.1.
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373 4.2.3. Clast shape parameters

- The SPO analysis from 13,327 clasts (Fig. 9; Launeau, 2004) in syn-emplacement breccias has enabled us to identify two categories of regressions between a/b ratio and the faulting distance (<10 m) of thrust lobe, at a distance of 28 km from the Pichu Pichu compound volcano. We have differentiated a logarithmic regression (Eq. 2 in Fig. 9A) for the mixed lava breccias with a/b > 1.43, and a linear regression for the jigsaw-clasts (Eq. 3 in Fig. 9A) along the fault zone. The clast breakage and cataclasis are more important with a/b values decreasing from 1.55 to 1.35. In comparison, the values of sheared matrix appear isolated with a/b > 1.6 for the abraded clasts.
- The ellipse *vs*. travel distance diagram shows decreasing values with four regressions (Eqs. 4-7 in Fig. 9B). Three linear regressions (Eqs. 4-6 in Fig. 9B) have been calculated for the thrust lava-rich breccias (Eq. 4), the cataclastic sheared matrix (Eq. 5), and the clast-supported jigsaw-breccias in a mixed matrix (Eq. 6). We have

found a power regression (Eq. 7 in Fig. 9B) for the basal lava sheared sigmoids with cataclastic shear bands of 384 dihedral lava-block. Blade-shaped clasts become convex with ellipse = 1 (Eq. 7 in Fig. 9B). Four points of 385 intersection (A-D in Fig. 9B) indicate similar values of ellipse between syn-emplacement structures 386 characterized by different regressions: between clast-supported jigsaw in a mixed matrix and lava sheared 387 sigmoids (A = 3.2, Eqs. 6-7); between thrust lava breccias and lava sheared sigmoids (B = 2.6, Eqs. 4 and 7) or 388 389 jigsaw-fractured clasts (C = 2.5, Eqs. 4 and 6). We distinguish an inherited clast shape for oblong lava blocks with a/b = 2.5 and ellipse = 4 (D, Eqs. 5 and 7 in Fig. 9B), implying textural relationships between these 390 391 cataclastic lithofacies along fault zones.

- Based on these regressions, a textural tree diagram shows the co-evolution between the lithofacies of lava-rich 392 393 breccias along the thrust lobe including inherited jigsaw-blocks with a/b = 2.5 and ellipse = 4 (D in Fig. 9C). Clast shape parameters help us to differentiate the cataclastic gradient in the matrix of the thrust lava-rich 394 395 breccias (Eq. 4), the matrix along sheared contacts (Eq. 5) and the basal lava sheared sigmoids (Eq. 7). The intersecting points imply a co-evolution between thrust lava-rich breccias (Eq. 4) and the inherited jigsaw-396 397 clasts in the transformed and mixed matrix facies (Eq. 6). These cataclastic relationships associated to the granular segregations in the graben may be the precursory stages to the matrix transformations into lahar 398 399 deposits. The syn-emplacement lithofacies characterize the kinematic transition in avalanche structural units such as jigsaw-fractured breccias and matrix along sheared contacts where it compressed in a series of thrusts 400 and then re-extended in graben structures. 401
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403 *4.3. Emplacement results*

404 Sedimentary features of Pichu Pichu thrust lobe enable us to differentiate structural segregation of lithofacies 405 along distal debris-avalanche fault zone with basal backthrust and inverted extensional fault. We differentiate (1) primary fracturing of clastic matrix with <40% matrix along thrust basal contact. Mesostructures along 406 sheared zones characterize syn-emplacement brecciation with decreasing granular sorting, cataclastic shear 407 bands along sigmoids structures. A co-evolution of lithofacies is inferred from features such as clast breakage, 408 fault cataclasis, cataclastic gradient with granular segregation, and thermal fracturing dilation. (2) In an 109 extensional sheared context, we observe fluidized cataclastic matrix in tension cracks and vertical injections. 410 411 The initial lithofacies assemblage disappears with inherited jigsaw-fits and matrix mixture in graben. Mixed 412 and transformed matrix may be related to cataclastic mixing with longitudinal sorting, which may be the precursory stages to the matrix transformation of the hybrid DAD into lahars. 413

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15 5. Discussion

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Structures, lithofacies assemblages and sedimentary analysis of syn-emplacement textures contribute to correlate the different stages of the cataclastic gradient in thrust avalanche breccias. Sedimentological parameters of the distal thrust lobe of the Pichu Pichu DAD are compared to a dataset from documented worldwide debris avalanches and associated lahar deposits. These have enabled the establishment of a textural classification of volcanic debris-avalanche deposits showing structural controls along internal fault zones.

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423 5.1. Tectono-volcanic control of large-scale collapses in Peru

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The mapped DADs at Pichu Pichu show that there was a succession of destabilizations with each deposits 425 126 having an H/L between 0.14 and 0.22, similar to other volcanic landslides including height, length, volume and area (Table 2, Fig. 1; Legros et al., 2000). We compare recurrent edifice collapses with long runout distances at 427 428 other volcanoes such as twelve DADs at Nevado de Colima, every 2.69 kyr on average, and eight DADs at Mt. Taranaki every 10 kyr on average (Capra and Macías, 2002; Zernack et al., 2009). Collapses have an average 429 runout distance of around ~10 km (Table 2) and are distinguished from the largest Pichu Pichu DAD collapses 430 with a ~28 km runout distance (<10 km³, H/L = 0.09, Fig. 1), similar to that of the Mt. St-Helens, block 3, at 431 ~20 km in the Toutle River valley (Voight et al., 1983). These morphometric and sedimentological 132 characteristics of the Pichu Pichu thrust lobe may be similar to Mt. St-Helens, St. Augustine, Shiveluch, 433 434 Colima, Taranaki, and Tutupaca volcanoes (Siebert, 1984; Glicken, 1986; Siebert et al., 1987; Beget and Kienle, 1992; Belousov et al., 1999; Capra and Macías, 2002; Belousov et al., 2007; Zernack et al., 2009; 435 Valderama et al., 2016, 2018), implying the Bezymianny-type eruptive sequence such as the associated 436 437 pyroclastic fragmentation (Bernard, 2015). Destabilization and collapse have been attributed to decompression of the magma reservoir beneath the collapsed edifice ($\gamma = -0.8-0.2$, Mt. St-Helens, Mackamman et al., 2014) 138 139 that has been inferred to reflect a switch in magmatic chamber (Ponomareva et al., 1998; Belousov et al., 440 1999).

