# LARGE-SCALE EXPLOSIVE ERUPTION AT HUAYNAPUTINA VOLCANO, 1600 AD, SOUTHERN PERU

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## INTRODUCTION

The largest explosive eruption in historical times (VEI 6) in the Andes took place in AD 1600 at Huaynaputina, a small, eroded stratovolcano in southern Peru (Central Andean Volcanic Zone). The eruption began on 19 February 1600 with a plinian phase following 4 days of intense seismic activity, and lasted at least until 6 March. Repeated tephra falls, pyroclastic flows, and surges devastated the landscape within an elliptic area about 90 · 60 km west of the volcano, claimed ~1500 lives, and affected indirectly all southern Peru. Earthquakes shook the town of Arequipa 75 km away and large-scale lahars (•0.18 km$^3$), likely fed by ignimbrites and triggered by lake outbursts, swept the 120-km-long valley of Rio Tambo and entered the Pacific Ocean during and after the eruption.

The erupted tephra (medium-K dacite), totalling 11.9-13.5 km bulk volume (DRE 7-9.5 km$^3$ ; Table 1), include eight deposits (Fig. 1) : (1) a widespread (~360,000 km$^2$, Fig. 2) and voluminous pumice-fall deposit (~8.1 km$^3$, DRE 4.6-4.9 km$^3$, Table 1) in one extensive lobe (), (2) several alternate ash layers, (3) ignimbrites 1.5-2 km$^3$ from pumice-rich flow deposits channeled •40 km in the Tambo canyon, with (4) ground-surge and ash-cloud surge deposits, (5) base-surge deposits, (6) crystal-rich flow/surge deposit toward the west-northwest, (7) unconfined ash-flow deposits with proximal lag breccias and ground surge deposits, which travelled at least 60 km from the vent over •1000-m-high topographic barriers, and (8) late ash-fall and surge deposits.

By linking up the seven series of events inferred from chronicles to measured deposits, we distinguish seven eruptive phases: plinian, ash-bearing, ignimbritic, phreatomagmatic, and emplacement of crystal-rich flows/surges, ash flows, and late ash falls and surges.

A plinian eruption column 33-35 km high was sustained at least 13 hours and lasted likely as much as 19 hours from 19 February to 20 February 1600. The volumetric eruption rate was short of $10^5$ $m^3/s$ and the mass eruption rate ranged from 1.2 to 1.75 x $10^8$ kg/s (Table 1). The plinian phase probably included the disruption of a hydrothermal system enclosed in the pre-AD 1600 amphitheater. Fallout dispersal has shifted through time, first from south to southwest, then to west and west-northwest, owing to three wind patterns over the vent area. Stratospheric winds in excess of 30 m/s carried aloft ash •600 km to west and west-northwest well into the Pacific Ocean. An area •100 000 $km^2$ was also covered by >1-cm-thick layer of co-plinian ash and co-ignimbrite ash (deposits 2 and 3).

The post-plinian ignimbritic phase and subsequent phreatomagmatic interactions promoted a catastrophic erosion, leading to the formation of four nested vents, and to the eruption of a crystal-rich magma toward the end of the event. Close association and sharp contact between two pairs of crystal-rich flow deposit and thin, overlying layers of vitric ash suggest that they result from segregation/elutriation during flow transport, owing to strong influence of the rugged topography on the emplacement of relatively small-volume, shallow pyroclastic density currents with internal stratification. At the end of the eruption, unconfined ash flows may have been strongly turbulent, pulsatory, subcritical flows (Ri >1, velocity 50-110 m/s), but so fluidized that they were able to surmount ridges •1000 m high as far as 60 km due west from source.

## CONCLUSION

Such a voluminous explosive eruption (VEI 6, Table 1) occurred in this site because : (1) an hydrothermal system was disrupted during the plinian phase, (2) hydromagmatic interactions followed the ignimbritic phase, and (3) a crystal-rich magma was tapped, and ash flows and surges were delivered toward the end of the eruption. Although the total DRE 7-9.5 $km^3$ volume of erupted tephra did not involve caldera collapse, ring-fractures cut through the vents and the floor of the pre-1600 amphitheater, pointing to the onset of a funnel-type caldera collapse. The lack of caldera collapse may be due to the unusual depth and/or to the size and shape of feeding dykes through the weathered volcanic bedrock. The AD 1600 eruption was the largest historical event in southern Peru, but was neither the single nor the largest event in the Huaynaputina eruptive history. Four large-scale (>1 $km^3$) eruptions from Huaynaputina and adjacent stratovolcanoes over the past 2500 years suggest a rapid regeneration of silicic magma and potential for voluminous explosive eruptions in southern Peru.