441 Excessive avalanche runout distances change against topographic obstacles (Socompa, Kelfoun et al., 2008) 442 and during channelization of the debris avalanches generating frictionites with distal dilution into lahars (Mont-443 Dore, Bernard, 2008; Bernard and van Wyk de Vries, 2017). In inverted extensional fault zones, the asymmetric structures of the Pichu Pichu thrust lobes show the mixed lithofacies with syn-cataclastic 144 445 transformations against the granodiorite horst to the south, precursory to the progressive dilution of the debris avalanche to form lahar deposits in the pull-apart basin of Arequipa. Volcanic substratum heterogeneity along 446 the DAD base (e.g., Legendre, 1999; Thouret et al., 2001), and topographic obstacles of the Arequipa batholiths 147 to the south may contribute to avalanche frictionite (Pichu Pichu, Legros et al., 2000). DAD deflection is 148 observed for the front lobes of the northern Pichu Pichu debris-avalanche deposits (no. 5 in Fig. 1A), along the 149 Río Andamayo, against the topographic obstacle of the south El Misti flank. A series of N130E strike-slip faults 450 are related to normal stress transfers in the Arequipa basin such as the Mollebaya N100E fault, implying 451 basement-tectonic controls on the channelized avalanche emplacement. A "bulldozer facies" (Fig. 2B; 452 Belousov et al., 1999) along the basal thrust contact with the ignimbrite deposits is observed at the eastern 453

DAD thrust lobe (no. 4 in Fig. 1A) in the Arequipa basin. In contrast the northern thrust lobe in the Arequipa basin filled by the ignimbrite and block-and-ash-flow deposits shows horst and graben structures in extensional spreading context. This area is where the transformation into lahar flow occurs only in a few hundred meters, a process of transformation that is similar to the El Misti deposits (DA1, Bernard et al., 2017). Graben areas are thus sites of water accumulation and transformation, while compressed areas and bulldozing retains the debris avalanche structure. This feature is similar to the Mount Meager 2010 debris avalanche, where inter-hummock areas are the sites of in-transport water concentration and debris flow (Roberti et al., 2018).

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463 5.2. Textural and sedimentological classification

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465 5.2.1. Sedimentological dataset and comparison

466 Sedimentological characteristics of the Pichu Pichu thrust lobe are compared with other DADs and associated lahar deposits in Peru and Canada (Table 3, Fig. 10A). The cumulative grain-size curves show the coarse grain-467 size fractions close to those of the lava breccias forming the ridges of the Tutupaca DAD with more fine-468 grained fractions from ~2 Φ , which contribute to matrix of the lahar deposits, similar to the Quebrada San 469 Lazaro valley deposits (El Misti, in Peru) and the Pardines reworked deposits in the French Massif Central 470 (Bernard, 2015). The polymodal grain-size distributions vary between 45 and 65% matrix for lava breccias of 471 472 the Tutupaca ridge DAD, the Pichu Pichu thrust lobe and the debris-flow deposits observed in the Meager frontal DAD in Canada (Bernard, 2015). 473

174 The ratio of matrix percent vs. sand-sized, matrix/gravel diagram shows a logarithmic regression (Eq. 9 in Fig. 10B), which correlates the fractured DAD with <40% matrix of the transformed lithofacies, and lahar deposits 475 176 with >60% matrix. The primary fractured matrix for the coarser fractions is observed in 78% of samples inside the Tutupaca ridge DAD and in 61% of samples in the Meager hybrid deposits (Bernard, 2015). In the hybrid 177 178 DAD lithofacies showing polymodal grain-size distributions, there are similar ratios of the proportions of the fractured breccias with <50% matrix and the transformed lithofacies with >70% matrix. Within the Pichu Pichu 179 480 DAD, we distinguish the thrust deposits with 66% fractured matrix, lava breccias with 32% transformed matrix. The cataclastic sorting of matrix lithofacies in graben may have contributed to the bimodal grain-size 481 distributions with 54.5% transformed matrix. The polymodal grain-size distributions of the reworked Pardines 182 deposits are associated with 41% primary fractured matrix mixed with 47% transformed matrix, produced by 483 the secondary fracturing generating the disappearance of the fractions of median grain-sizes around ~50% 184 (Bernard, 2015) during matrix transformations. Bimodal grain-size distributions are found in the transformed 485 DADs into lahar deposits in the Quebrada San Lazaro valley at Misti that have 45% transformed matrix and 186 54% primary fractured matrix, related to cataclastic sorting of these median grain-size fractions during 187 downstream spreading (Bernard et al., 2017). 188

490 5.2.2. Statistical dataset and comparison with debris-avalanches worldwide

We compare statistical grain-size parameters of the matrix-rich lithofacies in the -5 to 5 Φ size range from six 491 DADs to those of DADs in Peru, and their associated lahar deposits (Fig. 11). The skewness vs. kurtosis 192 diagram helps to distinguish the proximal gravitational collapse ($SK_G = 1-2.5$; K < 0.6; 1 in Fig. 11A) such as 493 194 lava breccias of the Tutupaca DAD ridges, the reworked Pardines deposits and the Pichu Pichu thrust lobe. The hybrid DADs are differentiated from the transformed deposits ($SK_G < 0.5$; K = 0.7-0.83; 2 in Fig. 11A) observed 195 in the DADs of Nevado de Colima (Capra and Macías, 2002) and at Taapaca (Bernard, 2008), as well as the 196 thrust lobes of the Pichu Pichu and El Misti volcanoes (Bernard et al., 2017). The intermediate skewness values 497 498 (-0.28 to +0.58; Folk and Ward, 1957) of the lava sheared sigmoids characterize the cataclastic matrix being fluidized by shearing and stretching, similar to the Pungarehu DADs (Roverato et al., 2014), the non-cohesive 199 debris-flow deposits and the hyperconcentrated flow deposits along the thrust lobes II and III of transformed 500 501 DAD at El Misti (Table 3; Bernard et al., 2017). This dataset involves the stretching and shearing of deposits, the cataclastic transformation of lava sheared sigmoids and inside the extruded, mixed matrix. These 502 transformations with mixed matrix lithofacies have resulted in higher kurtosis values around ~1 with $SK_G = 0$ -503 0.55 (3 in Fig. 11A; Bernard et al., 2017) such as Ruapehu, Meager, Chimborazo, and Ticsani DADs (Bernard, 504 505 2008; Keigler et al., 2011; Bernard, 2015).

The sorting index (σ) vs. median (Md) diagram helps to characterize the hybrid DADs (1 in Fig. 11B) between -506 507 2 and -1.5 Φ with σ = 1.9-2.4. Examples are the Pichu Pichu distal lobe and the Pardines reworked deposits in 508 the French Massif Central (Bernard, 2015). The values of the matrix transformed by dilution are shown in the 509 plot of the Pinatubo's lahar domain as well as the El Misti deposits with $Md > 0.5 \Phi$ (2 in Fig. 11B; Major et al., 1995; Bernard et al., 2017). Primary fractured matrix between -3 and -2 Φ with σ <1.5 (3 in Fig. 11B) in the 510 511 Meager hybrid deposits and the lava breccias of Tutupaca fault ridges show similar values to the inherited matrix inside the jigsaw-fit breccias in the transformed deposits, as observed in the distal graben of the Pichu 512 513 Pichu thrust lobe.

514 Fractal D-values of the 150 sieved samples of the debris-avalanche matrix from avalanche worldwide range between 2.3 and 2.7 (Table 3, Suzuki-Kamata et al., 2009), similar to the avalanche deposits of Flims (range 515 516 from 1.9 to 2.95; Dunning, 2006) and Val Pola (range from 2.3 to 3.1; Crosta et al., 2007). Extensional fracturing is 2-2.5 D values (Blekinsop and Fernandes, 2000) leading to granular disaggregation with fractal D-517 518 values between 2.13 and 2.22 (Hartmann, 1969). The primary and secondary fractures observed in the reworked Pardines deposits increase the fractal D-values (2.59; Kaminski and Jaupart, 1998; Bernard, 2015). 519 520 Energy fragmentation/energy potential vs. D values diagram (Fig. 11C; Crosta et al., 2007) shows the most frequent interval of computed values between the breakage models and modeling fracture toughness. Energy 521 522 ratios ranging from 0.01 to 1.2 for the Pichu Pichu DAD are between El Misti and Meager DAD values. These values related to the channelized DAD units transformed into debris-flow deposits are observed near Chiguata 523

and Molebaya in the southern thrust lobe against the granodiorite basement (Fig. 1).

The energy of the gravitational flank collapse (Crosta et al., 2007) with initial dilation is differentiated from inherited crushing along the volcano flank during transport. Dynamic fragmentation with structural controls characterizes the DAD fractal dimension, which is associated with the distal matrix transformations into lahar deposits.

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530 5.2.3. Sedimentological classifications of volcanic avalanche breccias

Statistical comparisons of avalanche breccias contribute to establishing a sedimentological classification for syn-emplacement processes of DAD structural units (Table 4). We discriminate faulted and hybrid DADs from the transformed lithofacies into lahar deposits. Inherited volcanic fragmentations (<22% matrix) of the collapsed edifices are differentiated from the fractured breccias with <50% matrix associated with granular disaggregation during the syn-transport transformations and the syn-sedimentary emplacement. Three textural classes of avalanche fault zones have been quantified in lava-rich breccias by the ellipse/a/b values of ~2.14 for the plane collapse, of 1.75 to 2 for the crushing, and <1.7 for the thermal effect of fragmentation (Table 4).

Sand-sized matrix percent and ellipse/a/b values are compared with fault textures (Fig. 12). The cataclastic 538 gradient of the Alto Jesus lava breccias characterizes the inherited jigsaw blocks with <20% matrix, followed 539 540 by primary fractures with 30-40% matrix and ellipse/a/b = 3.43, then the transformed DAD matrix and mixed matrix inside jigsaw breccias characterized by >50% matrix and ellipse/a/b = 1.15-1.4. This cataclastic 541 542 gradient along the DAD thrust lobe may be correlated to the Pichu Pichu frictionite generated along the water saturated ignimbritic basement in paleo-valleys (Legros et al., 2000). These conditions, including a differential 543 544 cataclasis, may be the precursory stages to the downstream transformations into lahar deposits observed in the Quebrada San Lazaro valley. DAD fault zones such as in the Mont-Dore volcanic massif show a lithofacies 545 546 evolution from basal sheared matrix along the fault gouge (20-30% matrix, ellipse/a/b = 2.92, Fig. 12), then primary and secondary fractured matrix (30-50% matrix, ellipse/a/b = 2.59), and finally the transformed 547 deposits (50-60% matrix, ellipse/a/b = 1.16, Fig. 12). These volcanic avalanche fault zones, that have produced 548 549 cataclastic gradient and frictionites against topographic obstacles, imply different syn-emplacement processes 550 as those observed in the Arequipa basin of the El Misti DAD and the DADs of the Limagne fault graben 551 (Bernard et al., 2017; Bernard and van Wyk de Vries, 2017). The cataclastic gradients of the Alto Jesus thrust lobe are close to those of the lava breccias studied in the Tutupaca fault ridges (Fig. 12; Bernard, 2015; 552 Valderama et al., 2016, 2018). We describe the jigsaw-fractured lithofacies (<20% matrix, ellipse/a/b = 1.85), 553 554 followed by faulted and mixed breccias (20-40% matrix, ellipse/a/b = 1.84-1.87), finally the transformed matrix-breccias recorded the inherited fractures (>40% matrix, ellipse/a/b = 1.63-1.73, Fig. 12). The textural 555 comparisons of Pichu Pichu thrust lobe with the Tutupaca fault ridges may suggest fault reactivation of lava 556 domes fractures (Bernard, 2015). 557

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560 5.3. Avalanche fault textures

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562 5.3.1. Cataclastic gradient along volcanic avalanche fault zones

Lithofacies and textural variations along the Pichu Pichu thrust lobe are compared to other debris avalanche textures (Fig. 13). As deduced from the SPO analysis, lava-rich breccias present unimodal clast distributions with increasing a/b values from 1.48 to 1.74, attributed to a lateral and vertical cataclastic gradient along thrust zones. We differentiate more than eleven syn-tectonic textures including jigsaw-fractured breccias with polymodal clast distributions and a/b values decreasing from 1.48 to 1.16 along avalanche fault zones. The bimodal distribution of the lava clasts is characterized by 2.26 fractal mean *D*-values (Fig. 3C, Table 3) and a power regression of ellipse values (Eq. 7 in Fig. 9B), probably due to secondary sheared cataclasis.

570 The ellipse/a/b vs. matrix percent diagram shows two regressions attributed to the differentiated cataclastic gradients between the faulted DADs and <25-30% breccia matrix (Eqs. 10-11 in Fig. 13). The linear regression 571 572 of lava-rich breccias (Eq. 10 in Fig. 13) characterizes a cataclastic gradient of the faulted breccias with <20% 573 matrix and a mean fractal D-value around ~2.46 (Table 3). Along the Alto Jesus thrust lobe, the jigsaw clasts 574 with ellipse/a/b = 2.08 are discriminated from the basal comminution of the lava sheared sigmoids with ellipse/a/b = 1.94 (Fig. 13). These values are close to those obtained in lava breccias of Tutupaca ridge DAD 575 (<17% matrix, Fig. 13). The cataclastic gradient (Eq. 10) of lava-rich breccias is linked to the cataclasis and the 576 577 fluidal transformations with >37.8% matrix along shear zones such as those in the Mont-Dore DADs and the Río Chili transformed deposits. The logarithmic regression (Eq. 11 in Fig. 13) correlates the lithofacies of 578 579 faulted DADs, with brecciation and cataclasis with <30% matrix (Tutupaca and Pichu DADs, Fig. 13), finally the transformed and fluidized lithofacies >45% matrix and ellipse/a/b = 3.01 such as the Río Chili 580 581 transformed deposits (Bernard et al., 2017). An intersect point around ~37.8% matrix with ellipse/a/b = 2.4-2.5characterizes the frictionites and injection structures (Mont-Dore, Bernard, 2015) associated to the cataclasis 582 583 and the fluidal matrix transformations. This suggests that a cataclastic co-evolution is observed between faulted 584 DADs and breccia matrix (Eqs. 10-11 in Fig. 13) with >37.8% fluidized matrix, a precursor lithofacies to the 585 distal avalanche transformations by dilution downstream (Bernard et al., 2017).