Table 1. Volcanological data for the AD 1600 plinian and ignimbritic eruption

| | |
|---|---|
| Extent of the plinian fallout (within 1-cm isopach) | ~100 000 $km^2$ |
| Extent of reported ash and dust fallout (from Fig. 1B) | ~360 000 $km^2$ |
| Volume of plinian ejecta (within 1-cm isopach and from Fig. 1B) | ~6.9 and 8.1 $km^3$ |
| Weight % ejecta < 1 mm (at 0.1T, thickness= 90 cm and 0.01 Tmax) | 73.5 and 98.3% |
| Weight % ejecta < 63 microns (at 0.1 T and 0.01 Tmax) | 57.6 and 93.4% |
| Minimum volume percent beyond 1 cm isopach | •17.5% |
| Minimum volume DRE (80% pumice, density 0.58-0.66 $g/cm^3$) | ~4.6 - 4.9 $km^3$ |
| Minimum volume of lithics (1-11% of fallout, density 2.4 $g/cm^3$) | ~0.8 - 1.05$km^3$ |
| Minimum volume of magma | ~3.6 - 4.1 $km^3$ |
| Duration of the plinian phase | 13 to 19 h |
| Mass eruption rate (SCS, 13-19 h, DRE magma, density 2.4 $g/cm^3$) | ~1.2-1.7 · $10^8$ kg/s |
| Volumetric eruption rate (same characteristics as above) | ~7.2 - 9.9 · $10^4$ $m^3/s$ |
| Peak mass eruption rate (SCS) | ~1.75 - 2 · $10^8$ kg/s |
| Peak mass eruption rate (WW) | ~3 · $10^8$ kg/s |
| Peak wind velocity (SCS) | ~32 - 33 m/s |
| Column height Ht | ~33 - 35 km (SCS) ; ~27 - 28 km (WW) |
| Column neutral buoyancy Hb | ~23.5 – 25.4 km (SCS) ; 20.5 – 21.3 km (WW) |
| Column radius R | ~8.5 – 9 km (SCS) ; 7 – 7.25 km (WW) |
| Half-thickness distance $b_t$ ; half-clast distance $b_c$ | ~8.25 km ; 7-7.5 km |
| Tropospheric injection | substantial |
| Stratospheric injection (inferred from ice cores and tree-ring chronology) | definite |
| Volume of ash layers (deposit 2) | 0.2 – 0.25 $km^3$ |
| Volume of channeled pyroclastic-flow deposits 3 (from Fig. 3B) | ~1.5 - 2 $km^3$ |
| Travel distance of channeled pyroclastic flows (Rio Tambo valley) | 40 - 45 km |
| Volume of pyroclastic-surge deposits (deposits 4 and 5) | ~0.05 - 0.06 $km^3$ |
| Volume of crystal-rich deposit (deposit 6) | ~0.5 - 0.6 $km^3$ |
| Volume of ash-flow deposit and late ash layers (deposit 7 and 8) | ~0.15 – 0.2 $km^3$ |
| Minimum travel distance of ash flows over •1000-m-high topographic barriers | 60 km |
| Volume of distal co-ignimbrite ash and/or co-plinian ash beyond 5-cm isopach | ~1.2 - 2.4 $km^3$ |
| Total bulk volume (plinian and post-plinian tephra) | ~11.9 - 13.5 $km^3$ |
| Total volume DRE (plinian and post-plinian tephra) | ~7 - 9.5 $km^3$ |
| Volcanic explosivity index | 6 |
| Volume of lahar deposits in Rio Tambo | average 0.12 $km^3$, maximum 0.18 $km^3$ |

SCS refers to the methods of Sparks (1986) and Carey and Sparks (1986) for a tropical atmosphere, using lithic and pumice isopleths fromThouret et al. (1999) and a magma temperature of 850 °C appropriate for dacite. WW refers to the method of Wilson and Walker (1987), assuming 1-3% magmatic water, 200-250 m vent radius, and 200 m/s muzzle velocity. MER is mass eruption rate of magma. VER is volumetric eruption rate, in terms of dense-rock equivalent (DRE) of a dacitic magma having a density of 2.4 $g/cm^3$

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