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587 5.3.2. Clast-shape comparison with worldwide DADs and lahar deposits

The mean ellipse *vs.* travel distance diagram for a DAD fault zone presents a linear regression (Eq. 12 in Fig. 14A). Three zones are correlated to the textural variations with structures: (1) the proximal planar collapse along faults (Cheix in Mont-Dore, Río Chili at Misti) with ellipse = 3.55-3.8; (2) the crushed lithofacies in rotational shear such as the jigsaw-fractured breccias tilted in a fluidized matrix along the Alto Jesus thrust lobe and the Perrier pseudotachylite with ellipse = 3-3.12; and (3) the thermal effect of fractures in lava breccias with ellipse <2.7 observed along the Tutupaca ridge DAD and in the Pichu Pichu mixed matrix.

594 The ellipse/a/b vs. matrix percent diagram shows four regressions for avalanche breccias (Eqs. 13-16 in Fig. 14B) compared to the faulted DADs and the transformed lahar matrix. A power regression (Eq. 13 in Fig. 14B) 595 characterizes the reworked DADs with the secondary fractured matrix around ~40%. These include Pichu 596 Pichu and El Misti thrust lobes, and the Mont-Dore fault zone with pseudotachylite and injection structures of 597 clastic and fluidized matrix. A linear regression for lahar deposits such as the El Misti transformed deposits 598 599 (Eq. 14 in Fig. 14B, Bernard et al., 2017) has the ellipse/a/b ranging from 1.32-3 around ~60-70% of fluidized matrix. Two intersected regressions (in C1, Eqs. 15-16 in Fig. 14B) characterize the transformed avalanche 500 501 deposits with a range of 42-60% of matrix: a logarithmic regression for the transformed and fluidized matrix such as the Pichu DAD with ellipse/a/b ranging from 1.7-2.59 (Eq. 15 in Fig. 14B); a linear regression 502 for the frictional faulted DADs and the associated pyroclastic deposits with ellipse/a/b between 1.51 and 2.59 503 (Eq. 16 in Fig. 14B). 504

Two points of intersection (A1 and A2 in Fig. 14B) show similar values around ~35% matrix related to the inherited clast-shapes with ellipse/a/b ~3.4 between the reworked DADs and the frictional faulted deposits, and ellipse/a/b ~3 for the transformed DADs. These four regressions intersect the faulted DAD regressions in B1 to B4 (Eqs. 12-16 in Fig. 14B) between 38-51% of matrix and ellipse/a/b ~2.5-3, implying that a cataclastic primary texture in fault zone such as inherited jigsaw-breccias recorded the initial dilation of the collapsed edifice.

The transformed DADs show a similar, cataclastic evolution linked with frictional faulted deposits (C1 and C2 511 512 in Fig. 14B), such as the cataclastic gradient in the Río Chili DAD (Bernard et al., 2017) with a fluidized matrix around 68% in C2 and ellipse/a/b = 1.4 (El Misti, Pichu Pichu, Mont-Dore, Eqs. 14-15). This convergent 513 514 evolution may be associated to the secondary fracturing along shear faults with a partial decompression of fluids generating extensional syn-transport transformations in the crushed deposits. Fractured matrix between 515 516 20-58% is attributed to thermal effect with ellipse/a/b < 2 such as at the Tutupaca ridge DAD and the graben of Pichu Pichu DAD. This intersects faulted DADs with <20% matrix (C3, Eqs. 9-10), reworked DADs around 517 518 ~45% matrix (C4, Eq. 13), and frictional faulted deposits between 55-58% matrix (C5, Eq. 16).

519 From the primary inherited textures linked with the collapsed edifice, a transitional stage of the cataclastic 520 transformations appears with a convergent evolution of DAD lithofacies along shear fractures during the runout process. Regressions of thermal effects (Fig. 14) intersect equally the reworked DADs and the frictional faulted 521 deposits, such as the Tutupaca ridge DAD and the Pichu Pichu thrust lobe. The vertical facies distributions 522 have recorded the initial decompression of the collapsed edifice generating the fluid phases related to the syn-523 eruptive DADs with the proximal associated deposits. The distal fault zones may contribute to produce clastic 524 matrix during decompression generating co-seismic fluids with the localised frictional heating between 45-60% 525 matrix and a fluidization into lahar deposits with ~70% matrix. The syn-emplacement cataclastic gradient is 526 related to the fluidized sole of seismogenic thrust, similar to the Perrier DAD fault zone (Mont-Dore, Bernard 527 and van Wyk de Vries, 2017), a precursory stage to syn-sedimentary transformations into lahar deposits. 528

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530 5.3.3. Last stages of distal emplacement process

531 The Pichu Pichu thrust lobes compared to other worldwide debris-avalanche deposits define the studied distal fault zone such as a channelized and faulted DAD, showing the hybrid lithofacies in an extensional context, a 532 precursory stage to syn-sedimentary transformations into lahar deposits. The comparison of sedimentary 533 534 characteristics of DAD matrix implies a syn-transport deflection of the Pichu Pichu thrust lobe against a topographic obstacle in the Arequipa basin generating primary and secondary fracturing along N130 strike-slip 535 536 faults cutting the basement. Lava breccias with secondary fractures are thrust on the basal fluidized matrix. Syn-emplacement brecciation is related to a co-evolution of lithofacies along the thrust lobe in rotational shear 537 538 (Figs. 3-4) such as clast breakage, cataclastic gradient and granular segregations, similar to the Tutupaca ridge DAD, the Meager hybrid deposits and the Pardines reworked deposits. 539

Basal sheared brecciation produced cataclastic and fluidized matrix, similar to the Pungarehu DAD and El 540 Misti transformed deposits (Roverato et al., 2014; Bernard et al., 2017). A typical lithofacies assemblage with 541 reverse grading (Francis, 1993) disappears in an extensional context with vertical injections and mixing. In the 542 graben, the clasts are sorted within the mixed and polymodal matrix. The distal hybrid DAD shows syn-543 544 sedimentary cataclastic mixing with longitudinal sorting such as the cataclastic gradient through the El Misti and Rio Chili deposits. Partial decompression of co-seismic fluids generates an extensional syn-transport 545 transformation in the crushed deposits with frictional heating and fluidization. Secondary clastic matrix may 546 547 contribute to transformations into lahars.

- 548
- 549

650 6. Conclusions

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Debris avalanche fault textures studied with quantitative sedimentological analyses help us to characterize the 552 553 internal structures of volcanic debris-avalanche deposits, at a distance of 28 km from the extinct Pichu Pichu 554 compound volcano. Along the thrust lobe, a cataclastic gradient is established in more than eleven syn-555 emplacement breccia structures including two polymodal lava sheared sigmoids, the bimodal matrix inside jigsaw-fit breccias, and the polymodal matrix mixed in the graben. The granular segregations and the 556 brecciation may be the precursory stages of the syn-sedimentary transformations of the debris-avalanche matrix 557 into lahar deposits. A thermal effect of clast fragmentation with dilation may be correlated with the distal 558 transformed deposits. 559

From the statistical dataset of eleven DAD structural units, we compare the transformed and hybrid deposits, the reworked DADs into secondary hybrid lithofacies and transformations into lahar deposits. Sand-sized matrix percent and fractal *D*-values range between 2.3 and 2.7 contribute to differentiate the primary cataclasis from the secondary extensional fractures leading to granular disaggregation and matrix transformations. Three textural classes of avalanche fault zones have been characterized by the ellipse/*a/b* values of ~2.14 for the planar collapse along faults, of 1.75 to 2 for the crushing, and <1.7 for the thermal effect of clast breakage. An inherited clast shape with a/b = 2.5 and ellipse = 4 suggests a co-evolution of avalanche lithofacies.

Equations have been developed that imply a syn-emplacement cataclastic gradient along avalanche fault zone. 567 Tectono-volcanic controls of recurrent avalanche deposits in Peru are differentiated such as Ticsani DAD (H/L 568 = 0.13, Bernard, 2008), Tutupaca ridge DAD with pyroclastic deposits (H/L = 0.12, Samaniego et al., 2015; 569 Valderama et al., 2016, 2018), Pichu Pichu and El Misti DADs (H/L = 0.11-0.24) transformed into lahar 570 deposits. These and the textural studies can be used to better assess the avalanche runout models extending in 571 distal tectonic basins, such as the pull-apart basin of Arequipa, which has acted as a sedimentary receptacle of 572 573 the DADs from three volcanic complexes with structural control, namely Chachani, El Misti and Pichu Pichu 574 volcanoes.

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| 341 | |
| 342 | Table |
| 343 | |
| 344 | Table 1 |
| 345 | Definitions and textures of the avalanche lithofacies compared to other lithofacies worldwide. |
| 346 | |
| 347 | Table 2 |
| 348 | Morphometric characteristics of eight debris-avalanche deposits (DADs) mapped from Google Earth and |
| 349 | published data on six DADs (Legendre, 1999; Legros et al., 2000; Thouret et al., 2001; Finizola et al., 2004; |
| 350 | Aguilar et al., 2015; Bernard, 2015; Bernard et al., 2017). Collapse scar parameters: 1. Shape; 2. Length (L); 3. |

Altitude (m). Avalanche parameters: 4. Age (Ma); 5. Runout distance (*L*); 6. *H/L* ratio; 7. Structures.

352

353 **Table 3**

Statistical grain-size parameters of the Pichu Pichu thrust lobe compared with other DAD characteristics (after Folk and Ward, 1957): 1. Median diameter (*Md*); 2. Matrix percent (≤ 2 mm); 3. Sand-sized matrix-gravel ratio; 4. Sorting index (σ); 5. Skewness (*SK*_G); 6. Kurtosis (*K*); 7-9. Fractal analysis with exponent *h* of the power regression and fractal *D*-values (correlation coefficients between 0.9-0.99, Suzuki-Kamata et al., 2009) correlated with range of clast sizes in millimeters; 10. Travel distance in meters.

359

360 **Table 4**

DAD sedimentological classification, including clast shape parameters correlated with syn-emplacement avalanche structures.

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364 **Figure captions**

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Fig. 1. Setting of the debris-avalanche deposits (DADs) of El Misti and Pichu Pichu volcanoes in south Peru. A. Landforms of the avalanche deposits in the Arequipa basin (~100 km²) from Google Earth. Insets top right show location of Pleistocene volcanoes in the CAVZ with their tectonic context. The outlined areas represent two DADs from Misti (DAD0, DAD1, Thouret et al., 2001; Bernard et al., 2017), three DAD structures and sliding lobes (nos. 1-5) coming from the Pichu Pichu compound volcano with reference box for image B; B.
Structures and geology in the NE area of the city of Arequipa showing the DAD thrust lobe (nos. 1-8) in
inverted extensional faults (nos. 9-15) which has been transformed into lahar deposits down valley.

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Fig. 2. Volcanic avalanche lithofacies of the thrust lobe at a distance of ~28 km from the extinct Pichu Pichu 374 375 compound volcano in Peru. A. Structural variations in lava-rich breccias of the Alto Jesus thrust DAD along four sections (1-4): under-thrust and upper thrust zones (1); conjugate thrust with boudinage of mixed layers 376 377 (2); aggradation at the front of the DAD thrust lobe (3); N30E-trending rotational shear (4). The lithostratigraphic section to the right shows the basal thrust contact of the matrix-rich DAD (MD), the red lava 378 379 block-rich facies (rLB), the grey lava block-rich facies (gLB), the interlayered and mixed matrix facies (M1-5), an unconsolidated brown clay-rich layer (bC), the discontinuous ash-rich pumice layers (I), layered lava-flow 380 breccias and debris-flow deposit (DF); B. Avalanche lithofacies along the thrust lobe in the Arequipa basin. The 381 lithostratigraphic section to the left shows basal deposits of thin, grey ash (A1), red lava block-rich facies 382 (rLB), grey lava block-rich facies (gLB), grey ash of angular clasts (A2), the non-cohesive brown clay-rich 383 layer (bC) with thrust ignimbrite (I), and layered lava breccias overlain by debris-flow deposits (DF). These 384 385 nomenclature lithofacies are referred in Figs. 3-5.

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Fig. 3. Lithofacies assemblage of the Alto Jesus thrust DAD (~5 km east of the city of Arequipa) showing 387 388 textural and structural variations. A. Sketch cross-section (N160E) of the thrust lobe: SSE side of thrust zone with basal under-thrust of the MD matrix-rich DAD (1), NE stretching of the M sandy matrix (2), aggradation 389 390 of the DAD lithofacies at the front and lateral extrusion (3-4), exhumation of lava-rich breccias to the East of thrust lobe (5), condensed succession of reworked deposits at the thrust front (6), N120 basal extrusion of 391 392 mixed lithofacies (7), thrust lobe faulted in horst and graben (8); B. Lithostratigraphic sections (1-8) of thrust units; C. Cataclastic gradient of syn-emplacement structures as observed in sections 1 to 8, with clast 393 394 distributions in a double log diagram calculated with the inertia method in *blue* compared to the intercept method in *pink* from SPO analysis (Launeau, 2004) and mean values of *a/b* ratio and *e* ellipse: jigsaw-fractured 395 396 blocks with a polymodal distribution in gLB (1); tension crack filled by shear fine-grained facies (M1-2) with a bimodal distribution (2); sigmoidal shape of polymodal jigsaw-breccias in gLB tilted in fluidized M2 matrix at 397 the front (3-4); cataclastic gradient of sheared lava breccias in rLB with an unimodal grain-size distribution (5); 398 jigsaw fracturing in clay clasts stretched in mixed matrix (gLB+M2) along basal shear thrust (6); jigsaw-clasts 399 stretched in MD+LB mixed matrix (7), sheared lava breccias between gLB and rLB in half-horst (8). These 900 nomenclature lithofacies are referred in Fig. 2. 901

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Fig. 4. Structures in lava-rich breccias along the Alto Jesus DAD lobe showing shearing at the base of the thrust section. A. Tension cracks with mixed matrix; B. Basal lava sheared sigmoids (S1 and S2) with

cataclastic shear bands of dihedral lava-block related to an antithetic rotational shear of 30° in coaxial deformation. These nomenclature lithofacies are referred in Fig. 2.

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Fig. 5. Lithostratigraphy of the frontal thrust lobe along inverted extensional faults observed at Pampa Blanca located in Figs. 1-2. A. Lithostratigraphic sections of thrust units (9-16) with mixed and transformed lithofacies; B. Lithofacies distribution observed in the thrust lobe (9-10) and under-thrust (11) with tilted deposits in horsts and grabens (12-14), and transformed deposits at the frontal lobe (15-16); C. Cataclastic gradient of the lava-rich breccias into the frontal thrust lobe with clast distributions, mean shape parameters such as a/b ratio and ellipse *e* values (Launeau, 2004). These nomenclature lithofacies are referred in Fig. 2.

- **Fig. 6.** Mixed and transformed units of the matrix-rich DAD observed in the Pampa Blanca graben. A. Outcrop picture with its interpreted section and SPO analysis from 1490 clasts (Launeau, 2004). The reverse graded matrix is unconformably overlain by debris-flow deposit. Inset box in A shows inherited jigsaw-fractured breccias in B; B. Enlarged area of jigsaw-fractured breccias with polymodal distribution and preferential clast dips at 80° in the cataclastic matrix.
- 920

Fig. 7. Sedimentological analysis of the debris-avalanche deposits in thrust lobe originated from the Pichu Pichu compound volcano. A. Cumulative curves of the matrix between -5 and 5 Φ of the DAD lobe; B. Sandygravel matrix percent *vs.* matrix-gravel ratio as shown through several textural variations in deposits.

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Fig. 8. Statistical grain-size parameters of the Pichu Pichu DAD lobe. A. Sorting index (σ) *vs.* median diameter (Φ). The outlined area represents the subpopulation values of the matrix collected in jigsaw-fractured breccias (thin lines, $\sigma < 2.1$; $Md = -6-3 \Phi$). The grey area represents the data obtained from the Pinatubo's lahar deposits (Major et al., 1995); B. Ellipse/*a/b vs.* sand-sized matrix percent. The grey area represents the data points of transformed DADs attributed to fluidized decompression. The pinkish area represents the data points of fractured matrix associated with thermal effect and associated pyroclastic deposits.

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Fig. 9. Clast shape analysis and co-evolution between several lithofacies of lava-rich breccias observed along the Alto Jesus thrust lobe. A. Diagram showing the relationships between a/b and travel distance, and two categories of regressions (Eqs. 2 and 3); B. Ellipse *vs.* travel distance showing decreasing values with four regressions (Eqs. 4 to 7); C. Textural tree diagram of lava-rich breccias associated to structural variations along the Alto Jesus thrust lobe. Inset sketch shows the textural tree diagram between lithofacies referred to in Figure 3C.

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Fig. 10. Sedimentological characteristics of the Pichu Pichu avalanche deposits compared with other DADs in

Peru and Canada, and transformed matrix into lahar deposits. A. Cumulative % vs. grain-size distribution (Φ) of Pichu Pichu thrust lobe with other DADs in Peru and Canada, and transformed matrix towards lahar deposits; B. The matrix percent vs. sand-sized matrix-gravel ratio allows us to distinguish four types of textural variations in lithofacies and deposits. Other DADs include (Bernard, 2015): Pichu Pichu: A. Alto Jesus; Pp. Pampa Blanca; Tr. Tutupaca ridges; Mont-Dore in French Massif Central: P. Reworked Pardines deposits; Transformed DAD deposits. M. Hybrid Meager DAD (Canada); Ndf. Transformed DADs in debris-flow

- deposit in the Quebrada San Lazaro valley at El Misti, in Peru (Bernard et al., 2017).
- Fig. 11. Statistical grain-size parameters of the matrix in the -5 to 5 ϕ size range from six DADs compared to 948 949 those of other DADs in Peru and associated lahar deposits. Mean values: A. Skewness vs. kurtosis; B. Sorting index (σ) vs. median diameter (Φ) with different zones: 1. Hybrid DADs between -2 and -1.5 Φ with σ = 1.9-950 2.4; 2. Transformed DADs into lahar deposits in the Quebrada San Lazaro valley with $Md > 0.5 \Phi$; 3. Primary 951 fractured matrix between -3 and -2 ϕ with σ <1.5. The outlined area with dotted lines represents the field of the 952 Pinatubo's lahar deposits (Major et al., 1995). The grey area represents the data obtained from the dewatered 953 954 DADs; C. Energy for fragmentation/energy potential vs. fractal D values (Crosta et al., 2007). The DAD units 955 are referred in Figure 10 with other DAD worldwide. Ch. Chimborazo; t. Taapaca; T. Ticsani (Bernard, 2008); 956 Nevado de Colima (Capra and Macias, 2002): D. DAD dam break-out; L. Lahar deposit; Transformed DADs. I. Cohesive Illiama lahar deposits (Waythomas et al., 2000); O. Osceola dewatering deposits (Scott et al., 1995). 957 958
- **Fig. 12.** Textural comparison of Pichu Pichu avalanche lithofacies with other DADs based on matrix percent and ellipse/a/b values.
- 961

Fig. 13. Lithofacies evolution along the avalanche thrust lobe at ~28 km from the Pichu Pichu compound volcano, compared to other DADs. Cataclastic lithofacies with structural control associated to synemplacement processes are characterized by the matrix percent, ellipse values and ellipse/a/b vs. matrix percent. The diagram shows two categories of regressions for cataclastic avalanche matrix (1) and faulted DADs (2).

967

Fig. 14. Clast shape parameters along the DAD fault zone related to emplacement process. A. Diagram showing ellipse *vs.* travel distance; B. Ellipse/*a/b vs.* matrix percent diagram. Dotted lines represent two regressions of lithofacies evolution along the Pichu Pichu fault zone as shown in Figure 13. The pinkish area represents the data points of fractured matrix related to thermal effect and associated pyroclastic deposits. The nomenclature lithofacies are referred to in Figure 10B with other DAD lithofacies. Mont-Dore in the French Massif Central: C. Cheix lateral levee; G. Perrier gouge; El Misti (Peru): Rc. Río Chili DAD. The grey area represents the data points of the proximal planar collapse along faults. The outlined area with dotted lines

- presents the field including crushed lava clasts along rotational shear (Bernard et al., 2017).
- 976

977 Supplemental File 1

- Statistical grain-size parameters vs. distance as deduced from the mixed lithofacies into graben of the Pichu
- P79 Pichu thrust lobe. A. Variations in segregations of the granular fractions along travel distance; B. Statistical
- grain-size parameters such as sorting index (σ), fractal *D*-values, sand-sized matrix-gravel ratio, kurtosis and
- 981 skewness vs. travel distance.



Fig. 1.







Fig. 2.





Fig. 4.



Fig. 5.



Fig. 6.



Fig. 7.



Fig. 8.



Fig. 9.



Fig. 10.



Fig. 11.

| | | | Sand-s | sized matrix % | | |
|---------------------------|-------------------------------|-------------------------|----------------------------------|----------------------------------|---------------------|--------------------------------|
| | <20% | 20-30% | 30-40% | 40-50% | 50-60% | 60-70% |
| Edifice DAD | Jigsaw fractured matrix | Basal sheare matrix | d Primary fractured matrix | Secondary fractured matrix | Transformed DADs | Lahar deposits |
| Pichu Pichu volcano | | | | | Res . | |
| Thrust DAD | Jigsaw-block | Lava sheared sigmoid | Lava breccias | Tilted jigsaw- | Sheared matrix | Mixed jigsaw -clasts |
| Ellipse/a/b | 2.08 | 1.94 | 3.43 | breccias 2.12 | 1.15 | 1.4 |
| El Misti volcano | | | | A decision | | |
| Río Chili DAD | | | | Jigsaw mixture | Cm 25 cm | ⁿ sit Mixed deposit |
| Ellipse/a/b | | | | 1.55-3.01 | 2.15 | 1.63 |
| El Misti volcano | | | | | | Martin . |
| San Lazaro transformed | | | 7 cr | n Tem | 6 cm | a sem |
| deposits | | | Reworked DAD | Jigsaw-fractured | Debris-flow | Hyperconcentrated |
| Ellipse/a/b | | | - | breccias 1.53 | deposit 2.01 | flow deposit 2.25 |
| Mont-Dore Massif | | See 1 | | | | |
| Perrier fault DAD | | Distal gouge | Sheared | Megablock contac | | lem riv |
| Ellipse/a/b | | 2.92 | basal contact | 2.59 | 1.16 | |
| Tutupaca | | | - Anderson | | | |
| Ridge DAD | 7 cm ¹ | Faulted breccias | Mixed breccias | Inherited frac | ctured breccias | <u>n</u>] |
| Ellipse/a/b | 1.85 | 1.87 | 1 84 | 1 73 | 1.63 | |

Fig. 12.



Fig. 13.



Fig. 14.

Table 1

Lithofacies and textures from worldwide examples

Bezymianni and Bandai-type DADs interstratified between syn-eruptive associated deposits. Polymodal grain-size Syn-eruptive distributions with hydrothermal alteration: block-rich debris facies with <30wt.% matrix (≤ 2 mm; Glicken, 1986); avalanche matrix-rich lithofacies with a lithological composition deposit, similar to the DAD blocks (Glicken, 1986); Mixed (DAD) lithofacies in the median zones with polylithological Tutupaca ridge DAD (Bernard, composition.

Gravitational mass-flow deposit showing collisional textures in cataclastic breccias with jigsaw-fractured breccias due to granular interactions with dynamic fragmentation (Capra and Macías, 2002; Davies and Mc Reworked Savenney, 2006, 2009). Coarsely stratified, poorly sorted hybrid DAD breccias with inherited megaclasts interstratified between DAD and lahar deposits (Nevado de Colima, Capra and Macías, 2002; middle unit of the Ruapehu deposits, Keigler et al., 2011).



Observed deposits

2015)



Pardines reworked deposits

(Bernard, 2015)

Volcanic debris facies up to 70-90% of poorly sorted clasts related to rapid flow dynamics (Schmidt, 1934; Vallance and Scott., 1997) showing cataclastic breccias, inherited Transformed jigsaw-fractured breccias (Citlaltepetl, Carrasco-Núñez et DAD into al., 1993; Mt. Rainier, Scott et al., 1995). Sandy fraction lahar St-Helens, Glicken, (40-60%, e.g., Mt. 1986) of deposits hyperconcentrated flow deposits due to dilution downstream. Transitional laminar flow to turbulence (Pierson and Scott, 1985).



El Misti hyperconcentrated flow deposits (Bernard et al., 2017)

| | Collapse scars | | | | | | Volcanic debris-avalanche deposits | | | |
|----------------------|----------------|---------------------------|-----------|-------------------------|-----------------|-----------|------------------------------------|---|--|--|
| | - | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | |
| Volcanoes | | Shape | L (km) | Max. altitude (m) | Age (Ma) | L (km) | H/L | Structures | | |
| El Misti | DAD1 | U-shaped scar | 4.2 | 3961 | 112 ka | 12 | 0.24 | Thrust lobes cut down by the Quebrada San Lazaro | | |
| | DAD0 | Subdued | | 4000 | 830 ka | 25 | 0.11 | Tilted megablocks in the Río Chili canyon | | |
| Estribo- Chachani | | | | | 0.908- 0.694 | | | Lava breccias | | |
| | 1 | Horseshoe- shaped scar | 3 | 5155 | | 8 | 0.2 | Sliding lava-flow lobes | | |
| | 2 | Horseshoe- shaped scar | 4.36 | 5371 | | 12.7 | 0.17 | Transverse megablocks with lateral spreading | | |
| Pichu Pichu | 3 | U-shaped scar | 8.14 | 5416 | 1.2-1.6 | 10 | 0.19 | Lateral levee and channelized deposits | | |
| | 4 | Five nested scars | 10.8 | 5425 | | 28 | 0.09 | Asymmetric thrust lobe due to distal spreading and showing inverted extensional fault | | |
| | 5 | U-shaped scar | 5 | 5247 | | 10 | 0.22 | Stretched lobes against topographic obstacles | | |

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|----------------------------------|-------------|--------|------------------|------|-----------------|---------|----------------|-------|----------|--------------|
| | Md | Matrix | Matrix | _ | SV | V | Fractal values | | Range of | Travel |
| | (\varPhi) | % | -graver ratio | 0 | SΛ _G | Λ | h | D | (mm) | (<i>m</i>) |
| Lava sheared | -3.03 | 27.4 | 0.376 | 2.39 | 0.48 | 0.84 | 0.457 | 2.08 | 0.25-1.6 | 1 |
| sigmoids | -3.13 | 31.8 | 0.466 | 2.41 | 0.58 | 0.75 | 0.451 | 2.09 | 0.13-1.6 | 2 |
| | -2.51 | 30.9 | 0.447 | 2.18 | 0.36 | 0.77 | 0.449 | 2.1 | | 3 |
| Alto Jesus | -1.34 | 45 | 0.822 | 2.36 | 0.11 | 0.78 | 0.367 | 2.26 | 0 25-1 6 | 4 |
| DAD | -0.79 | 51.7 | 1.07 | 2.58 | -0.13 | 0.57 | 0.242 | 2.51 | 0.25 1.0 | 5 |
| | 0.005 | 58.9 | 1.433 | 2.2 | -0.28 | 0.64 | 0.229 | 2.54 | | 6 |
| Alto Jesus mean values | -3-0 | 27-58 | 0.37-1.43 | 2.35 | -0.2- 0.5 | 0.5-0.8 | 0.265 | 2.469 | 0.5-8 | - |
| Jigsaw- | -5.3 | 14.6 | 0.17 | 2.02 | 0.98 | 0.88 | 0.38 | 2.24 | 1 to 8 | |
| fractured | -3.25 | 22.8 | 0.3 | 2 | 0.53 | 0.9 | 0.6 | 1.8 | | 1 |
| breccias | -4.05 | 21.8 | 0.28 | 2.13 | 0.95 | 0.88 | 0.53 | 1.93 | 0.25-16 | |
| | -5.25 | 10.2 | 0.11 | 1.86 | 0.4 | 1.69 | 0.55 | 1.88 | 0.063-16 | |
| Matrix in the | -4.25 | 35.6 | 0.55 | 3.13 | 1.7 | 0.63 | 0.27 | 2.44 | 0.25-32 | 1 |
| grahen | -0.4 | 56.8 | 1.31 | 2.46 | -0.3 | 0.66 | 0.24 | 2.5 | 0.25-16 | 2 |
| gruben | -0.6 | 54.5 | 1.2 | 2.59 | -0.15 | 0.7 | 0.26 | 2.46 | 0.25-8 | 3 |
| Domno Dionoo | 0.95 | 75.4 | 3.07 | 2.07 | -0.43 | 0.92 | 0.15 | 2.68 | 0.25-16 | 5 |
| | 0.35 | 68.4 | 2.16 | 2.09 | -0.27 | 0.81 | 0.248 | 2.5 | 0.25-8 | 5 |
| DAD | 0.6 | 66 | 1.94 | 2.43 | -0.68 | 0.76 | 0.188 | 2.62 | | 6 |
| | -0.1 | 59.6 | 1.48 | 2.64 | -0.53 | 0.66 | 0.218 | 2.56 | 0.25-16 | 7 |
| Pampa Blanca mean values | -5-0.9 | 10-75 | 0.11-3 | 2.31 | -0.6- 1.7 | 0.6-1.6 | 0.334 | 2.33 | 0.5-8 | - |
| Tutupaca DAD ridges | -3.05 | 22.82 | 0.29 | 1.31 | 2.52 | 0.52 | 0.42 | 2.158 | 0.5-8 | - |
| Meager hybrid DAD | -2.23 | 23.21 | 0.44 | 1.29 | -0.04 | 1.07 | 0.28 | 2.43 | 0.5-16 | - |
| El Misti transformed DAD | -0.83 | 53.93 | 1.17 | 1.85 | 0.28 | 0.75 | 0.337 | 2.325 | 0.5-4 | |
| Pardines reworked deposits | -1.67 | 44.46 | 1.09 | 2.03 | 1.05 | 0.58 | 0.2 | 2.599 | 0.5-2 | - |

| | | Equat | ions | Resulting lithofacies and deposits | | | |
|---------------|----------|-----------------|-----------------|---|---------------------------------|--|--|
| Sand-sized | | | | Lava domes, primary and secondary fractures | | | |
| matrix % vs. | f(x) = 1 | $5.4 \ln(x) + $ | - 48.67 (9) | Hybrid debris-avalanche deposit | | | |
| matrix/gravel | | m r ig. | 1011 | Transformed debris-avalanche deposit | | | |
| | Kurtos | is (SK_G) | Skewness (K) | | | | |
| Statistical | 1-2.5 | | < 0.6 | Faulted DAD | | | |
| grain-size | < 0.5 | | 0.7-0.83 | Hybrid debris-avalanche deposits | | | |
| parameters | 0- | 0.55 | 1-1.07 | Transformed DAD matrix into lahar deposit | | | |
| | Sorting | index vs. 1 | nedian diameter | Fracturation, hybrid D | DAD, lahar deposits | | |
| | a/b | Ellipse | Ellipse/a/b | | | | |
| | 1.66 | 3.551 | 2.146 | Cheix lateral levee in Mont-Dore Massif | Planar collapse in fault | | |
| | 1.743 | 3.74 | 01/02/15 | Río Chili DAD of El Misti volcano | trough | | |
| Clast shape | 1.5 | 3.12 | 2.08 | Thrust lava breccias Pichu Pichu DAD | Collapse of lava flows | | |
| parameters | 1.702 | 2.988 | 1.755 | Perrier DAD fault zone in Mont-Dore Massif | Crushing | | |
| | 1.501 | 2.538 | 1.691 | Transformed matrix mixed in graben Pichu Pichu DAD showing inverted extensional faults | Thermal effect of fragmentation | | |
| | 1.69 | 2.728 | 1.609 | Tutupaca ridge DAD | | | |